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Estimation of concrete strength combining rebound hammer and Windsor probe test methods

Kursat Esat Alyamac[1], Yavuzhan TAS[2], Zulfu Cinar ULUCAN[1], and Merve Acikgenc ULAS[3]

[1] Firat University, Engineering Faculty, School of Civil Engineering, Elazig, TURKEY
[2] Ministry of Transport, 8th Regional Directorate of Highways, Elazig, TURKEY
[3] Firat University, Architecture Faculty, Elazig, TURKEY

ABSTRACT: Strength estimation of existing buildings is a key challenge for civil engineers who need to feed structural computations with material data. Specifically, it is critical to determine the in-place strength of concrete to establish the safety of the concrete structures. Both destructive and nondestructive test (NDT) methods are utilized to determine the concrete strength of existing buildings. Among these, NDT techniques are sensitive first to physical properties and provide only an indirect way towards material mechanical performances. NDTs are currently used in combination with the destructive test (core-drilled) or another nondestructive test, which provided more direct information. Rebound Hammer and Windsor Probe Tests are among the most widely used NDT methods regarding concrete strength assessment. In this paper, Rebound Hammer and Windsor Probe Test results were combined to determine the compressive strength of concrete using respond surface method. As a result, a combined NDT method was obtained to estimate the strength of concrete. Furthermore, this combination can be useful for urban regeneration studies, which include a lot of reinforced concrete buildings.

1 INTRODUCTION

Since the late 1800s, structures such as houses, roads, and bridges, has been started to construct using the concrete. In the first years, the most important parameter for concrete was thought to be the amount of cement in the mixture. Later, when the effect of the water-to-cement ratio on the concrete strength was noticed, it was understood that the most important key issue for determining the concrete quality was the compressive strength (Abrams, 1927). The concrete compressive strength could be easily determined with the samples taken during the pouring concrete. However, as the time passed by, the requirements and productions have improved, and estimation of the in-place strength of the concrete has become an absolute necessity (Jones, 1949).

The core drilling technique is the first method to obtain the in-place strength of the concrete. This technique is reliable and has high accuracy; however, it is not an efficient test method due to not practical and economical (Wagner et al., 1977). For this reason, especially after the 1940s, different tests and devices have been developed to determine the in-place strength of the concrete (Kolek, 1958). These tests, named nondestructive test (NDT), are often, even today, using by combined with core drilling method. These combined methods are more effective than each of NDT method since each NDT method alone cannot estimate the strength of the concrete with high accuracy sufficiently (Malhotra, 1984).

The greatest benefits of NDT test methods are to reduce the number of required core samples when they combined with the core drilling method to determine the in-place strength of the concrete of an element or construction (Wedgwood, 1987). Nevertheless, the using of the core drilling method prevents to determine the in-place strength of the concrete, practically. In order to overcome this problem and also to efficiently estimate the in-place strength of concrete, combined NDT methods have been developed in the last decade (Breysse, 2012). The aim of the combined NDT methods is to determine the in-place strength of the concrete with high accuracy, practically and economically (Sbartaï et al., 2012).

Significant applications are being carried out for the structures in some countries where have located in the active seismic zone and there have been important losses many times in the destructive earthquakes (Yon et al., 2015). These studies can be summarized as two main subjects: 1) Strengthening of the structures which have inadequate or low resistance under seismic loads, 2) Reconstruction of the structures. In both cases, the NDT methods must be utilized. Using of the NDT methods is not only required for these reasons but also for many other reasons: quality control, curing times, formwork stripping times, fault diagnosis on existing reinforced concrete structures, and research works (Naderi, 2007). The key issue can be stated as follows: if the compressive strength of the one or few structures wants to determine, a standard NDT method can be utilized. However, if the compressive strength of the hundreds or thousands of the buildings such as an urban regeneration project is to be determined by a short/limited time, the NDT method which will use for this project must be an efficient namely practical, reliable and economical method. The requests of this kind of great projects make the use of combined NDT methods almost necessary (Alyamac, 2014).

The purpose of this study is to present an efficient combined NDT method. Popular NDT methods which are rebound hammer test and Windsor probe test used in this paper. These standard NDTs were combined to determine the compressive strength of concrete using respond surface method. As a result, a combined NDT method was obtained to estimate the in-place strength of concrete.

2 NONDESTRUCTIVE TEST (NDT) METHODS

There are a lot of NDT methods to determine the in-situ properties of the materials such as strength, cracks in the materials, delamination or voids behind the surface, the thickness of a layer, permeability, corrosion, carbonation or chloride penetration, alkali-aggregate reaction, et al. (Breysse, 2012). The standard NDT methods are surface hardness methods, penetration resistance methods, ultrasonic pulse velocity method and maturity method (Malhotra et al., 2004). In this study, Schmidt rebound hammer test and Windsor probe test are utilized, and their details are described below. These tests are currently the most widely used NDT tests. The reason why these two NDTs are combined and used is that Schmidt rebound hammer test is based only on the surface hardness. However, Windsor probe test is based on both hardness of the surface hardness and hardness of concrete components. High accurate results will be obtained with the combined method.

2.1 Rebound Hammer Test

The test hammer for concrete was developed by Ernst Schmidt in the early of the 1940s (Kolek, 1958). In this test, the surface hardness is used to estimate the in-place compressive strength of the concrete (ASTMC805/C805M−13a, 2014). A typical chart for the relationship between the rebound number (R) and the compressive strength of the concrete is shown in Fig. 1 (Hannachi et al., 2014). The curves in this chart based on the samples from 14 to 56 days for cylinder compressive strength and also the surface is smooth and dry. This test is almost the most popular method among the NDT methods (Rojas-Henao et al., 2012). Although the rebound hammer test is quick, practical, and economical, it is affected by many factors such as the type of cement, type of coarse aggregate, the rigidity of the surface, the age of the test samples, carbonation of the concrete surface. These limitations have the critical effects on the accuracy of the test results (ACI_2281r_03, 2003).

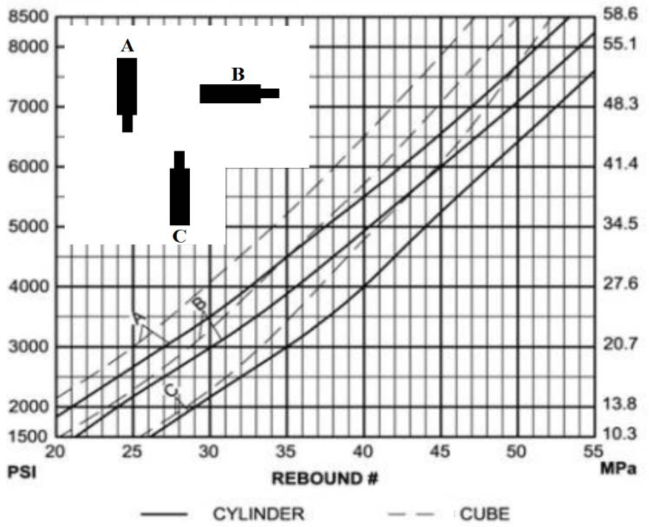

Figure 1. Conversion curves between the rebound numbers (R) and the compressive strength of the concrete.

2.2 *Windsor Probe Test*

Among the penetration test methods currently feasible, the most popular and commonly used is the Windsor probe test (Swamy et al., 1984). These methods are based on the measuring of the depth of the penetration of the steel probes into the concrete and provide a result of the penetration resistance of the concrete that can be related to its strength. Test equipment of Windsor probe test system was developed at the end of the 1960s in the USA (Fig. 2) (Malhotra, 1974).

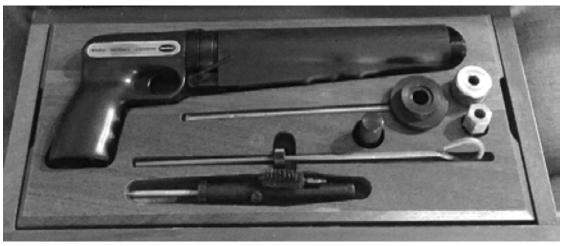

Figure 2. Windsor probe test equipment.

The method of testing is that a steel probe which is hardened steel alloy with 6.35 mm diameter, 79.5 mm length drives into the concrete by a powder-actuated driver which has two different power level (the standard and low power). After the operation, the exposed probe length is measured which has a high correlation with the compressive strength of the concrete (ASTMC803/C803M-03, 2010). Finally, the Table 1 that shows the relationship between the compressive strength and the exposed probe length is used to estimate the compressive strength of the concrete (Company, 2012).

The most important limitation for Windsor probe test is a minimum thickness of the concrete member to be tested and minimum acceptable distance, between the test locations or minimum distance from a test location to any edges of the concrete member. But this test method is simple to operate and quick and also has resulted in high accuracy (Lopes et al., 1999).

Table 1. Relationship between the compressive strength of the concrete and the exposed probe length for the low-power range of the Windsor probe system according to operator's manual of James Instruments

Aggregate Mohs No	Exposed probe length (mm)	f_c (MPa)	Exposed probe length (mm)	f_c (MPa)	Exposed probe length (mm)	f_c (MPa)	Exposed probe length (mm)	f_c (MPa)
3	36.1	10.7	38.3	12.7	40.6	14.8	43.0	17.0
	45.7	19.4	48.3	21.8	51.3	24.5	54.3	27.2
	57.5	30.1	60.8	33.1	64.2	36.2	-	-
7	46.1	10.7	47.8	12.7	49.5	14.8	51.3	17.0
	53.4	19.4	55.4	21.8	57.7	24.5	60.0	27.2
	62.4	30.1	64.9	33.1	67.5	36.2	-	-

3 METHODOLOGY AND ANALYSIS OF COMBINING NDT METHODS

In this study, the combined method has been developed by using Schmidt rebound hammer test and Windsor probe test in two steps. In the first step, the present data in the literature has been used (Malhotra, 1974). After the analyses, it has been concluded that the combined method is more efficient than the Schmidt rebound hammer and Windsor probe tests. The second step is the production of a general formulation for the combined method. The final combined method has been developed by using the values of R in Fig.1 and the values of the exposed probe length in Table 1.

In both steps, response surface methodology (RSM) has been utilized widely as an efficient tool to determine the relation between parameters and responses has been used when the data are analyzing (Alyamac et al., 2017). The RSM has several advantages, such as the efficiency to predict the model for each response, to construct a robust model with a small number of experimental data points, to assess the interaction effect between the factors and to locate the optimal response (Myers et al., 2016). The variables are rebound hammer number (R), and exposed probe length (w) and also the response is the compressive strength of the concrete. A commercially available software package (Design-Expert) is used to design the analysis by using the section of the historical data design (Inc., 2016).

In the first step, an RSM model with a total of 15 concrete mixes, which were produced by Prof. Malhotra (1974) with gravel and limestone aggregates was constructed (Malhotra, 1974). The reason why the data of research that belong to Prof. Malhotra were used in this study is because his paper simultaneously includes the NDT results for the different mohs number. The relationship between the compressive strength and the rebound hammer test and also probe penetration test is given separately in Fig. 3. The combined model with the same data is presented in Fig. 4. The model F-value of 51.27 and R-squared of 0.90 implies the model is significant. Fig. 4 displays that the combined model more effective than the separate test methods.

The variables defined for analysis of the final combined method are shown in Table 2 and also The analysis of variance (ANOVA), mainly utilized to determine the F-value and P-value, was performed to verify the adequacy of the model. The ANOVA results of the model are presented in Table 3.

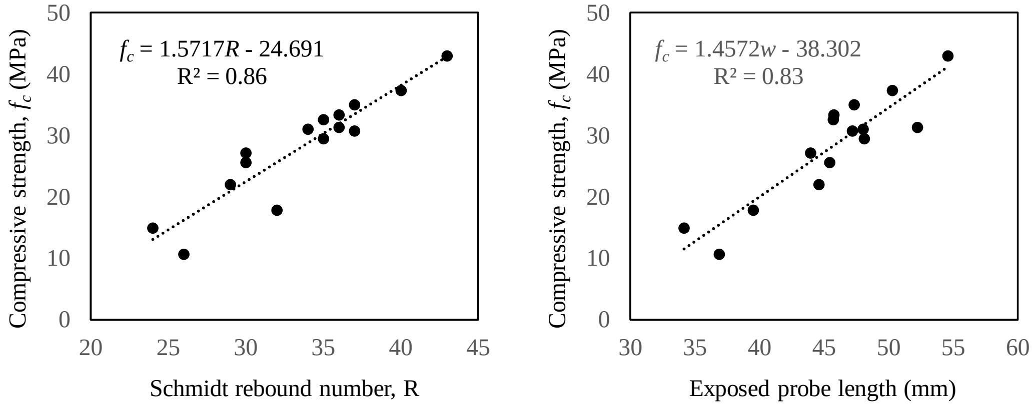

Figure 3. The relationship between the f_c and the R (left side) and also w length (right side).

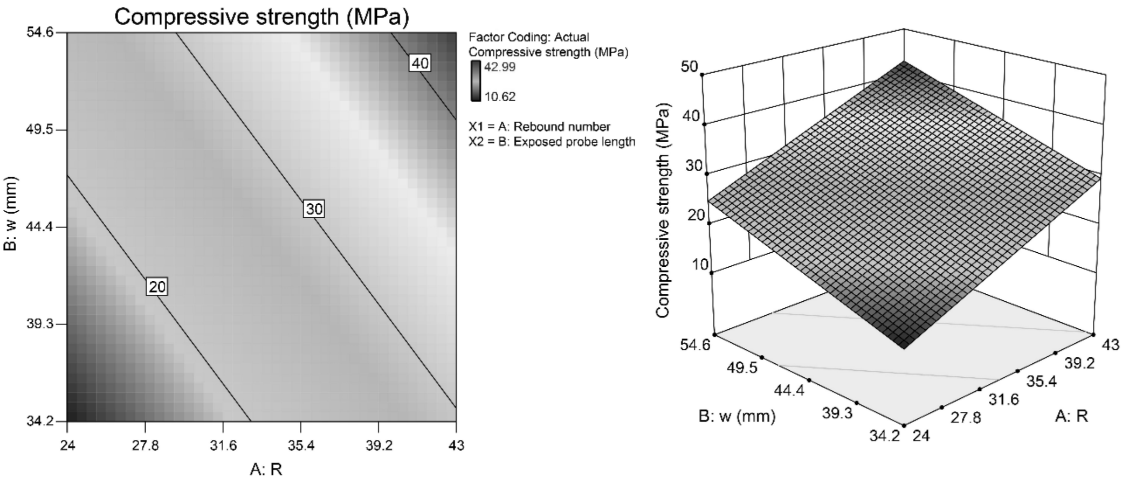

Figure 4. Response surface 2D-3D plots indicating interaction effects of the variables on f_c.

The P-value is less than 0.001, which indicate that the lack-of-fit is not significant compared to the pure. Also, the Pre R-Squared of 0.99 is in very good agreement with the Adj. R-Squared of 0.99. All these results obtained by ANOVA display that the model is significant (Table 4).

Table 2. Variables and range of variation

Aggregate Mohs No	Symbols		Range of variation		
	Real	Coded	-1	0	+1
3	R	X_1	20	30	40
	w	X_2	36.1	50.15	64.2
7	R	X_1	20	30	40
	w	X_2	46.1	56.80	67.5

Table 3. Results for full regression models

Responses	MSE	F-value	Model P-value
Compressive strength (Mohs No: 3)	240	<0.0001	<0.0001
Compressive strength (Mohs No: 7)	240	<0.0001	<0.0001

Table 4. ANOVA results for fitted numerical models (actual factors)

Model terms	Compressive strength (Mohs No: 3)		Compressive strength (Mohs No: 7)	
	Coefficient	P-value	Coefficient	P-value
X_1	0.172	0.0015	0.198	0.0006
X_2	0.611	<0.0001	0.442	0.0002
$X_1 X_2$	0.0027	0.0018	0.0068	0.0007
C (constant)	-16.71	-	-19.92	-

4 RESULT AND DISCUSSIONS

ANOVA results showed that the best model to fit the correlation among the compressive strength of concrete and the rebound number and also exposed probe length is linear, as listed in Table 4. Fig. 5 and 6 displays the response surface 2D-3D plots indicating the effect of R number, and w length on the compressive strength results for an aggregate Mohs number of 3 and 7, respectively.

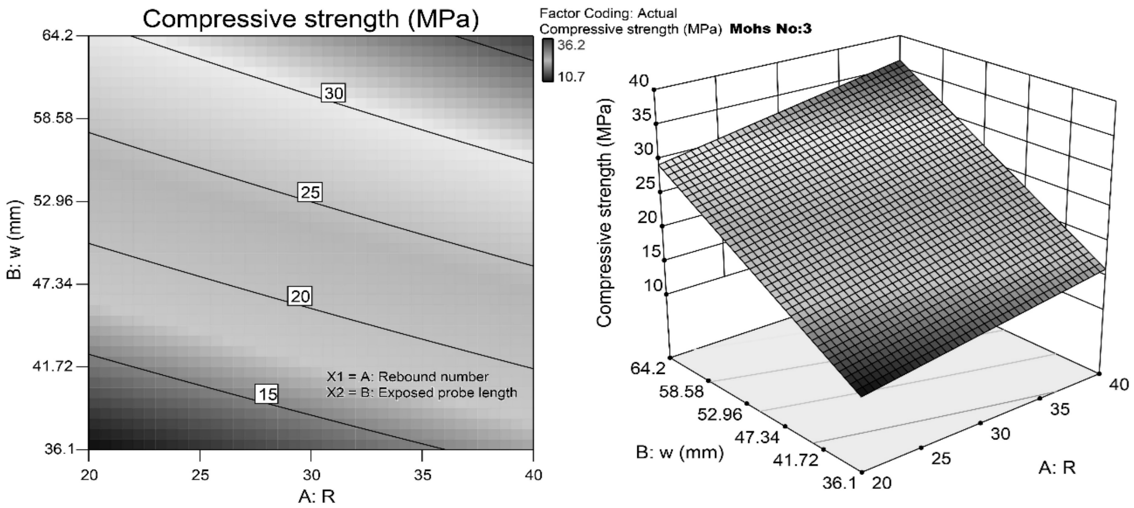

Figure 5. Response surface 2D-3D plots indicating interaction effects of the variables on fc. (Mohs: 3).

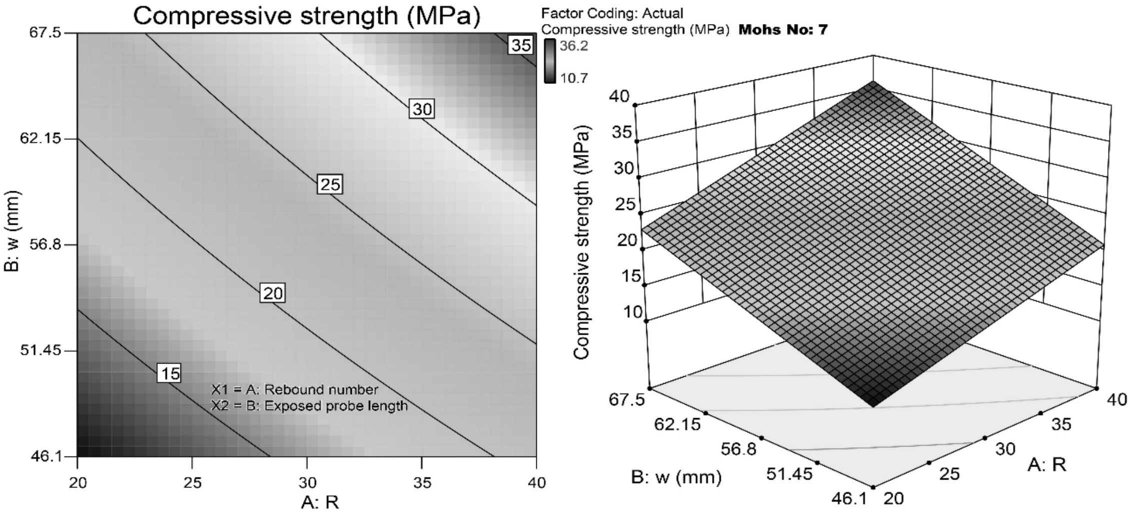

Figure 6. Response surface 2D-3D plots indicating interaction effects of the variables on fc. (Mohs: 7).

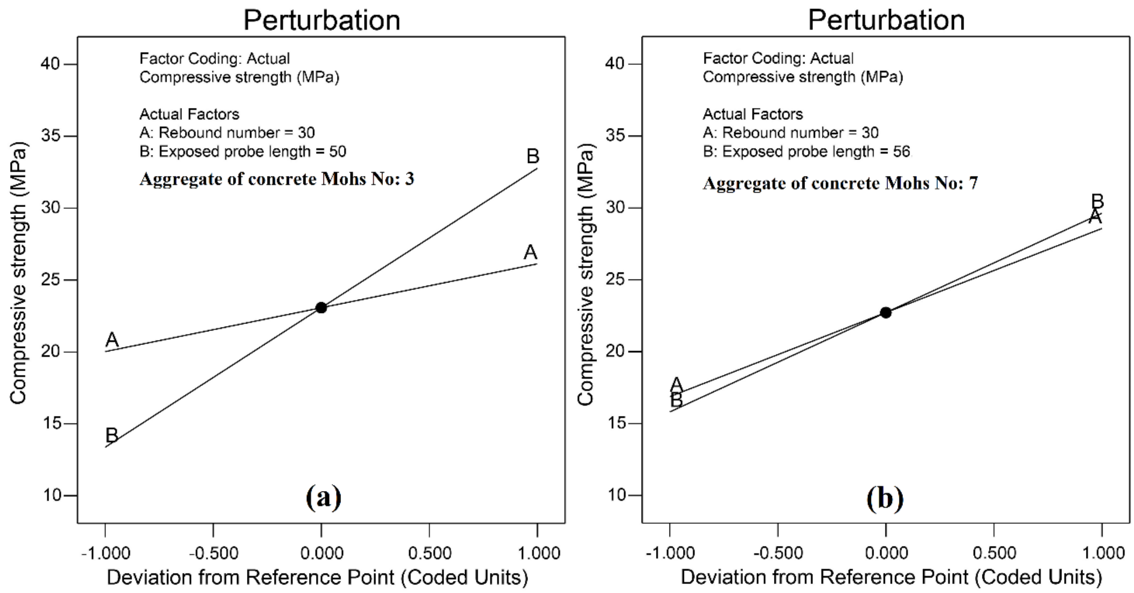

Figure 7. Trace plot of the compressive strength (aggregate Mohs number of a) 3 and b) 7).

As indicated in Fig. 5 and 6, the rebound number and the exposed probe length have significant effects on the compressive strength of the concrete. These effects can be seen in Fig. 7 as a trace plot. These effects mean that Schmidt and Windsor Tests can effectively determine the strength properties of the concrete together. The slopes of the curves are different from each other in Fig. 7a but, they are almost the same in Fig. 7b. The reason for this difference is the hardness of the aggregates. It is obvious that the strength of the aggregate is very effective on the results of rebound hammer and probe penetration test as well as the new combined test. Both the rebound hammer test and the probe penetration test are really good option to estimate the in-place strength of the concrete structures. In addition, the combined method with these tests is the best option. The probe penetration test results are more meaningful than the results of the rebound hammer test, which is a surface hardness tester only. The probe can penetrate up to about 50 mm in concrete, so the probe penetration test results are affected lesser degree by surface conditions (Malhotra et al., 2004).

The suggested combine method can effectively be used for the urban regeneration projects to determine the compressive strength of the hundreds or thousands of the buildings in limited time.

5 CONCLUSION

In this study, an efficient combined method was developed to estimate the in-place strength of the concrete. As a result of the analyses, the following conclusions can be drawn:

- The new combined method, which consists of Schmidt rebound hammer and Windsor probe tests can be used efficiently to estimate the in-place concrete strength. For example, it is possible to estimate the concrete strength of many existing buildings such as urban regeneration projects.
- When these two tests, rebound hammer and probe penetration, combined to estimate the concrete strength, the results showed that this combination is efficient. However, detailed experimental studies of both early and advanced age should be performed in order to be able to use this method more efficiently.

- The new combined method is not only practical and reliable but also economical when it compared to the core drilling method.

References

Abrams, DA, 1927. *Water-cement ratio as a basis of concrete quality*. Journal Proceedings.
ACI_2281R_03, 2003. In-Place Methods to Estimate Concrete Strength, Farmington Hills, American Concrete Institute, 44.
Alyamac, KE, 2014. Earthquake Resistance and Future Planning of Existing Buildings in Elazig/TURKEY (in Turkish). *The International Congress on Elazig from the Past to the Present*. Elazig, Turkey. 1**:** 583-600.
Alyamac, KE, Ghafari, E and Ince, R, 2017. Development of eco-efficient self-compacting concrete with waste marble powder using the response surface method, *J Clean Prod* 144: 192-202.
ASTMC803/C803M-03, 2010. Standard Test Method for Penetration Resistance of Hardened Concrete, West Conshohocken, 4.
ASTMC805/C805M−13A, 2014. Standard Test Method for Rebound Number of Hardened Concrete, West Conshohocken, ASTM International, 4.
Breysse, D, 2012. *Non-Destructive Assessment of Concrete Structures: Reliability and Limits of Single and Combined Techniques: State-of-the-Art Report of the RILEM Technical Committee 207-INR*, Springer Science & Business Media.
Breysse, D, 2012. Nondestructive evaluation of concrete strength: A historical review and a new perspective by combining NDT methods, *Construction and Building Materials* 33: 139-163.
Company, JI, 2012. Windsor Probe System Operator's Manual, NDT James Instruments**:** 76.
Hannachi, S, and Guetteche, MN, 2014. Review of the Rebound Hammer Method Estimating Concrete Compressive Strength on Site. *Proceedings of International Conference on Architecture And Civil Engineering (ICAACE'14)***:** 118-127.
Inc., S-E, 2016. Design-Expert software. Minneapolis, MN, USA.
Jones, R, 1949. The non-destructive testing of concrete*, *Magazine of Concrete Research* 1(2): 67-78.
Kolek, J, 1958. An appreciation of the Schmidt rebound hammer, *Magazine of Concrete Research* 10(28): 27-36.
Lopes, SMR and Nepomuceno, MCS, 1999. *Penetration resistance tests on high strength concrete*.
Malhotra, V, 1974. Evaluation of the Windsor probe test for estimating compressive strength of concrete, *Matériaux et Construction* 7(1): 3-15.
Malhotra, V, 1984. *In Situ Nondestructive Testing of Concrete - A Global Review*. Journal Proceedings, Amer Concrete Inst.
Malhotra, VM and Carino, NJ, 2004. *Handbook on Nondestructive Testing of Concrete*, CRC Press.
Myers, RH, Montgomery, DC and Anderson-Cook, CM, 2016. *Response Surface Methodology*, John Wiley & Sons, Inc.
Naderi, M, 2007. New twist-off method for the evaluation of in-situ strength of concrete, *J Test Eval* 35(6): 602-608.
Rojas-Henao, L, Fernández-Gómez, J and López-Agüí, JC, 2012. Rebound Hammer, Pulse Velocity, and Core Tests in Self-Consolidating Concrete, *ACI Materials Journal* 109(2).
Sbartaï, Z-M, Breysse, D, Larget, M and Balayssac, J-P, 2012. Combining NDT techniques for improved evaluation of concrete properties, *Cement and Concrete Composites* 34(6): 725-733.
Swamy, RN and Alhamed, A, 1984. Evaluation of The Windsor Probe Test to Assess Insitu Concrete Stregth, *Proceedings of the Institution of Civil Engineers Part 2-Research and Theory* 77(JUN): 167-194.
Wagner, F, Hall, K and Meininger, R, 1977. Concrete core strength—The effect of length to diameter ratio, *Journal of Testing and Evaluation* 5(3): 147-153.
Wedgwood, F, 1987. NDT 20 years on—a personal opinion, *NDT&E Int* 20(1): 63-66.
Yon, B, Sayin, E, Calayir, Y, Ulucan, ZC, Karatas, M, Sahin, H, Alyamac, KE and Bildik, AT, 2015. Lessons learned from recent destructive Van, Turkey earthquakes, *Earthquakes and Structures* 9(2): 431-453.