The use of drilling tests to assess the strength of building materials: Review of existing methods and a proposed new technique

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ABSTRACT: Although many test methods for estimating the strength of building materials already exist, new methods are still being developed to address changes in materials, their usage, and performance. This paper presents a comprehensive review of various drilling-based test methods, which have been historically used to assess the strength of such materials as wood, rocks, mortars, and concrete. The review includes critical analysis of the purpose of each method, along with the description of the specifics of the methodology as well as the discussion of the advantages and the disadvantages of individual techniques. The information generated during the review was used to develop a novel nondestructive testing (NDT) technique, the drilling rate (DR) method. The paper presents an example of the application of the DR method to predict the strength of 8 different series of portland cement mortars.

1 INTRODUCTION

The nondestructive testing (NDT) methods are routinely used for accessing the properties of variety of materials, with existing devices being modified (or new ones being produced) to meet the ever changing technolgical needs (Wedgwood, 1987), (McCann and Forde, 2001). Although several NDT methods for in-place strength determination of various construction materials already exist (e.g., the Schmidt rebound hammer, ultrasonic pulse velocity, and penetration tests, (Malhotra and Carino, 2004)), the researchers and engineers are continuously looking for more efficient techniques. One class of such promising techniques includes a drilling-based methods (Pamplona et al., 2007).

To date, the drilling-based test methods have been successfully applied to test properies of such materials as rocks, mortars, wood and concrete (Rovero et al., 2016). The results of these tests clearly indicate that the drilling-based test methods have a big potential in the area of estimation of strength and other properties of the materials (Matteo and Roberto, 2007).

The purpose of this paper is to present an overview of drilling-based test methods as applied to the evaluation of properties of building materials. In addition, an example of the application of a novel NDT technique, the drilling rate (DR) method, is also presented.

2 DRILLING-BASED TEST METHODS

The use of various forms of drilling-based test methods to estimate material properties dates back to the early 1900s. This section presents a short review of the main trends in the development and use of these methods. Although all of these methods are based on the principle of monitoring the drilling resistance, each one uses different ways to quantify the values of the resistance with measurements of force, energy, and torque, being the most common. The following sections present (in the chronological order) several of the drilling-based test methods that have been used for determination of mechanical properties of the materials.

2.1 Softening Coefficient Test

As reported by Siedel (Siedel, 2010), Julius Hirschwald (Hirschwald, 1908) was the first researcher who explored the use of the drilling test to indirectly determine mechanical properties of the materials. He used a steel drill bit attached to the handwheel powered drilling device to determine the drilling resistance of the natural stone specimens under dry and wet conditions. The drilling resistance was defined as a number of revolutions of the hand-wheel needed to drill a 10 mm deep blind hole in the stone.

The presence of water in the natural stones usually causes a decrease in strength compared to the strength of dry stone. Hirschwald suggested a drilling-based test to quantify this moisture-related loss of strength. Specifically, he proposed that the loss of strength can be quantified by calculating the so-called "softening coefficient" μ_b (originally called "Erweichungskoeffizient"). The softening coefficient was defined as $\mu_b = \beta_w/\beta_t \leq 1$ where β_w represents number of revolutions of the handwheel in water saturated specimens and β_t: represents a number of revolutions of the handwheel in dry specimens). The use of the softening coefficient allowed for quantitative assessment of the negative effects of moisture on the mechanical properties of stone and the concept itself served as the source of inspiration behind development of many subsequent drilling-based test methods.

2.2 Dynamostratigraphy Test

Dynamostratigraphy test, which was developed by Chagneau and Levasseur in 1989, is based on a measurement of the axial drilling force during the drilling operation. The test is conducted using a device called dynamostratigraph, which uses a drill bit operating at constant (preset) speed and which simultaneously measures both, the value of the axial drilling force *(R)* and the drill displacement (*x*), (Chagneau and Levasseur, 1992). Both of these parameters are recorded throughout the drilling operation. The recorded values of (*R*) give a direct measure of the mechanical resistance of the material. At the same time, a plot of (*R*) vs. (*x*) allows for determination of the thickness of the layer with the same resistance (composition). The drilling operations are performed using a spindle speed of 400 rpm and masonry drill bit with a diameter of 4 mm.

2.3 The PNT-G Test

The PNT-G test was first introduced in 1989 (Gucci and Moretti (1989)), and was subsequently modified (improved) in 1995 (Gucci and Barsotti (1995)). This test is based on measurement of the amount of energy required to drill a blind hole, with a depth of 5 mm, using mechanical drilling device (Gucci and Barsotti, 1995). An electronic circuitry, which is integrated within the drilling device, measures and displays the amount of energy expended during the drilling operation. The drilling operations are performed using a masonry drill bit with a diameter of 4 mm. Based on their studies, Gucci and Barsotti demonstrated that the drilling work (energy) can be correlated with the compressive strength of the mortars. (Gucci and Barsotti (1995)).

The procedure for obtaining the value of the compressive strength proposed by Gucci and Barsotti involved drilling of 15 blind holes (spaced roughly 2 cm apart) in the mortar specimens and monitoring the values of energy (work) associated with the drilling process. The measured values of energy were then converted into the compressive strength of the mortar by means of previously established calibration curves. The PNT-G method was used to estimate the in-place strength of the mortars by De Vekey and Sassu, who concluded that it is a reliable and practical method for such applications (De Vekey and Sassu (1997)). Subsequently, in 2004 the PNT-G method was adopted (under the name ”drill energy method”) as a RILEM recommended technique for “indirect determination of surface strength of the unweathered hydraulic cement mortar” (RILEM (2004)). Rovero and his co-workers (Rovero et al. (2016)) utilized the PNT-G method to determine the in-place strength of the mortars in the historic masonry building.

Although the PNT-G method worked well when used to assess the in-place strength of mortars used in the masonry buildings, it is not applicable for determination of the in-situ strength of concrete. This is because the depth of the drill hole called for in this test is only 5 mm, which is much smaller than a diameter of coarse aggregate used in a typical concrete.

2.4 Recent Developments in the Drilling Resistance Techniques

Since the early 2000s, substantial progress has been made in development of various drilling resistance techniques, resulting in the introduction of several commercial systems (e.g. DURABO, TERSIS and DRM) to the market, especially for applications involving conservation and restoration of the historical stone structures (Siegesmund and Snethlage, 2014, Pamplona et al., 2007). The basic approach behind all of these tests is practically the same as that originally proposed by Hirschwald (see section 2.1). This approach involves the use of mechanical drilling machine (equipped with suitable drill bit) to create a hole of a predefined length in the material which is being evaluated. Usually, the pressure on the drill bit and the rotational speed (or the penetration rate) are kept constant while the equipment automatically measures either the time, linear force, torque or energy required to achieve the desired penetration depth (Pamplona et al., 2007). In newer devices, the recorded data is automatically converted to the drilling resistance values using the software supplied with the equipment.

The drilling resistance of the material is a function of many variables, including the cutting tool type (i.e. the drill bit tip design), the wear of the cutting tool and the variation in the drilling force (Pamplona et al., 2007). The typical diameters of drill bits used in the drilling resistance tests are in the range of 4~8 mm, with the spindle speeds in the range 100~1200 rpm (Tiano et al., 2000, Rodrigues et al., 2002, Pamplona et al., 2007). The maximum depth of the drilled hole in the drilling ressistnce tests is approximately 50 mm (Matteo and Roberto, 2007).

Although all of the variables mentioned in the previous paragraph will influence the calculated value of the drilling resistance, this test has been found to offer relatively accurate way to determine the changes in the homogeneity of the material with depth (Felicetti, 2012, Nogueira et al., 2014).

3 DRILLING RATE METHOD

Previous research (Rodrigues and Costa, 2004, Pamplona et al., 2007) successfully demonstrated that drilling resistance tests can be used to estimate the in-situ strength of the relatively homogenous materials such as natural stones or masonry mortars. However, the existing methods suffer from two major limitations with respect to their applicability to heterogeneous composite materials. First, in most of the reported applications the depth of the blind hole was less than 5 mm. While that length of the hole may be sufficient for relatively homogenous materials, it is certainly not adequate for determination of the strength of composite materials with distinctive local variations in the hardness of the constituents (e.g. hardened cement paste and the aggregate). The second limitation is associated with the fact that in the heterogeneous materials the value of the thrust force on the drill bit constantly changes during the drilling operations. As the thrust force changes, so do the reaction forces at the drill bit. Due to these changes, certain simplifying assumptions are utilized when interpreting the data and these assumptions negatively affects the accuracy of the results. To alleviate some of these shortcomings, a novel method, the "Drilling Rate (DR) Method" has been recently proposed (Alyamac and Olek, 2016). This paper presents the example of application of this method to determine the compressive strength of the series of eight different portland cement mortars.

3.1 Experimental Details

Type I ordinary portland cement and natural sand aggregate with a maximum size of 4.75 mm, specific gravity 2.61, fineness modulus 2.89 and water absorption of 2.3 % were used to prepare all mortar mixtures. A total of eight different mixtures were produced to evaluate the relationship between the drilling rate and the compressive strength of the cement mortars. The mixture proportions of the mortars are given in Table 1.

Table 1. Mixture proportions of the mortars used in the study

Mix no	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	w/c	Mix no	Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	w/c
DR1	661.7	271.3	1305	0.41	DR5	531.1	212.5	1566	0.40
DR2	527.3	263.7	1436	0.50	DR6	305.9	183.5	1827	0.60
DR3	496.8	273.3	1436	0.55	DR7	275.7	193.0	1827	0.70
DR4	469.7	281.8	1436	0.60	DR8	177.3	124.1	2088	0.70

For each mixture, three cylindrical specimens (102 mm –diameter × 203 mm-length) were cast and used to determine the compressive strength following the procuders of ASTM C39 (ASTM C39, 2016). In addition, four 102 mm × 76 mm × 406 mm (width × height × length) beam specimens were cast from the same mortars and used to perform the drilling rate test. All test specimens were demolded after 24 h and were then cured in water at room temperature. Both, the drilling rate tests and the compressive strength tests were performed at the age of 28 days.

The drilling rate test involved drilling of nine blind holes (each 51 mm long) in each of the four test specimens. The drilling was performed in the vertical direction using the 6.35 mm diameter Bosch BlueGranite™ drill bit, which has been widely used by others in similar applications. All drilling operations were performed using constant thrust force of 300 N and the spindle speed of 140 rpm. During the drilling tests both, the drilling depth and the drilling time were simultaneously recorded with the help of a digital camera. The recorded values were then used to establish the drilling rate for each sample and for each series of mortars. Specimens from the same series of mortars were simultaneously tested in compression to determine their actual strength values. Using the relationship between the drilling rate and compressive strength of the mortars, two in-situ strength prediction models were developed.

3.2 Test Results

Due to space limitations, only one example of the test results (in this case for all specimens from the DR3 mortar series) is presented in Table 2. The drilling rate shown in Table 2 was calculated as the slope of the drilling depth vs. drilling time curves (shown in Figure 2).

Table 2. Drilling rates of the specimens of DR3.

Spindle speed (rpm)	Specimen No	Drilling rate *(DR)*		$\frac{DR\ (Zone-1)}{DR\ (Zone-2)}$
		Zone-1	Zone-2*	
	S1	1.555	0.217	7.2
	S2	1.802	0.222	8.1
140	S3	1.049	0.220	4.8
	S4	1.588	0.223	7.1
	Average.	**1.448**	**0.221**	**6.6**

* Drilling rates from Zone-2 were used to correlate with strength properties.

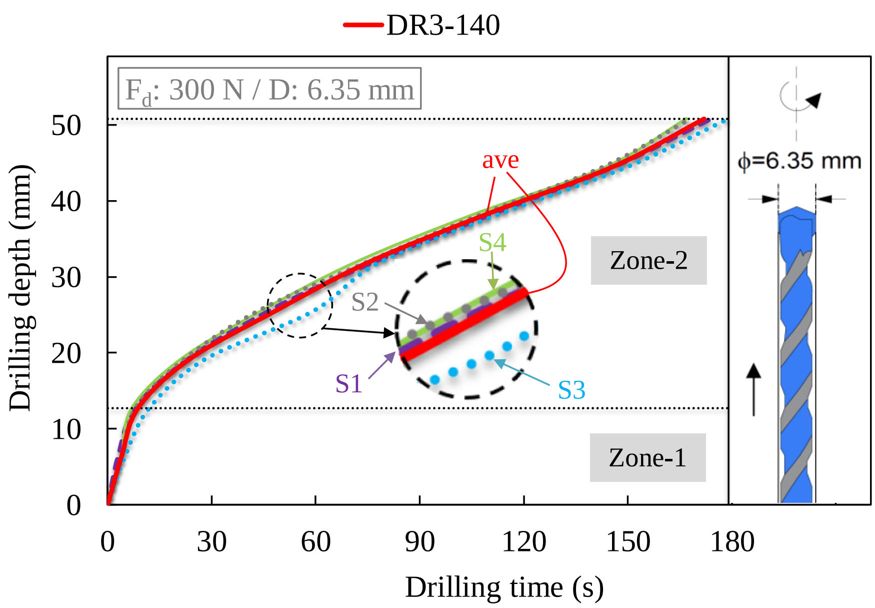

Figure 2. Drilling depth vs. drilling time curves for DRT3 mortars.

The examination of curves shown in Figure 2 reveals that each of them has two distinctive slopes (the same behavior was observed for specimens from all of the other mortars series). The higher (initial) slope was observed for drilling depths smaller than about 13 mm (i.e. located in "Zone-1"). For drilling depths greater than about 13 mm (i.e. located in "Zone-2"), the value of the slope of the curve becomes considerably smaller. Since the diameter of the drill bit used in the study was 6.35 mm, the change of the slope coincides with the depth equal to about twice the diameter of the drill bit. In fact, when calculating the values of the drilling rates for the respective zones, the depth of the drill hole associated with the boundary between Zone-1 and Zone -2 was assumed to be exactly 12.7 mm. As seen in Table 2, the ratio of the drilling rates obtained from Zones 1 and 2 varied from about 5 to 8.

The differences in the slopes of the curves within the individual zones reflect changes in the material cutting process. Initially, when the blades of the drill bit start cutting the specimen the spindle speed will tend to decrease (the actual level of decrease being a function of the strength of the specimen). However, the spindle speed stabilized (i.e. it reached nearly constant value) at the depth corresponding to the boundary between zones 1 and 2 (i.e. when the hole was approximately 13 mm long (or about twice the diameter and the drill bit)).

The average values of the calculated drilling rates (*DR*), the corresponding values of the compressive strength of cement mortars (f_c) and the coefficient of variation of the test results (*CoV*) are given in Table 3. As can be seen from Table 3, the values of coefficient of variation were relatively low, ranging from about 0.3 to 6.9.

Table 3. Average values of drilling rates and compressive strengths.

Mix No	Spindle speed (rpm)	Average Drilling rates* (mm/s)	*CoV* (%)	Compressive Strength (MPa)	*CoV* (%)
		28-day			
DR1	140	0.153	4.2	53.6	0.6
DR2	140	0.192	4.6	40.9	1.8
DR3	140	0.221	1.2	36.2	3.5
DR4	140	0.246	1.8	31.0	0.3
DR5	140	0.169	3.3	46.3	0.5
DR6	140	0.297	6.9	19.4	3.9
DR7	140	0.408	2.6	13.9	3.2
DR8	140	0.811	5.7	3.9	3.3

* Drilling rates have been calculated from the depth-time data throughout the Zone-2.

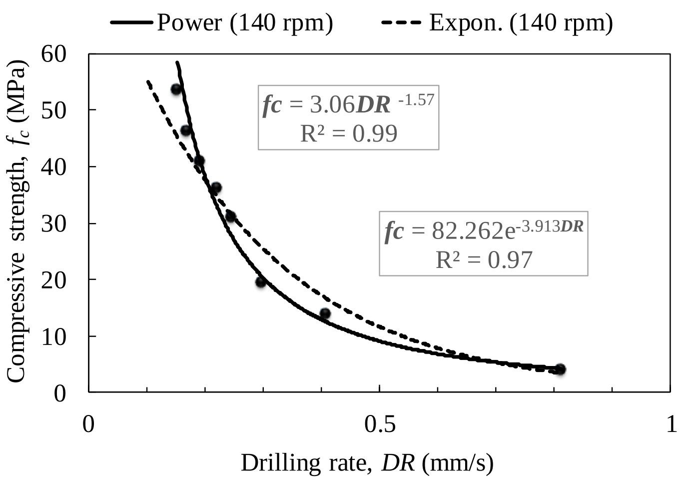

Figure 3. Relationship between the compressive strength and the drilling rate of the mortars.

The compressive strengths data for all mortar series plotted against the drilling rates are shown in Figure. 3. Since the values of the drilling rates associated with Zone-2 reflect the actual drilling rates, these values were used when establishing correlations shown in Figure 3.

As expected, the drilling rate *(DR)* was found to increase with the decrease in the compressive strength of mortars. The values of the coefficient of determination (R^2) for the *DR* values versus f_c were found to be 0.99 and 0.97, respectively, for power and exponential curves. Higher values of R^2 indicate a good relationship between the data and the resulting regression curve (Bartlett and MacGregor, 1999).

4 DISCUSSION AND THE FUTURE STUDIES

Although many standardized NDTs can be found in the existing literature, including the rebound hammer test (Kolek, 1958), ultrasonic pulse velocity test (Long et al., 1945), and penetration test (ACI, 2003), many new NDT methods are constantly being developed by researchers (Naderi, 2007, Selcuk et al., 2012) to address the changing testing needs. Among the methods being developed are the drilling-based methods, as they offer relatively quick and minimally destructive ways to estimate the strength of building materials. They may also offer some advantages when attempting to examine in-place strength of heavily reinforced concrete elements as such elements are difficult to examine using the traditional NDT methods (Malhotra and Carino, 2004).

To use the proposed drilling rate method more efficiently in the future, additional research will be required which will have to focus on examining more extensive set of drilling test parameters. It is hoped that such study will generate robust precision and bias information that can be used to develop a standardized, drilling rate based NDT method for estimation of the in-place strength of building materials.

The most significant disadvantage of drilling-based test methods is that they cause the damage to the tested elements. Although this damage is a micro and negligible, these test methods call as the NDT. Furthermore, the drilling-based test methods have many advantages. These are so efficient to determine the strength properties of construction materials, fire effects, and thickness of layers of the materials.

5 SUMMARY

This paper presents a review of various drilling-based test methods available in the literature for in-situ determination of the resistance (strength) of the building materials. In addtion, an example is presented of the application of the newly developed drilling rate (DR) method for determination of the compressive strength of portland cement mortars. The main points of this paper can be summarized as follows:

- The drilling-based test methods have demonstrated a great potential as an alternative to traditional NDTs for estimation of the in-place strength of the building materials.
- The use of the drilling rate (DR) test method resulted in a highly accurate models for prediction of the compressive strength of the portland cement mortars.

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References

ACI 228.1R-03, 2003. *In-Place Methods to Estimate Concrete Strength*, American Concrete Institute, Farmington Hills, MI, USA.

Alyamac, K.E., and Olek, J., 2016. A Novel Method to Estimate the In-place Strength of Conrete: Drilling Rate Method. *Purdue International Scholar Research Symposium*. Purdue University, West Lafayette, IN, USA.

ASTM C39/C39M−16, 2016. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM International, West Conshohocken, PA, USA.

Bartlett, F.M., and Macgregor, J.G., 1999. Variation of in-place concrete strength in structures, *ACI Mater J*, 96(2): 261-270.

Chagneau, F., and Levasseur, M., 1992. Dynamostratigraphy, a new type of mechanical test, *Materials and Structures*, 25(4): 239.

De Vekey, R., and Sassu, M., 1997. Comparison of nondestructive in-situ mechanical tests on masonry mortars: The PNT-G method and the Helix method. *Proceedings of the 11th International Brick/Block Masonry Conference*, Shanghai, China.

Felicetti, R., 2012. Assessment of deteriorated concrete cover by combined while-drilling techniques. *Journal of Infrastructure Systems*, 18(1): 25-33.

Gucci, N. and Barsotti, R., 1995. A non-destructive technique for the determination of mortar load capacityin situ. *Mater Struct*, 28(5): 276-283.

Hirschwald, J., 1908. *Die Prüfung der natürlichen Bausteine auf ihre Wetterfeständigkeit*. W. Ernst & Sohn.

Kolek, J., 1958. An appreciation of the Schmidt rebound hammer, *Magazine of Concrete Research* 10(28): 27-36.

Long, B.G., Kurtz, H.J., and Sandenaw, T.A., 1945. An Instrument and a Technique for Field Determination of the Modulus of Elasticity, and Flexural Strength, of Concrete (Pavements), *ACI Journal Proceedings*, 41(1): 217-232.

Malhotra, V.M., and Carino, N.J., 2004. *Handbook on Nondestructive Testing of Concrete*, CRC Press.

Matteo, C and Roberto, F, 2007. New NDT Techniques for the Assessment of Fire-damaged Concrete Structures. *Fire Safety Journal, 42(6):461-472*.

McCann, D.M., and Forde, M.C., 2001. Review of NDT methods in the assessment of concrete and masonry structures. *NDT&E Int*, 34(2): 71-84.

Naderi, M., 2007. New twist-off method for the evaluation of in-situ strength of concrete. *J Test Eval*, 35(6): 602-608.

Nogueira, R., Ferreira Pinto, A.P., and Gomes, A., 2014. Assessing mechanical behavior and heterogeneity of low-strength mortars by the drilling resistance method. *Constr Build Mater*, 68: 757-768.

Pamplona, M., Kocher, M., Snethlage, R., and Barros, L.A., 2007. Drilling resistance: overview and outlook. *Z Dtsch Ges Geowiss*, 158(3): 665-676.

RILEM, 2004. Indirect Determination of the Surface Strength of Unweathered Hydraulic Cement Mortar by the Drill Energy Method. *Mater and Struct*, 37: 485-487.

Rodrigues, J.D., and Costa, D., 2004. A New Method for Data Correction in Drill Resistance Tests for the Effect of Drill Bit Wear/Eine neue Methode zur Korrektur der Ergebnisse von Bohrwiderstandsmessungen, um den Einfluss des Abriebs am Bohrer zu berücksichtigen. *Restor Build Monum*, 10(3): 219-236.

Rodrigues, J.D., Pinto, A.F., and Da Costa, D.R., 2002. Tracing of decay profiles and evaluation of stone treatments by means of microdrilling techniques. *J Cult Herit*, 3(2): 117-125.

Rovero, L., Alecci, V., Mechelli, J., Tonietti., U and De Stefano, M., 2016. Masonry walls with irregular texture of L'Aquila (Italy) seismic area: validation of a method for the evaluation of masonry quality. *Mater Struct*, 49(6): 2297-2314.

Selcuk, L., Gokce, H.S., Kayabali, K. and Simsek, O., 2012. A Nondestructive Testing Technique: Nail Penetration Test. *ACI Struct J*, 109(2): 245-252.

Siedel, H., 2010. Historic building stones and flooding: changes of physical properties due to water saturation. *Journal of Performance of Constructed Facilities*, 24(5): 452-461.

Siegesmund, S., and Snethlage, R. Eds, 2014, *Stone in architecture: properties, durability*, Springer-Verlag Berlin Heidelberg.

Tiano, P., Filareto, C., Ponticelli, S., Ferrari, M., and Valentini, E., 2000. Drilling force measurement system, a new standardisable methodology to determine the stone cohesion: prototype design and validation. *Internationale Zeitschrift für Bauinstandsetzen und Baudenkmalpflege*, 6(2): 115-132.

Wedgwood, F, 1987. NDT 20 years on—a personal opinion. *NDT&E Int*, 20(1): 63-66.