BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Volumul 63 (67), Numărul 3, 2017
Secţia
CONSTRUCŢII. ARHITECTURĂ

# ACCURACY IN PREDICTING THE COMPRESSIVE STRENGTH OF CONCRETE USING SONREB METHOD

BY

**COSTEL CHINGĂLATĂ*, MIHAI BUDESCU and RADU LUPĂŞTEANU**

"Gheorghe Asachi" Technical University of Iaşi
Faculty of Civil Engineering and Building Services

Received: August 18, 2017
Accepted for publication: September 21, 2017

**Abstract.** The SonReb method is a non-destructive procedure that is used for determining the compressive strength of existing concrete elements. This procedure consists in applying the results provided by the rebound hammer (RH) and the ultrasonic pulse velocity (UPV) methods, in specific analytical models. Generally, the results provided by the combined method are more accurate than those given by either UPV or RH methods. The analytical models that are used for the SonReb are developed empirically and consist in regression mathematical principles.

This paper is structured in two parts: the first one presents the general principles and the main advantages of the SonReb method, while the second part focuses on checking the accuracy of the existing analytical models. For this reason, 11 empirical mathematical equations frequently used in the estimation of the compressive strength values of concrete elements, have been selected. The variables of the mathematical equations are only referring to the experimental data given by the two non-destructive methods, UPV and RH. By comparing the estimated values of the compressive strength with the ones obtained by destructive tests, it has been concluded that only 3 of the 11 models provide accurate and precise results.

**Keywords:** concrete compressive strength; SonReb method; analytical models; comparative study; prediction accuracy.

---

*Corresponding author: *e-mail:* costel.chingalata@tuiasi.ro

## 1. Introduction

Evaluating the compressive strength of concrete elements belonging to existing buildings is an important challenge for civil engineers since it requires complex destructive or non-destructive test (NDT) methods. The most important factors that are considered when the appropriate test methods are selected consist in: the degree of damages that are induced to the concrete element during the investigation, the overall costs, duration and complexity of the procedure and the impact upon the normal operation and service of the building (Malhotra, 1976).

The NDT methods represent a feasible alternative to the classical invasive approaches, which usually consist in core extraction and laboratory tests. Moreover, the Eurocode 8 accepts and recommends complementing the extraction of cores from concrete elements with non-destructive tests, to correctly estimate their mechanical properties (Concu *et al.*, 2016). For an accurate estimation of concrete compressive strength, many researchers have recommended the combination of more non-destructive methods to reduce the errors induced by materials, environment or by the testing procedures.

One of the most utilized NDT method consists in combining the results of the Rebound Hammer (RH) and Ultrasonic Pulse Velocity (UPV) tests. This procedure is known as SonReb method. According to RILEM 43 CND (RILEM Draft Recommendation, 1993) the use of the SonReb combined method for the prediction of the concrete compressive strength may have the following advantages (Pucinotti, 2007):

a) by applying the RH and UPV test methods, the compressive strength is evaluated at both surface and in-depth levels, respectively;

b) the tests are rapidly carried out;

c) both methods should provide a similar level of accuracy in the estimation of the compressive strength;

d) since both tests are non-destructive, there is no need of special preparation of samples;

e) the concrete elements are not damaged during the testing procedure.

The combination of the two non-destructive methods, UPV and RH respectively, for the estimation of the compressive strength of concrete elements requires some correlations which can be determined based on the statistical regression of the experimental data and should be calibrated through compressive tests carried out on cores or laboratory prepared specimens (Concu *et al.*, 2016).

Performing the non-destructive tests to predict the concrete compressive strength must be made by considering the following main steps: (i) checking the aspect of the concrete, at surface level, to identify potential differences in homogeneity, (ii) establishing the location and the number of testing zones as a function of the imposed level of knowledge and (iii) determining the physical properties of the concrete element that may affect the results (Masi & Vona, 2009).

The aim of this paper is to check the accuracy of several mathematical models that can be used in estimating the compressive strength values of the concrete elements investigated with RH and UPV methods. The compressive strength values obtained by applying the destructive and non-destructive tests on 16 extracted specimens have been taken from the experimental work provided by Nobile and Bonagura (Nobile & Bonagura, 2013).

## 2. SonReb Method

The SonReb method consists in the combination of two simple non-destructive methods, rebound hammer (RH) and ultrasonic pulse velocity (UPV). This approach is mostly used for the estimation of the compressive strength values of existing concrete elements. The method was developed by RILEM Technical Committees, based on the research carried by the Romanian engineer I. Facaoaru (Facaoaru, 1961).

The results provided by RH and UPV tests may be influenced by a sufficiently large set of factors, depending on the investigated concrete element. For example, it has been found out that the compressive strength of concrete determined by NDT methods increases with the size of the aggregates, thus giving higher strengths than the actual ones, determined by traditional invasive methods (Arioz *et al.*, 2009). Also, the moisture content has an opposite effect on the two NDT methods that are applied in the SonReb procedure, by increasing the velocity of the ultrasonic pulse and by decreasing the rebound number (Masi & Chiauzzi, 2013). Nevertheless, the compressive strength values provided by the SonReb method are more accurate, when compared to those obtained by simple methods, based on the opposite influence of the same parameter over the simple non-destructive method results (Kheder, 1999; Qasrawi, 2000; Erdal, 2009; Masi & Vona, 2009; Huang *et al.*, 2011; Hannachi & Guetteche, 2012; Nobile & Bonagura, 2013; Concu *et al.*, 2016). Thus, the improved accuracy of the compressive strength values determined by applying the SonReb method is a result of the self-correcting mechanism for the induced errors.

The mathematical models that are proposed for the SonReb method can be divided into two general categories. The first one refers to those models that predict the compressive strength of the concrete based only on the experimental results provided by the RH and UPV methods. The second category refers to a more complex set of models that are considering an additional set of parameters that describe the compositional and physical properties of the concrete (age, water over cement and aggregate over cement ratios, moisture content, temperature etc.).

The most important advantage of combining the RH and UPV methods consists in obtaining an in-depth description of the investigated material. Thus, the combination of a surface hardness method (RH), which provides strength values for the outer side of the concrete on a depth of about 2,...,3 cm, with UPV method that characterizes the inner side of the element, can enhance the accuracy in assessing the compressive strength of the concrete element.

## 3. Mathematical Models for Estimating the Compressive Strength of Concrete

The SonReb method of approximating the compressive strength of concrete consists in applying the results provided by the non-destructive tests in some mathematical models. There is a high number of available models which were proposed by different research groups, as a result of complex experimental programs. Most of them focused on providing closed-form equations with high degree of applicability, which can be used in estimating the compressive strength for many concrete mixes. However, when some specific properties of the material are known (age, density, water over cement and aggregate over cement ratios), the obtained strength values have an increased degree of accuracy (Huang *et al.*, 2011).

There are some types of multiple variable empirical models available in the literature. The most commonly used models are the double power law, having the expression presented in Equation 1 and the bi-linear models, presented in Equation 2. Both types are considering the results obtained only from non-destructive tests, correlated with three dimensionless parameters determined by calibration with destructive testing results.

$$f_c = a \times UPV^b \times RN^c , \tag{1}$$

$$f_c = a + b \times UPV + c \times RN , \tag{2}$$

where: $f_c$ is the concrete compressive strength, [MPa]; *UPV* – ultrasonic pulse velocity, [m/s] or [km/s]; *RN* – rebound number or index; *a, b, c* are dimensionless correlation parameters that are determined based on regression analysis.

Table 1 presents the most common and reliable multiple variable models that were proposed by different research groups. These models are based on regression mathematical principles.

**Table 1**
*Mathematical Models for Assessing the Concrete Compressive Strength*

| Eq. no. (Code) | Proposed equations | Author, year |
|---|---|---|
| 1 (B1) | $f_c = 8.397 \times UPV + 0.000635 \times RN^3 - 25.568$ | Bellander, 1979 |
| 2 (T) | $f_c = 0.745 \times RN + 0.951 \times UPV - 0.544$ | Tanigawa *et al.*, 1984 |
| 3 (G) | $f_c = 0.0286 \times RN^{1.246} \times UPV^{1.85}$ | Gasparik, 1984 |
| 4 (L&P) | $f_c = 1.2 \times 10^{-9} \times RN^{1.058} \times UPV^{2.446}$ | Di Leo & Pascale, 1994 |
| 5 (A) | $f_c = 0.00153 \times (UPV^4 \times RN^3)^{0.611}$ | Arioglu *et al.*, 1996 |
| 6 (R) | $f_c = 1.532 \times RN + 5.0614 \times UPV - 39.57$ | Ramyar *et al.*, 1996 |
| 7 (K) | $f_c = 0.0158 \times UPV^{0.4254} \times RN^{1.1171}$ | Kheder, 1999 |
| 8 (M) | $f_c = 1.88 \times 10^{-12} \times RN^{2.256} \times UPV^{2.737}$ | Masi *et al.*, 2007 |
| 9 (E) | $f_c = 0.42 \times RN + 13.166 \times UPV - 40.255$ | Erdal, 2009 |
| 10 (C) | $f_c = 10^{-4.251} \times RN^{0.686} \times UPV^{1.281}$ | Cristofaro *et al.*, 2009 |
| 11 (B2) | $f_c = 4 \times 10^{-6} \times RN^{1.88148} \times UPV^{0.8084}$ | Bufarini *et al.*, 2011 |

## 4. Comparative Case Study

The aim of this study is to check the accuracy of the mathematical models presented in Table 1, by comparing the results obtained through non-destructive testing with the ones determined by applying destructive tests on the extracted specimens. Thus, the first two columns in Table 2 contain the results of the NDT methods (UPV and RH), while the third one lists the compressive strength values which were obtained by destructive laboratory tests ($f_{ck}$). Columns 4-14 present the predicted compressive strength values, calculated by applying the mathematical equations.

In order to compare the prediction accuracy of the mathematical models, for each set of compressive strength values, three statistical parameters have been computed (the root-mean-square error (RMSE), the coefficient of determination ($R^2$) and the mean-absolute percentage error (MAPE)). The results of the statistical interpretation are presented in Table 3.

**Table 2**
*Input Data and Estimated Compressive Strength Values*

| Input Data | | | Predicted compressive strength | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RN | UPV (m/s) | $f_{ck}$ (MPa) | B1 | T | G | L&P | A | R | K | M | E | C | B2 |
| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) | (11) | (12) | (13) | (14) |
| 34.72 | 2470 | 10 | 21.75 | 27.67 | 12.66 | 10.18 | 9.30 | 26.12 | 23.06 | 10.85 | 6.85 | 14.19 | 17.51 |
| 38.89 | 2450 | 12.6 | 32.35 | 30.76 | 14.36 | 11.25 | 11.22 | 32.41 | 26.09 | 13.71 | 8.34 | 15.18 | 21.53 |
| 36.39 | 2830 | 17.5 | 28.80 | 29.26 | 17.26 | 14.92 | 14.13 | 30.50 | 25.75 | 17.51 | 12.29 | 17.44 | 21.35 |
| 31.9 | 3250 | 17.8 | 22.34 | 26.31 | 18.93 | 18.21 | 15.57 | 25.75 | 23.58 | 19.00 | 15.93 | 19.02 | 18.64 |
| 37.22 | 2960 | 18.5 | 32.03 | 30.00 | 19.29 | 17.05 | 16.43 | 32.43 | 26.92 | 20.83 | 14.35 | 18.76 | 23.10 |
| 38.83 | 2930 | 18.7 | 36.21 | 31.17 | 19.96 | 17.40 | 17.32 | 34.75 | 28.10 | 22.29 | 14.63 | 19.06 | 24.81 |
| 34.61 | 3285 | 18.9 | 28.34 | 28.36 | 21.37 | 20.38 | 18.55 | 30.08 | 25.94 | 23.52 | 17.53 | 20.40 | 21.92 |
| 39.34 | 3120 | 20.6 | 39.29 | 31.73 | 22.79 | 20.57 | 20.69 | 36.49 | 29.29 | 27.26 | 17.35 | 20.85 | 26.75 |
| 39.78 | 3140 | 23.25 | 40.77 | 32.08 | 23.38 | 21.14 | 21.45 | 37.27 | 29.73 | 28.45 | 17.79 | 21.18 | 27.46 |
| 36.84 | 3500 | 25.6 | 35.57 | 30.23 | 25.97 | 25.42 | 24.29 | 34.58 | 28.58 | 32.20 | 21.30 | 23.09 | 25.95 |
| 39 | 2965 | 27.8 | 37.00 | 31.33 | 20.52 | 17.99 | 17.98 | 35.19 | 28.38 | 23.26 | 15.16 | 19.41 | 25.26 |
| 41.44 | 3470 | 29.3 | 48.76 | 33.63 | 29.60 | 28.19 | 29.51 | 41.48 | 32.47 | 41.01 | 22.84 | 24.76 | 32.15 |
| 38.39 | 3490 | 32.16 | 39.67 | 31.38 | 27.20 | 26.37 | 26.02 | 36.91 | 29.89 | 35.06 | 21.82 | 23.67 | 27.97 |
| 45.45 | 3750 | 36.8 | 65.54 | 36.88 | 38.34 | 37.58 | 42.26 | 49.04 | 37.21 | 62.47 | 28.21 | 29.13 | 40.73 |
| 47.28 | 3900 | 54.1 | 74.29 | 38.39 | 43.30 | 43.13 | 50.00 | 52.60 | 39.54 | 76.03 | 30.95 | 31.48 | 45.28 |
| 47.33 | 4095 | 56.5 | 76.14 | 38.61 | 47.45 | 48.65 | 56.44 | 53.67 | 40.42 | 87.10 | 33.54 | 33.53 | 47.20 |

For each set of results, the compressive strength values obtained by applying the mathematical equations have been compared to those provided by the destructive tests. The statistical interpretations of the results, by comparing the specific values of the coefficient of determination and root-mean-square error, are presented in Figs. 3 and 4, respectively.

**Table 3**
*Statistical interpretation of the estimated compressive strength values*

| Statistical interpretation | Proposed Multi-Variable Equations | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | B1 | T | G | L&P | A | R | K | M | E | C | B2 |
| RMSE [MPa] | 16.11 | 11.32 | 4.35 | 4.56 | 3.63 | 12.19 | 8.93 | 12.25 | 10.00 | 9.01 | 5.52 |
| $R^2$ | 0.868 | 0.874 | 0.974 | 0.969 | 0.983 | 0.896 | 0.912 | 0.907 | 0.751 | 0.841 | 0.965 |
| MAPE [%] | 66.19 | 50.98 | 10.49 | 10.72 | 10.07 | 59.63 | 38.03 | 24.42 | 26.23 | 17.26 | 23.18 |

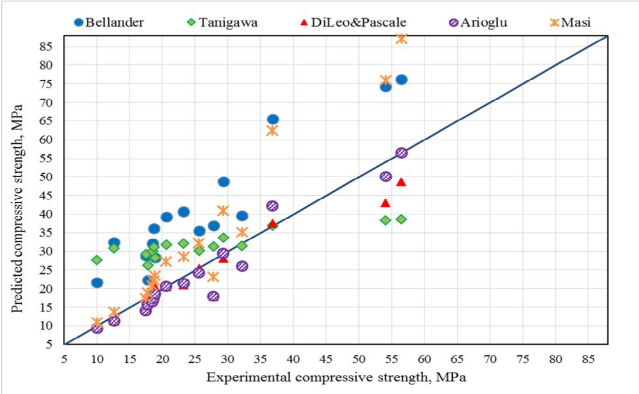


Fig. 1 – Predicted values for concrete compressive strength.

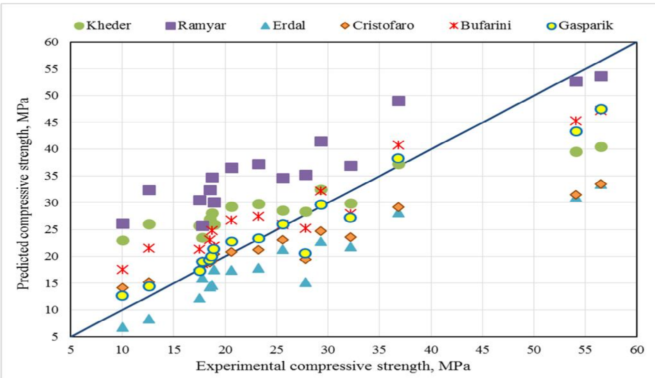


Fig. 2 – Predicted values for concrete compressive strength.

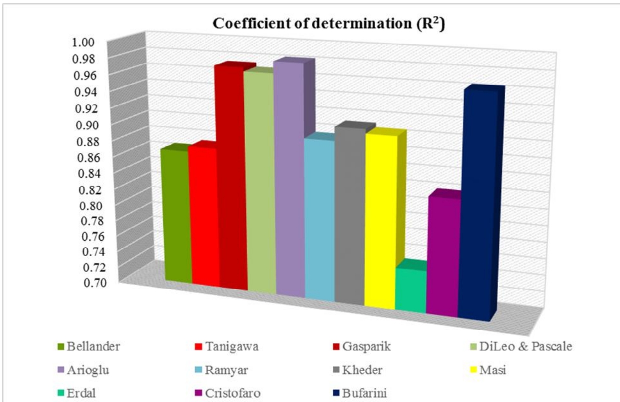


Fig. 3 – The values for the coefficient of determination corresponding to the predicted compressive strength results.

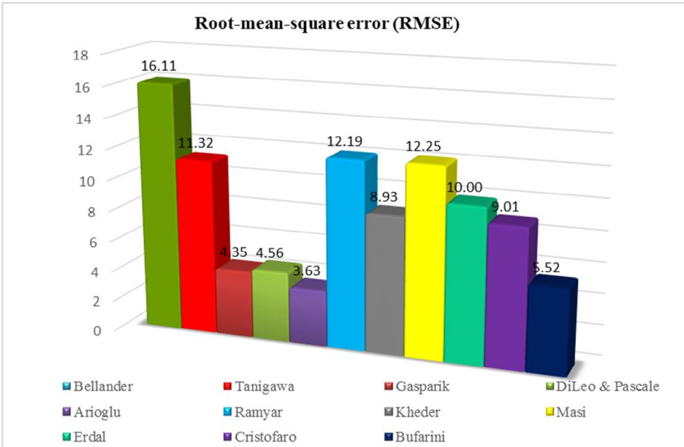


Fig. 4 – The values for the root-mean-square error corresponding to the predicted compressive strength results.

## 5. Conclusions

This paper presents the most utilized and reliable multiple variable equations, based on mathematical regression principles, that are being used in the estimation of the compressive strength for the concrete elements. The mathematical models that were analyzed in this study have only two variables (the results of the RH and UPV tests). This case study aims to check the validity and the accuracy of prediction for the selected mathematical models by comparing the estimated compressive strength results provided by applying the empirical models with the real ones, which were previously obtained by invasive laboratory tests. For each group of values, the predicted compressive strengths were first compared to the effective ones and second, statistically interpreted and graphically illustrated.

By analyzing the first two graphs (Fig. 1 and 2), one can conclude that the closest values for the compressive strength are estimated by applying the equations proposed by Gasparik, DiLeo & Pascale and Arioglu, having root-mean-square errors of 4.35 MPa, 4.56 MPa and 3.63 MPa respectively. The superior accuracy degree of these three models is also validated by the graphs presented in Figs. 3 and 4. Nevertheless, it can be observed that for the effective compressive strength values greater than 40 MPa, the accuracy of prediction is decreasing for all models, excepting the equation proposed by Arioglu and Ramyar.

By comparing the RMSE values, it can be observed that only three of the eleven (27%) proposed mathematical models (Gasparik, DiLeo & Pascale and Arioglu) provide reliable values of the compressive strengths, since the error is less than 5 MPa. This indicates that the compressive strength values of the concrete elements can be only predicted with a high degree of accuracy if the non-destructive results are correlated with the ones obtained by destructive tests.

**Acknowledgements.** The authors would like to express their appreciation to the organization committee of the Conference for PHD Students of Technical University of Jassy. The outcomes displayed in this paper were presented to the above-mentioned conference which took place on May 29 – 30, 2017.

## REFERENCES

Arioz O., Tuncan A., Tuncan M., Kavas T., Ramyar K., Kilinc K., Karasu B., *Use of Combined Non-Destructive Methods to Assess the Strength of Concrete in Structures*, Afyon Kocatepe University, Journal of Science, 147-154 (2009)

Concu G., De Nicolo B., Trulli N., Valdes M., *Combined Non Destructive Testing for Concrete Compressive Strength Prediction*, Concrete Repair, Rehabilitation and Retrofitting, **IV**, London (2016).

Erdal M., *Prediction of the Compressive Strength of Vacuum Processed Concretes Using Artificial Neural Network and Regression Techniques*, Scientific Research and Essay, **4**, *10*, 1057-1065 (2009).

Facaoaru I., *Contribution à l'étude de la relation entre la résistance du béton à la compression et la vitesse de propagation longitudinale des ultra-sons*, RILEM Bull, **12**, 125-154 (1961).

Hannachi S., Guetteche N.M., *Application of the Combined Method for Evaluating the Compressive Strength of Concrete on Site*, Open Journal of Civil Engineering, **2**, 16-21 (2012) http://dx.doi.org/10.4236/ojce.2012.21003.

Huang Q., Gardoni P., Hurlebaus S., *Predicting Concrete Compressive Strength Using Ultrasonic Pulse Velocity and Rebound Hammer*, ACI Materials Journal, V 108, *4* (2011).

Kheder G.F., *A Two Stage Procedure for Assessment of In Situ Concrete Strength Using Combined Non-Destructive Testing*, Materials and Structures, Vol. 32, pp. 410-417 (1999).

Malhotra V.M., *Testing Hardened Concrete: Non-destructive Methods*, ACI, monograph no. *9*, Detroit, USA (1976).

Masi A., Chiauzzi L., *An Experimental Study on the Within-Member Variability of the In Situ Concrete Strength in RC Building Structures*, Construction and Building Materials, **47**, 951-961 (2013).

Masi A., Vona M., *Estimation of the In-Situ Concrete Strength: Provisions of the European and Italian Seismic Codes and Possible Improvements*, Eurocode 8 Perspectives from the Italian Standpoint Workshop, 67-77, Napoli, Italy (2009).

Nobile L., Bonagura M., *Accuracy on Non-Destructive Evaluation of Concrete Compression Strength*, The 12th Int. Conference of the Slovenian Society for Non-Destructive Testing ``Application of Contemporary Non-Destructive Testing in Engineering, Slovenia, 2013.

Pucinotti R., *The Use of Multiple Combined Nondestructive Testing in the Concrete Strength Assessment: Application on Laboratory Specimens*, (2007) consulted on ndt.net.

Qasrawi H.Y., *Concrete Strength Combined Nondestructive Testing Methods Simply and Reliably Predicted*, Cement and Concrete Research, **30**, 739-746 (2000).

* * * *Recommendation for in situ Concrete Strength Determination by Non Destructive Combined Methods*, RILEM NDT 4, Compendium of RILEM Technical Recommendations, E&FN Spon, London, 1993.

* * * *Romanian Code for Seismic Evaluation of Existing Buildings*, P100-3/2008.

## ACURATEȚEA ESTIMĂRII REZISTENȚEI LA COMPRESIUNE A BETONULUI UTILIZÂND METODA SONREB

(Rezumat)

Metoda SonReb este o procedură nedistructivă utilizată pentru determinarea rezistenței la compresiune a elementelor existente din beton. Această procedură constă în aplicarea rezultatelor furnizate de metoda bazată pe recul (RH) şi cea a impulsului ultrasonic (UPV), în modele analitice specifice. În general, prin aplicarea metodei combinate se obțin rezultate de o acuratețe superioară, comparativ cu cele furnizate prin utilizarea oricărei metode simple, UPV sau RH. Modelele analitice utilizate pentru metoda SonReb au fost dezvoltate empiric şi sunt bazate pe principii matematice ale regresiei.

Această lucrare este structurată în două părți: prima parte prezentă principiile generale şi principalele avantaje ale metodei SonReb, în timp ce a doua parte constă în verificarea acurateței rezultatelor obținute aplicând modelele analitice existente. În acest sens, au fost selectate 11 modele matematice empirice frecvent utilizate în estimarea rezistenței la compresiune a betonului. Ecuațiile matematice utilizează doar rezultatele experimentale obținute aplicând metodele UPV şi RH. Prin compararea valorilor estimate ale rezistenței la compresiune cu rezultatele obținute aplicând metode distructive, se poate concluziona că numai 3 dintre cele 11 modele furnizează rezultate precise, de o acuratețe ridicată.