Z. dt. Ges. Geowiss., 158/3, p. 665–676, 13 figs., 1 tab., Stuttgart, September 2007 **Article**

Drilling resistance: overview and outlook

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Pamplona, M., Kocher, M., Snethlage, R. & Aires Barros, L. (2007): Drilling resistance: overview and outlook. [Bohrhärtemessungen: Übersicht und Ausblick.] – Z. dt. Ges. Geowiss., 158: 665–676, Stuttgart.

Abstract: Drilling resistance technique is a valuable tool to be used in the field of conservation and restoration of our cultural heritage. Strength and strength profile measurements allow scientists to detect forms of deterioration and address adequate conservation actions. In this paper the drilling technique is described regarding its development during the last century and its function principle. Some advantages and some limits are highlighted. A correspondence between drilling force and drill bit diameter is established, so results obtained with bits of different diameter can be directly compared. Using results from different sources a linear relation between drilling resistance (DR) with uniaxial compressive strength (UCS) is derived. Furthermore, the drilling resistance and UCS values were related to the well-known Mohs hardness scale. A wider spreading of the drilling resistance method can be achieved by direct comparison with other strength parameters if the correlation expressed in this paper is further tested.

Kurzfassung: Bohrhärtemessungen sind ein wertvolles Instrument zur Untersuchung und somit zum Erhalt unseres kulturellen Erbes. Festigkeitsbestimmungen sowie die Messung der Festigkeiten entlang von Bohrprofilen ermöglichen es Wissenschaftlern, Schäden zu detektieren und entsprechende Maßnahmen einzuleiten. In diesem Artikel wird die Technik der Bohrhärtemessung anhand ihrer Entwicklung und ihres Funktionsprinzips während der letzten 100 Jahre erklärt. Es werden die Vorteile sowie die Grenzen der Methode aufgezeigt. Ein Zusammenhang zwischen der gemessenen Bohrhärte und dem verwendeten Bohrerdurchmesser wird aufgestellt, sodass künftige Ergebnisse, die mit unterschiedlichen Bohrern erzielt werden, miteinander verglichen werden können. Verwendet man die Ergebnisse unterschiedlicher Quellen, lässt sich ein linearer Zusammenhang zwischen Bohrhärte (DR_i) und Druckfestigkeit (UCS) zeigen. Darüber hinaus wird der Zusammenhang zwischen der Bohrhärte und der Mohs'schen Härteskala aufgezeigt. Ein erheblich erweiterter Anwendungsbereich der Methodik könnte durch die Korrelation mit anderen Festigkeitskennwerten erreicht werden, wenn sich die in diesem Artikel aufgezeigten Zusammenhänge durch künftige Untersuchungen bestätigen ließen.

Keywords: drilling resistance, drill bit diameters, uniaxial compressive strength, Mohs hardness

Schlüsselwörter: Bohrhärte, Bohrerdurchmesser, einaxiale Druckfestigkeit, Mohs'sche Härte

1. History and development

1.1. Background

Julius Hirschwald (1845–1928) was a German scientist who worked mainly in the field of natural building materials. Among the various inventions and discoveries made by him, a drilling machine (Hirschwald 1908) was used since 1908 to study the resistance of dry and wet stones.

In his drilling tests Hirschwald paid attention to the stone structure (mineralogical composition, grain size, and binding material) and its behaviour under water (softening). He wanted to measure the weakest point of the material that determines its failure.

Among sandstones, greywackes, dense limestones and clay rich schists he noticed that moisture mainly affects the binding material for sandstones and greywackes. He took care that the drilling tests were carried out in a way that the mineral grains of the stone were not crushed or ground but only detached (disintegrated) from the grain structure. Even though this requirement could not be completely fulfilled, the special construction of his drilling apparatus yielded approximately sufficient results, because:

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DOI: 10.1127/1860-1804/2007/0158-0665
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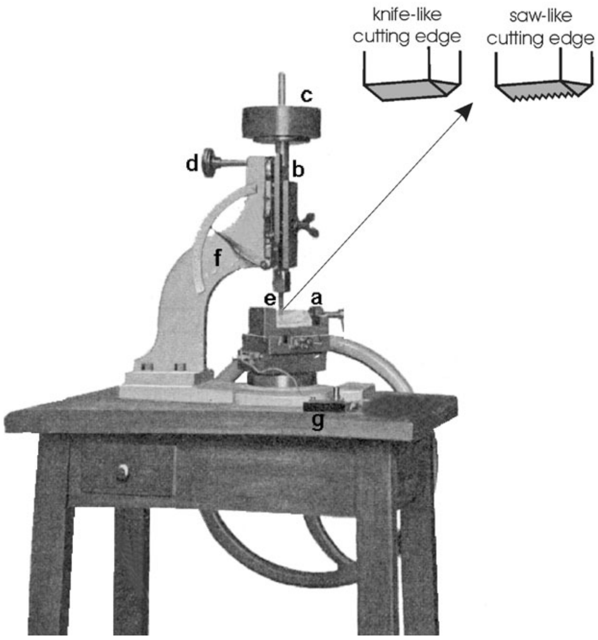

Fig. 1: First drilling resistance machine (from Hirschwald 1908).

Abb. 1: Der erste Apparat zur Bestimmung der Bohrhärte (aus Hirschwald 1908).

- for dense stones the drill tip had an even, knife-like cutting edge and for coarse-grained stones the drill tip had a saw-like cutting edge (drawing in Fig. 1). The cutting edge was eccentrically fixed on the drill bit tip so that with every rotation it was pressed from the side against the single grains, which were broken out from the softer binding material,
- the pressure on the drill bit could be regulated and adapted by different loads so that constant pressure could be maintained and the mineral grains would not be crashed.

The drilling apparatus (Fig. 1) was made of a flat, four-side drilling rod (Fig. 1: b) to which a drill steel was fixed (Fig. 1: e) with two eccentric cutting edges. The rod could be moved in vertical direction. On its top there was a plate for putting the loads (Fig. 1: c). By means of a lever (Fig. 1: d) the whole equipment could be softly let down to the sample or lifted from it. The sample which had been carefully formatted was fixed in a sample holder (Fig. 1: a). The fixing system rested on a sledge which could be moved into two perpendicular directions, so that the sample could be placed on every desired position. The complete sample holder was rotated with the help of a wheel. Hirschwald's apparatus worked in the way of a modern lathe; instead of rotating the cutting tool the sample was rotated. The revolutions number was determined by a counting device (Fig. 1: g). A pointer (Fig. 1: f) indicated the penetration of the cutting tool into the stone. As soon the requested penetration depth was reached a clock was triggered.

Moreover, it seems that Hirschwald dealt already with the problem of the cutting tool wear, as he mentioned that to sharpen the extremely hard cutting tool tip and to bevel the edges exactly in the necessary angle he used a special carborundum-grinding slice (Hirschwald 1908).

Hirschwald's aim was to determine the ratio between wet and dry drilling resistance. This so called "softening coefficient" was calculated from the number of revolutions necessary to obtain the same drilling depth in wet and in dry conditions. Both experiments were carried out with the same pressure on the cutting tool.

1.2. State of the art

The accelerated deterioration on natural building materials, mainly observed on natural stones during the 60s and 70s, and the need of reducing the interventions as much as possible led to further developments on drilling machinery.

The Institute of Building Physics (IBP) of the Fraunhofer Society in Holzkirchen (Munich/Germany) designed in 1963 a machine (Fig. 2: A) and developed it further to the commercial portable Durabo III S (Fig. 2: B) in the beginning of the 90s.

At the RWTH Aachen (Germany) a workshop was held in 1989 about "rotary drilling as low destructive testing method" applied in the field of stone conservation (Alfes et al. 1992).

A wider awareness of the advantages obtained by measuring the stone strength properties was achieved in 1992 by a publication from Alfes, Breit & Schiessl in an International Congress (as referred by Delgado Rodrigues & Costa 2004). In their work the stone hardness was measured with an indentation ball, not only on the outer surface but also in depth, along the profile of drilled cores.

In 1996 an international group of researchers started the European EC Hardrock Project (SMT4-CT96-2056). The aim was to develop a new kind of drilling machine and set up a standardized method. Since 2001 the DRMS (Drilling Resistance Measurements System) (Fig. 2: C) is on the market produced by Sint Technology (Italy). Since 2004 another drilling machine (Tersis; Fig. 2: D) is produced by Geotron-Elektronik, Germany.

2. Methodology

2.1. Field of application

The drilling resistance is a technique mainly directed towards building materials and architectural heritage safe-

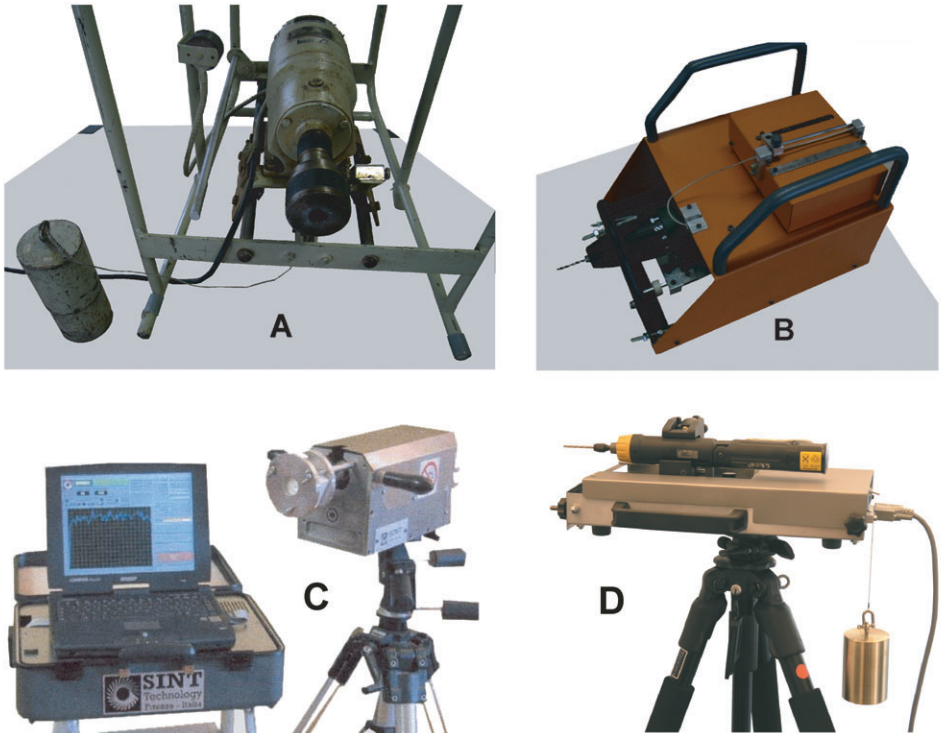

Fig. 2: Drilling machines from the 60s to nowadays (photos A, B and D taken from Geotron-Elektronik, photo C taken from Sint Technology).

Abb. 2: Bohrhärteprüfmaschinen von 1960 bis heute (Fotos A, B und D von Geotron-Elektronik, Foto C von Sint Technology).

guard. As mentioned by Exadaktylos et al. (2000) its application can vary from the in situ assessment of stone quality, both at a quarry and in a monument, to the determination of weathering extent in depth on ancient and modern buildings, so that appropriate conservation procedures might be better established and evaluated.

The drilling resistance is frequently used in wood construction, to assess in situ the beam's integrity and their resting points as well as the stability of trees along alleys.

2.2. Measurement description

In what concerns the machines features (Tersis and Durabo III S; Fig. 2: D and B) have a similar functional basis, which corresponds to that one developed by Hirschwald (Section 1.1.) since they measure the **time** to achieve a defined penetration depth with constant pressure and constant rotation speed. In contrast, DRMS (Fig. 2: C) measures the **force** that is necessary to achieve a certain depth in time, while the rotational speed and the penetration rate are constant.

The DRMS machine is equipped with two precision motors: a drilling motor able to keep a predefined rotation speed constant and a stepper motor that guarantees a predefined penetration rate (Delgado Rodrigues et al. 2002). In DRMS version 2.01 the drilling parameters are max. depth (until 50 mm), penetration rate (1–40 mm/min), revolution speed (100–1200 rpm), drill bit diameter (3–10 mm), and depth resolution (low = 0.1 mm/step and high = 0.05 mm/step). The drilling force is measured by a load cell. The maximum load is 100 N and its resolution is ± 1 N, which was determined with a calibration load cell with capacity until 250 N and precision ≤ 1 %.

Within the European EC Hardrock Project some DRMS models were provided with the torque measurement system (which has two load cells); however such model is not dealt in this paper.

2.3. Calibration materials

Very homogeneous materials have been used for calibration purposes, as for example the artificial reference sample (ARS) and a machinable glass ceramic. The first is made of porcelain with 28.4 % accessible water porosity and 61.3 MPa uniaxial compressive strength (UCS). Its production is described by Tiano et al. (2000b). The second is Macor®, produced by Corning, composed of 55 % fluorophlogopite mica and 45 % borosilicate glass, with 0 % porosity and 345 MPa UCS. Due to its precise features and reliability, Macor was proposed to be regularly used as calibration material by an European project about Stone Durability Qualification (Tiano et al. 2005).

2.4. Performance

The drilling resistance method provides many advantages since it is reliable, sensitive, and micro-destructive; it allows fast running measurements in situ and in laboratory and can be used even on scaffoldings.

About the method drawbacks, it should be mentioned the drill bit variability, the cutting tool wear, the dust transport problems, and the lack of comparison between drilling resistance, strength, and hardness.

On the next section some of the main contributions given by different authors to reduce or eliminate the aforementioned disadvantages of the drilling resistance method are addressed, especially considering the DRMS machine (Sint).

3. Solutions proposed to avoid drawbacks

3.1. Drill bit variability

The most commonly used drill bits on drilling resistance are shown in figure 3. From left to right, the Leonhardt hard steel drill bit used by Durabo III S, the Tersis PKD (polycrystalline diamond) drill bit used by Tersis, the Porzner PKD drill bit also used by Durabo III S, the Diaber (polycrystalline diamond) produced by Sint and the Fischer (hard steel) Punte Super DD (SDD) both used by DRMS.

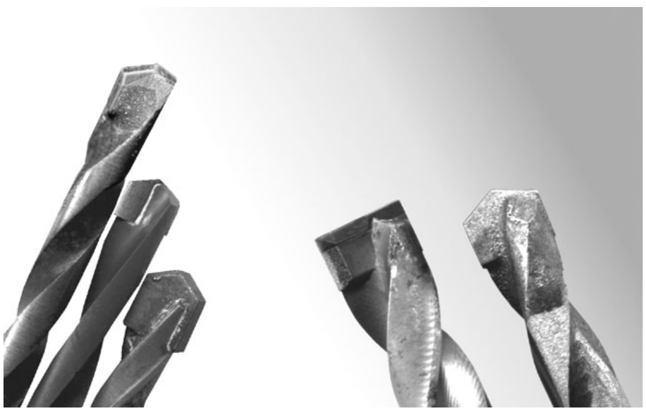

Fig. 3: Five most common drill bits used in drilling resistance measurements. Different tip design (flat or bevelled edges) and substrate material (diamond or Widia-hardened steel) consequently leads to different drilling resistance values.

Abb. 3: Die fünf häufigsten verwendeten Bohrer. Unterschiedliche Geometrien der Bohrerspitzen (flach oder geneigt) und unterschiedliche Materialien (Diamant oder Widia-Stahl) führen zu unterschiedlichen Ergebnissen.

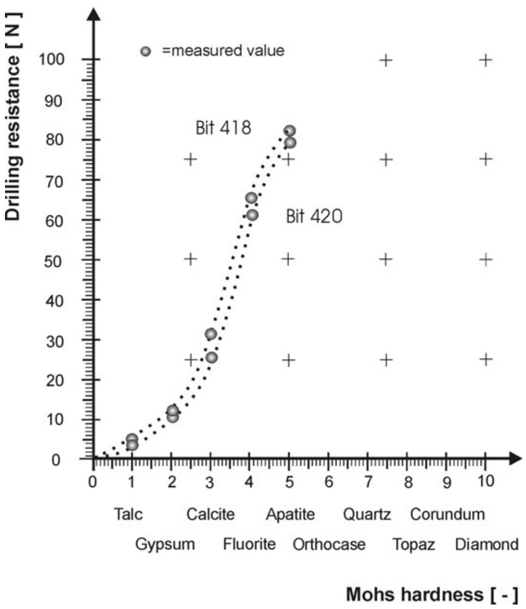

Fig. 4: Values of two extreme drill bits within a set of 6 Diaber drill bits, on Mohs minerals.

Abb. 4: Bohrhärtebestimmungen mittels zweier Diamant-Bohrer (Diaber) an Mineralien der Mohs'schen Härteskala („Maxima"- und „Minima"-Bohrer eines Sets von 6 Stück).

In the context of the EC Hardrock Project, Widia drill bits from masonry industry (Fischer SDD) were tested by drilling the first hole in the ARS. According to Tiano (2000) high variability on the measured forces was noticed (variation coefficient of 16 % in 190 specimens) due to small differences either in the hardness or in the geometry. Later on, diamond drill bits were specially constructed (Diaber – Sint) to reduce the cutting tool variability which led to less scattering results (variation coefficient of 7 % in 10 specimens). Since then, diamond drill bits are normally preferred to the Widia ones.

Although a better control exists on the Diaber drill tips production it is still advisable to evaluate how scattering a set of these might be, before making use of them. A possible and similar test to the one used by Tiano (2000) is to make a few holes in a calibration material and determine the extreme values (maximum and minimum forces) of the drill bit set.

Based on experimental data (Figs. 4 and 5) it was found that the calculated average value of the maximum and minimum force bits coincides with the measured value of the middle force bit. Moreover, this effect is valid for a wide range of minerals with different hardness.

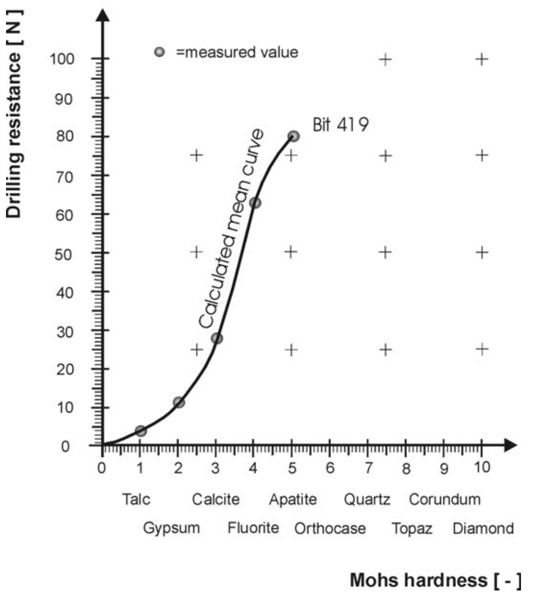

Fig. 5: Values of the mean drill bit within a set of 6 and calculated average values from the extreme drill bits (Fig. 4).

Abb. 5: Bohrhärtewerte des „Medium"-Bohrers (Diaber) an Mineralien der Mohs'schen Härteskala, überlagert mit der aus den Werten der Abbildung 4 errechneten Mittelwertkurve.

Since 100 N is the DRMS upper limit of measurable forces, Apatite is the hardest mineral which can be measured by using a 5 mm drill bit. The average values showed in figures 4 and 5 were calculated from 3 measurements with standard deviation varying between 0 and 3 %. The working conditions were: 10 mm depth, 10 mm/min penetration rate and 600 rpm, 5 mm drill bit diameter and low resolution acquisition mode.

3.2. Wear effect on the cutting tool

The wear effect is a major problem concerning abrasive stones measurements, because the drilling resistance increases during the tool working life even when drilling a more or less homogeneous material (Fig. 6). Attempts to correct this effect are based on the assumption that the wear is constant and so an abrasion rate can be estimated.

Calibration materials are used at the beginning and at regular intervals during the tool working life; for example in figure 7 ARS is measured after every 5 holes group. Correction formulas are then applied to the measured drilling forces, based on the drilled length and resistance value of the first hole.

To calculate the abrasion rate of a stone for a specific drill bit Delgado Rodrigues & Costa (2004) stressed out the importance to record the drilling history of the drill bit. Moreover, each drill bit should be used under defined conditions, only for one type of stone and within a specific purpose during the entire lifetime of the drill bit. Finally, the authors emphasised that instead of using a "universal" calibration material, a similar stone sample to the stone under study should be kept as reference, since the measured wear effect can be very different for materials with different composition and abrasiveness, even if the initial drilling resistance value is similar, as reported in figure 7.

Equations to correct the wear of the cutting tool have been proposed by many authors. Pfefferkorn (2000) established a correction function for Durabo III S (described in the previous section) considering the product of drill bit tip working life (time) and a constant abrasion rate during time, which is then subtracted from the measured value (Eq. 1).

$$B_i = B_i' - \alpha \cdot \sqrt{t_i} \quad (1)$$

with: B_i = corrected drilling resistance, in s/mm; B_i' = actual measured drilling resistance increased virtually as a result of the drill bit abrasion, in s/mm; α = abrasion constant, in s/mm $s^{-0.5}$ and t_i = drilling time, in s.

Singer et al. (2000) adapted Pfefferkorn's equation to the DRMS, subtracting from the measured values the product of increasing resistance rate and drill bit working life (in this case drilling distance) (Eq. 2).

$$DF_{i,c} = DF_{i,uc} - \frac{(DF_{n+x} - DF_n)}{d_{n+x}} \times d_i \quad (2)$$

with: $DF_{i,c}$ = corrected drilling force at point I, in N; $DF_{i,uc}$ = uncorrected drilling force at point I, in N; DF_{n+x} = average drilling force, drill hole (n+x), in N; DF_n = average drilling force, drill hole n, in N; d_{n+x} = drilling distance of all drilled holes (n+x), in mm; d_i = drilling distance at point I, in mm.

Delgado Rodrigues & Costa (2004) improved Singer et al. (2000) correction function in order to avoid negative values due to very weak layers. A first hole is drilled into the calibration material and during the drill bit working life more holes are drilled into the calibration material, at regular intervals. The increased values on the calibration material are divided by its initial force (1^{st} hole) and plotted as a function of the total drilled length. A linear regression is adjusted to the data, in one or more trends, and the correspondent equation(s) display the wear function(s). To correct the data each measured force (average between 2 and 8 mm in a 10 mm hole) is divided by the result of the regression equation at that specific point (Eq. 3).

$$Fc_i = \frac{Fm_i}{a + bx_i} \quad (3)$$

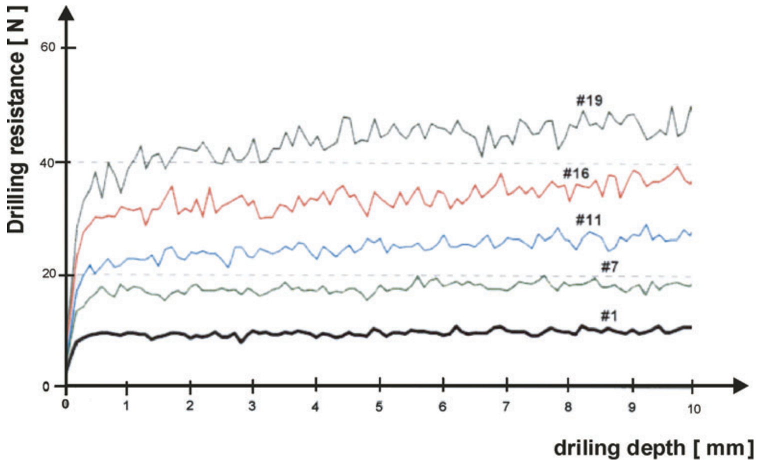

Fig. 6: Increasing wear effect by drilling successive holes in an abrasive material (Sander sandstone), using a Diaber drill bit ∅ 5 mm at 600 rpm and 10 mm/min advancing rate (from Delgado Rodrigues & Costa 2004). Curve number 1 and 19 represent the same resistance value.

Abb. 6: Zunehmender Einfluss der Abnutzung der Bohrerspitze auf das Ergebnis, verursacht durch abrasives Material (Sander Schilfsandstein). Benutzt wurde ein Bohrer der Fa. Diaber, Durchmesser 5 mm mit 600 Umdrehungen in der Minute und 10 mm/min Vorschub (aus Delgado Rodrigues & Costa 2004). Die Kurven Nr. 1 und Nr. 19 repräsentieren dieselbe Bohrhärte.

with: Fc_i = corrected resistance at point i, in N; Fm_i = measured resistance at point I, in N; a = ordinate at the origin; b = angular coefficient of the regression line and x_i = total length drilled with the concerned drill bit until point i.

Massey (2004) proposed an alternative equation to apply in the case of heterogeneous materials, where large variations in the drilling force are expected within one sample (due to hard and soft layers). For such material, a range of values is expected for the 1st hole, which will increase with the drilling length due to the drill bit wear. So, to calculate a wear rate more than one line must be plotted, one for each region of material strength. Massey's equation derives from Delgado Rodrigues & Costa (2004) and takes into account a correction factor that is not constant; instead, it depends on the force magnitude at a drilled point which corresponds to the strength of that layer (Eq. 4).

$$Fc_i = \frac{Fm_i - y}{d_i + |x|} \; |x| + y \qquad (4)$$

with: Fc_i = corrected resistance at point i, in N; Fm_i = measured resistance at point i, in N; x and y are the coordinates of the common intersection point and d_i = total length drilled with a particular drill bit up to point i.

3.3. Dust accumulation in the drill hole

Recently, studies were carried out by Mimoso & Costa (2006) in order to reduce the packing effect due to dust accumulation and the chisel edge contribution on indentation. Indentation is the compression caused by an indenter over a surface. The chisel edge is the edge of the drill tip where the cutting lips are connected. In drilling resistance measurements, the indentation corresponds to the initial part of the graph in which the force grows rapidly (Mimoso & Costa 2006) and where drilling is mainly characterised by hammering, so cutting is not yet taking part of the process.

The pilot hole method is also used in mechanical engineering to reduce the chisel edge contribution on the thrust force (forward force produced by the engine). For example, Won & Dharan (2002) pre-drilled composite laminates with a pilot hole so that the bounded layers would not separate due to the thrust force and the drilling process would occur without delamination.

According to Mimoso & Costa (2006) a consequence of the pilot hole method is the indentation reduction

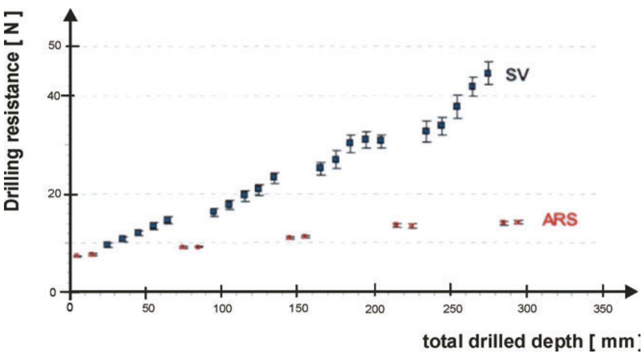

Fig. 7: Differential abrasion increase of one Diaber drill bit ∅ 5 mm, measured on two materials with identical initial drilling resistance value. Total of 20 holes made on Sander sandstone (SV) and 10 holes made on artificial reference sample (ARS) under the same working conditions (from Delgado Rodrigues & Costa 2004).

Abb. 7: Unterschiedliche Abnutzungsraten eines Diaber-Bohrers (Durchmesser 5 mm), ermittelt an zwei Materialien mit identischem Anfangsbohrwiderstand (20 Bohrungen in Sander Schilfsandstein [SV], 10 Bohrungen in ein Referenzmaterial [ARS]). Alle Bohrungen wurden mit identischen Einstellungen durchgeführt (aus Delgado Rodrigues & Costa 2004).

(compression effect) by the chisel edge and the measurement area decrease to 40 % (considering a 5 mm drill bit over a 3 mm pilot hole) so, the thrust values decrease. Namely, the authors measured for Carrara marble and a soft Portuguese limestone a force reduction of 55 % and 72 %, respectively, by using a Fischer SDD (Widia) 5 mm drill bit over a 3 mm pilot hole. However, such reduction of the drilling resistance narrows the measured values to a range where differences between stone types and grain cohesion (before and after consolidation treatment) are closer to the resolution limit (± 1N).

For special cases a combination of pilot hole and pressured air may be used to improve the reproducibility of results (Mimoso & Costa 2006), although such procedure turns the method less handy especially for in situ measurements.

Pfefferkorn (2000) mentioned that hindrance of drill dust increases with drilling depth and “apparently is strongly dependent on the pore structure and moisture content of the material”. The author noticed a relatively constant zone until 18 mm, after which an increasing slope would become evident. The constant zone should be used to calculate the average drilling force value in order to avoid the dust transport effect.

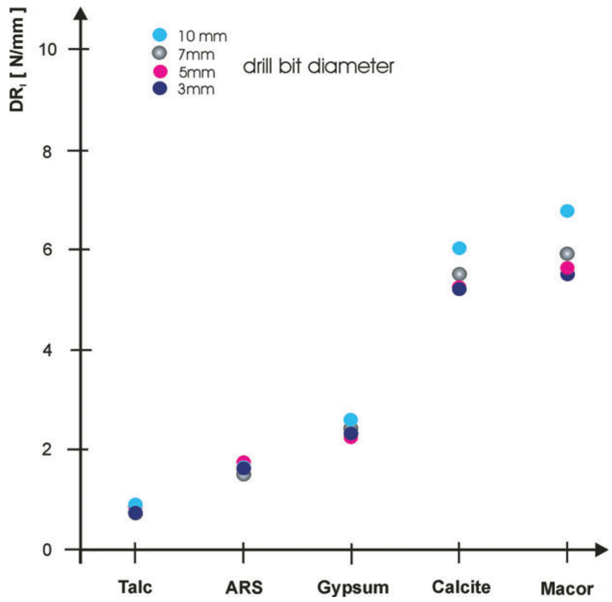

Fig. 8: Correspondence between diameter independent drilling resistance (DRi, see Eq. 5) and drill bit diameter for a range of materials with different hardness.

Abb. 8: Zusammenhang zwischen der vom Bohrerdurchmesser unabhängigen Bohrhärte (DRi, s. Gleichung 5) und dem Bohrerdurchmesser (für unterschiedliche Materialien mit unterschiedlicher Härte).

4. Investigation results

4.1. Drilling resistance versus drill bit diameter

In drilling resistance measurements a 5 mm diameter drill bit is normally used. Measuring very hard materials might be not possible due to the DRMS machine limited force of 100 N so, in this case it might be useful to use a 3 mm diameter to reduce the drilling force. In an opposite way, it might be useful to use a 7 or 10 mm drill bit diameter in very soft materials in order to increase the sensitivity of the measurement. So, by using different diameters an optimisation of the DRMS response can be achieved.

On the other hand, data collected with different drill bit diameters should be comparable. To fulfil this purpose experiments were made with Diaber drill bits (diameters ranging from 3 to 10 mm) for a range of materials within the DRMS limits of detection.

The tested working conditions were: 10 mm depth, 10 mm/min penetration rate, 600 rpm and low resolution. Results were calculated by using equation (5) in which

Tab. 1: Measured and converted drilling resistance values by using different Diaber drill bit diameters. The drilling resistance values are the average of two determinations.

Tab. 1: Gemessene und korrigierte Bohrwiderstandswerte von Diaber-Bohrern unterschiedlicher Durchmesser. Die Bohrwiderstandswerte sind jeweils der Mittelwert aus zwei Einzelmessungen.

	DR_m [N]				DR_i [N/mm]			
l = drill bit ∅	3 mm	5 mm	7 mm	10 mm	3 mm	5 mm	7 mm	10 mm
Talc	2.3	4.4	5.3	8.8	0.8	0.9	0.8	0.9
ARS	4.8	8.8	10.8	16.3	1.6	1.8	1.5	1.6
Gypsum	6.9	11.3	17.0	25.6	2.3	2.3	2.4	2.6
Calcite	15.6	26.1	38.5	60.1	5.2	5.8	5.5	5.9
Macor	16.4	28.1	41.4	67.7	5.5	5.6	5.9	6.8

the length of the Diaber cutting tip is equal to the drill bit diameter (Tab. 1):

$$DR_i = \frac{DR_m}{l} \quad (5)$$

with: DR_i is the diameter independent resistance value in N/mm; DR_m is the measured resistance value in N and l is the length of the cutting tip in mm.

In figure 8 a very good correspondence exists between DR_i (see Eq. 5) for different drill bits diameters considering a range of Mohs hardness from 1 to 3 (talc, ARS, gypsum, calcite, and Macor). By drilling Macor with a Diaber drill bit ∅ 10 mm the measured values are near to the limit of maximum force (100 N).

Worse results would be obtained, for the tested materials and working conditions, if results were expressed in force divided per cutting area (MPa).

Due to the very good results obtained in figure 8, in this paper all further experimental drilling results are expressed in N/mm.

4.2. Comparison of drilling resistance to uniaxial compressive strength and hardness

Regarding the technical advantages of drilling resistance and the lack of a common methodology to measure stone hardness (scratch hardness, penetration hardness, and rebound hardness), the DRMS was proposed as a standardized tool for characterising stone hardness and assessing consolidation treatments (Tiano et al. 2000a). Furthermore, researchers are trying to establish a correlation between drilling resistance and other mechanical properties, as for example uniaxial compressive strength (UCS), so that a wider material characterisation may be achieved by using only one method.

State of the art

Detournay & Defourny (1992) followed an earlier suggestion made by Fairhurst & Lacabanne (cited by Detournay & Defourny 1992) that the bit-rock interaction is characterised by the coexistence of rock cutting and frictional contact. The authors defined specific energy of a single cutter (E) as the parallel force per area of the cut (Eq. 6) and drilling strength (J) as the normal force per area of the cut (Eq. 7). These both forces, parallel and normal, include the cutting and frictional components.

$$E = \frac{F_s}{A} \ (\text{N/mm}^2) \quad (6)$$

and

$$J = \frac{F_n}{A} \ (\text{N/mm}^2) \quad (7)$$

where F_s is the parallel force of the single cutter, A is the area of the cut and F_n is the normal force of the single cutter.

Detournay & Defourny (1992) defined that intrinsic specific energy ε quantifies a complex process of rock destruction and generally depends on various factors, such as rock type, the rake angle of the cutter, the cutter material, pressure on the rock surface, etc.

For an ideally sharp cutter without friction the measured drilling specific energy E is equal to the intrinsic specific energy of the material $\varepsilon = E$. So, both quantities E and ε have obviously the same general meaning; however, E represents the energy spent by unit volume of rock cut, irrespective of the fact that the cutter is sharp or blunt, while ε is meaningful only for the cutting action (Detournay & Defourny 1992).

For a blunt PDC (polycrystalline diamond cutter) the relation between E and J is described by equation (8) when cutting and frictional processes are taking place simultaneously.

$$E = E_o + \mu J \quad (8)$$

with $E_0 = (1-\mu\zeta)\varepsilon$ and $J = \varepsilon\zeta$.

μ is a coefficient of friction; ζ is the ratio of the vertical to horizontal force acting on the cutting face (ratio of E over J when there is no friction) and ε is a constant defined as the “intrinsic specific energy” of the material (see above). So, the cutting process of a single cutter is characterised by two constants: ε and ζ; and the friction process is characterised by the parameter μ.

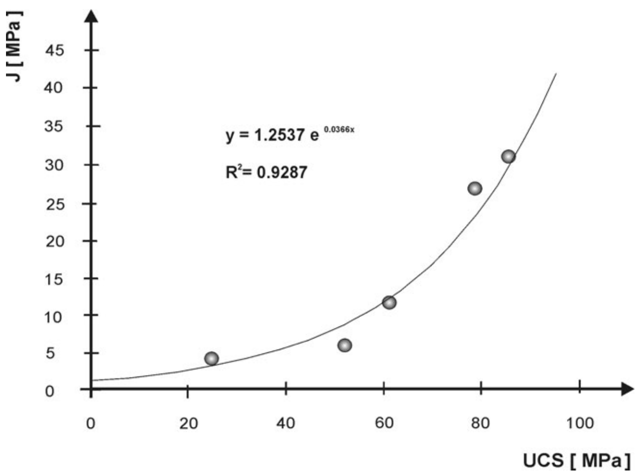

Fig. 9: Exponential relation between drilling strength (J) and uniaxial compressive strength (UCS) for 5 types of stones (from Exadaktylos et al. 2000).

Abb. 9: Exponentieller Zusammenhang zwischen Bohrerkraft (J) und einaxialer Druckfestigkeit (UCS), ermittelt an 5 Gesteinen (aus Exadaktylos et al. 2000).

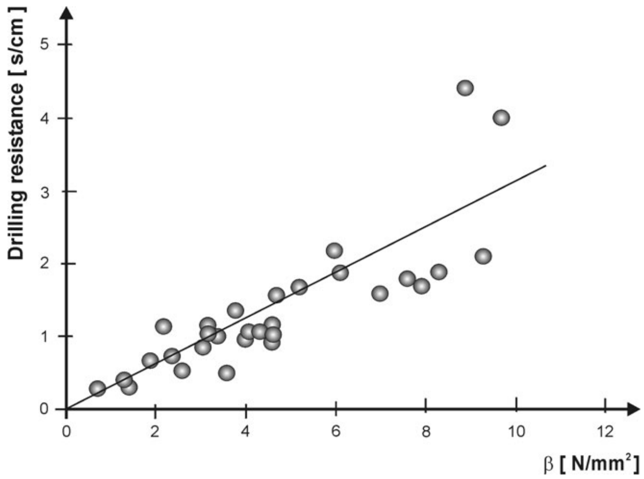

Fig. 10: Linear regression between drilling resistance and biaxial flexural strength for sound stones determined with the Durabo machine (data from Wendler & Sattler 1996, regression line from the authors).

Abb. 10: Linearer Zusammenhang zwischen Bohrhärte und biaxialer Biegezugfestigkeit für unverwitterte Gesteine, ermittelt mit der Durabo Bohrhärteprüfmaschine (Werte nach Wendler & Sattler 1996, Regressionsgerade von den Autoren).

Proceeding from a single cutter (above) to the more generalised model of a drag bit composed of many single cutters, Exadaktylos et al. (2000) established a comparison between UCS and drilling strength J, in this case J being defined by W/aδ (Detournay & Defourny 1992). J combines thrust (W) or weight on bit (expressed in N), bit radius (a), and depth of cut per revolution (δ). Since is given as a function of rotational speed and penetration rate, it is possible to correlate UCS with drilling strength (J) from data obtained by different operational conditions (Exadaktylos et al. 2000). A group of 5 stones with a common range of UCS values within monuments (from 25 to 86 MPa) was measured by UCS and drilling resistance and a regression between both properties was found (Fig. 9) (Exadaktylos et al. 2000).

However, the relation expressed in figure 9 does not cross the y-axis at zero, as it would be expected that zero UCS corresponds to zero drilling strength. A linear regression seems to be more adequate to express the relation between these variables and results from Wendler & Sattler (1996) are in good agreement with this statement. The authors measured different sandstones, from low hardness (clay bounded) to high hardness (with siliceous binding). Drilling resistance measurements were made with a Durabo III S machine and the biaxial flexural strength was determined according to Prim & Wittmann (1985). Results are expressed in figure 10.

Leonhardt et al. (1991) also proposed a linear regression to estimate the relation between drilling resistance and biaxial flexural strength. Due to peculiarities of the Durabo III S design their results can not be compared to the data of Wendler & Sattler (1996) and therefore are not presented in this paper. On the other hand, Lotzmann & Sasse (1999), measuring untreated and consolidated sandstones, did not confirm any correlation between drilling resistance (measured with Durabo III S in s/mm) and biaxial flexural strength. They concluded that the drilling method would yield adequate information about the state of the deterioration but would be unsuitable to quantify the success of consolidation treatments.

Considering the Mohr-Coulomb theory to describe the response of a material to stress, shear stress derives from a combination of compressive and tensile stresses and in this sense the biaxial flexural strength is a combined effect of compressive and tensile strength. Considering that biaxial flexural strength and drilling resistance have a linear relation (Fig. 10) it may be very likely that similarly drilling resistance and UCS also have a linear relation. The next section presents and discusses data regarding this issue.

Uniaxial compressive strength

Published data on DRMS drilling resistance measurements and on UCS determinations were used to establish a relation between both properties. Results from UCS tests were made according to EN 1926 (1999) within the McDUR European project (Tiano et al. 2002) and drilling resistance measurements were made by the

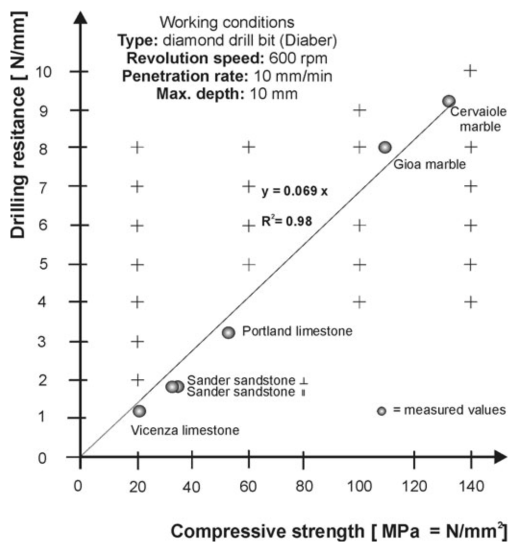

Fig. 11: Linear correlation between drilling resistance (DRi) and compressive strength (UCS) for a Diaber drill bit (from Tiano et al. 2002).

Abb. 11: Linearer Zusammenhang zwischen Bohrhärte (DRi) und uniaxialer Druckfestigkeit (UCS) für einen Diaber-Bohrer (nach Tiano et al. 2002).

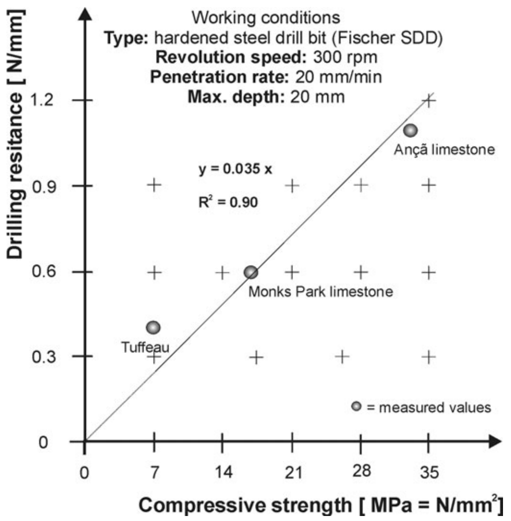

Fig. 12: Linear correlation between drilling resistance (DRi) and compressive strength (UCS) for a SDD drill bit (from Delgado Rodrigues & Costa 2000).

Abb. 12: Linearer Zusammenhang zwischen Bohrhärte (DRi) und uniaxialer Druckfestigkeit (UCS) für einen Fischer SDD-Bohrer (nach Delgado Rodrigues & Costa 2000).

BLfD (Bavarian State Department of Historical Monuments) within the same project. Figure 11 presents the correlation between UCS and drilling force independent from the drill bit diameter (see 4.1.) for limestones (Portland Whitbed and Vicenza Arcari), sandstone (Sander), and marbles (Gioa and Cervaiole) using a 5 mm Diaber drill bit.

Another correlation is presented (Fig. 12) for a 5 mm Fisher SDD drill bit based on experimental data collected by Delgado Rodrigues & Costa (2000) for siliceous-limestone (Tuffeau) and limestones (Monks Park and Ançã). Drilling resistance results are expressed in DR_i [N/mm] in accordance to equation (5).

Although both series of drilling resistance measurements were carried out with different drill bits and different working conditions, results from both diagrams show a good linear correlation.

Even if the relation between DR and UCS is not completely solved up to now, the measurements made by Wendler & Sattler (1996), Leonhardt et al. (1991), Tiano et al. (2002) and Delgado Rodrigues & Costa (2000) indicate most likely a linear correlation.

Hardness

Another attempt to compare cohesion parameters was made by drilling minerals and relating their Mohs hardness with their drilling force. The DRMS measurement system (until 100 N) is restricted to minerals with a Mohs hardness ≤ 5 for a 5 mm Diaber drill bit. A parabolic relation is shown in figure 13 which is probably caused by the non-linearity of the Mohs hardness scale.

5. Conclusions

The present article describes the development of the drilling resistance method in a chronological perspective. The drilling machines and drill bits available on the market are mentioned but emphasis is given to the Sint apparatus and Diaber drill bits.

Research made by different authors to overcome the method drawbacks is presented and discussed.

Measured values are proposed to be expressed independently from the drill bit diameter so that results can be optimised by adapting the bit diameter to the hardness of the material under investigation. Furthermore, this conversion allows the comparison of data acquired with different drill bit diameters, highlighting the potential of the drilling technique.

In this work attempts were made to establish a relation between UCS and drilling resistance considering diamond and Widia drill bits. A linear regression was obtained in both cases, which is in good agreement with literature data (except Lotzmann & Sasse 1999) measured with a Durabo III S machine, encouraging further research to be made in the future regarding this issue.

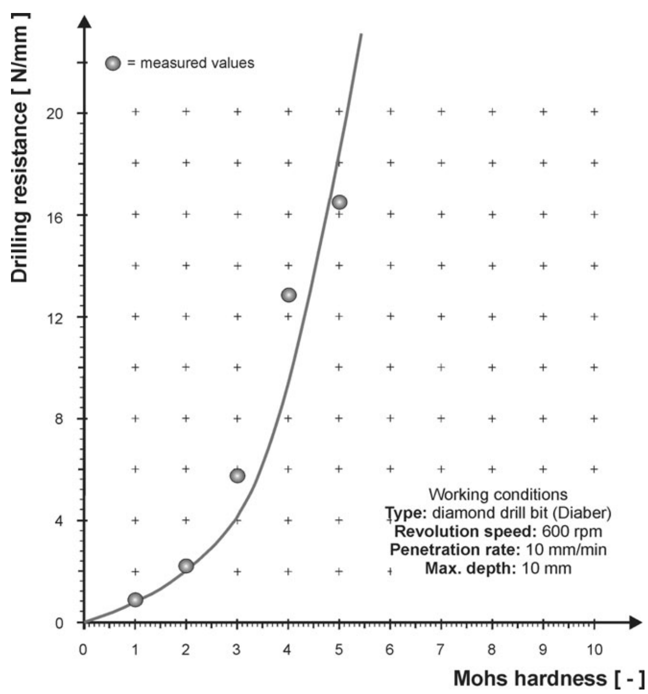

Fig. 13: Relation between drilling resistance (DRi) and Mohs hardness for a diamond drill bit (Diaber).

Abb. 13: Zusammenhang von Bohrhärte (DRi) und Mohs'scher Härte für einen Diaber-Bohrer.

Moreover, a correspondence between drilling force and Mohs hardness was established, so that further comparisons can be made with the measured resistance values. In this case, an exponential correlation was obtained due to the ordinal (non-linear) Mohs scale.

The technique is very promising in the field of stone conservation but its application in situ is faced with some restrictions, as a variable level of substrate humidity and a "lack of homogeneity in weathered building materials, so the absolute values of the drilling force have to be considered as indicative and can not necessarily be used as reference for other buildings" (De Witte & Oostvogels 2000).

Further developments should also be made regarding the drill bit shape, since Hirschwald's concept is more modern than the presently available drill types as it considered knife and saw types, which were meant to improve the disintegrating effect on a range of stones with different binding media.

Drilling resistance is a method mainly used in Europe and since 2004 three machines are available on the market. Since a wider use of this technique is expected in the near future, its possibilities and limitations (some of these taken into account already in 1908 by Hirschwald) are addressed in this paper, in order to provide the necessary knowledge so that the best profit of drilling resistance can be taken.

6. Acknowledgements

M. Pamplona thanks Prof. Dr. M. J. Melo for the fruitful discussions about drilling resistance and thanks the Portuguese Science and Technology Foundation for the Ph. D. grant SFRH/BD/10543/2002. Kind thanks are due to R. Sobott for the "Leonhardt" drill bit photograph and to A. Benincasa from Sint for providing us so fast with the ordered materials.

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Manuscript received: 10.02.2007
Accepted for publication: 25.04.2007