# ON SITE DRILLING RESISTANCE PROFILES OF NATURAL STONES

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***Abstract***

The Drilling Resistance Test consists of drilling a hole at a defined constant rotational speed and constant penetration rate and measuring the penetration force versus depth. The force is measured continuously by a load cell and a graph showing the force versus depth is displayed after the test.

The fluctuations in the drilling resistance around the mean value can be attributed to, amidst other causes, non-homogeneities in the material, such as different sedimentation layers, different grain size and resistance, micro and macro cracks etc.

This paper presents the on site application of the DRMS Cordless technology to natural stones with the statistical treatment of test results. This data treatment is focused in taking into account the spatial non-homogeneity

The repeatability of the drilling resistance test method is determined using the results obtained when drilling with the DRMS Cordless two homogeneous materials, a Carrara Marble (White P marble) and the ARS (Artificial Reference Stone).

## 1 Type of Methodology

### 1.1 DRMS Cordless and its components

The DRMS Cordless device (Fig.1) was designed to perform simple and precise Drilling Resistance tests on stone materials and on mortars by continuous measurement, during the penetration of a drill bit, of the force necessary to drill a hole in the investigated material [1].

During testing the rotation speed and the penetration rate are kept constant. The portability of the equipment means it can be used both in laboratories and *in situ*.

The system continuously measures both the penetration force and the actual drill position. All acquired data (force and drill position) and test description features are memorised and can be processed with a dedicated software, developed by SINT Technology, and are transmitted directly to a PC through an USB serial data connection.

The main components of the system are:

- Mechanical device: equipped with 2 different motors, one to maintain the rotational speed constant, and the other one to keep the penetration rate constant. A load cell is used to measure the force during the drilling operation.
- Stepper and rotating motor control board: programmable parametric values by RS232 connection, constant speed PWM control, high output current (Max 8 A), encoder to control speed and position.
- Precision strain gage amplifier (Gain = 100).
- Data Acquisition Board: USB port connection on portable computers, 12 bit of resolution with PGA (Programmable Gain Amplifier).
- Software: the acquired data is transmitted, during testing, to a PC through the USB serial data connection. The software, developed with LabVIEW™ (National Instruments), has many features related to the graphic data representation, loading and saving data files from the archive. Some important features are the following: complete test management, graph of force and torque against depth, mobile averaging of acquired data, possibility to visualize up to 6 test files together, possibility to calculate the average curve relating to a number of tests, printing of calculated data, exporting data in text format, direct data input to the standard database.
- Monopod: it can be adjusted in height from 800 to 1600 mm.

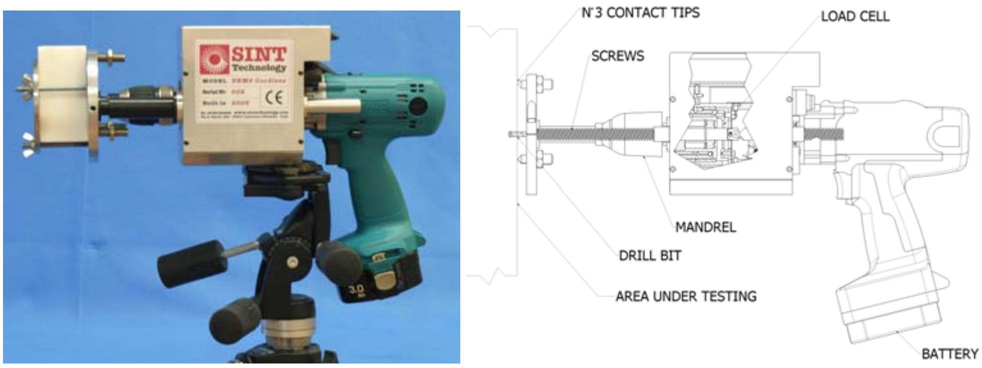


Fig. 1: DRMS Cordless

The rotational speed of the drill is controlled by the electronic device (PWM DC motor driver with a tacho feedback), in order to keep the speed constant during the entire drilling work: it ranges from 20 to 1000 rpm. Even the penetration rate of the drill is maintained constant during drilling, and ranges from 1 to 80 mm/min.

The position of the drill, referred to the surface of the target (starting point), is always known because it is directly checked by the software. The measurable force is comprised between 0 and 100 N. It is possible to investigate up to 50 mm inside the specimen, but the usual hole depth performed is 10-15 mm.

The principal advantages of the system are the following.

- Allows direct measurements of the Drilling Force during the drilling operation

- Metrologic traceability. The Drilling Force can be calibrated against a load cell in the laboratory
- Allows detailed information about the variation of the material strength with depth.
- Evaluation of consolidating treatments, in terms of depth and strength
- Possibility to perform drilling tests in every direction
- Abrasivity effect reduction with special diamond drills
- Possibility of abrasivity effect correction
- Light (5.5 kg), easy to use in scaffolding.

### 1.2 Drill bits

The drilling must be done with a suitable drill capable of producing a hole with a flat bottom surface, made of a wear resistant material. A drill bit made with the application of a polycrystalline diamond plaque was adopted (Fig. 2).

Fig. 2: Diamond drill bit

The wear effect is very low. Calcareous stones have very little influence on the bit wear, whereas abrasive stones and mortars can damage the sharpness of bit and consequently bit performances [11].

## 2 Type of parameter that is preferentially measured and of material monitored

The Drilling Resistance is the parameter which is principally measured. The test method can be applied in natural stone, in mortars and in concrete.

The test consists of drilling a hole at a defined constant rotational speed and constant penetration rate and measuring the penetration force versus depth. The force is measured continuously by a load cell and a graph showing the force versus depth is displayed after the test.

For each hole the mean value of the drilling resistance is calculated. This calculation is relevant to the portion of the graph which does not include the initial part.

The *Mean Drilling Resistance* $DR_p$ of the *p-th* hole is defined as the average value of the *m-q* samples of the profile:

$$DR_p = \frac{1}{m_p - q_p} \sum_{i=q_p}^{m_p - q_p} DR_{i,p}$$

$i$ index of the data sample (i = 0, 1, 2, …, m-1)

$m_p$ total number of data samples in the force versus depth profile, relevant to *p-th* hole

$q_p$ number of discarded data samples due to the effect of drill bit penetration, relevant to *p-th* hole.

Another parameter is the *Index of Non Homogeneity through Depth (INHD)* of the population of the *p-th* hole, defined as the ratio of the precision index to the Mean Drilling Resistance (assuming of scattering mainly due to stone non-homogeneities of the material in the direction perpendicular to the surface):

$$INHD_p(\%) = \frac{S_p}{DR_p} * 100$$

where *Sp* is the *Precision Index* of the population of the *p-th* hole, as the best estimator of the standard deviation.

The Drilling Resistance can be correlated to the mechanical properties of the natural stone, like UCS or Hardness [9], [13]

## 3 In situ application

The drilling tests with the DRMS Cordless apparatus were performed at the south wall of Florence Cathedral (Fig. 3 and 4).

Figure 3. Florence Cathedral. View from south.

Figure 4. In situ test area.

Florence cathedral was built in the period between 1296 al 1466. It is covered with Carrara marble, Prato's green "serpentinite" and marly limestones from the Chianti hills. The areas where these materials are mined have changed over time and it is therefore clear that there are many varieties used for building and for replacements even specifically relating to white marbles.
The tests were performed on a calcitic marble with a xenoblastic structure characterised by zones with grain size of 50 - 100µm, very abundant, and zones with crystal dimensions of 200 - 300µm. The grain boundaries are straight and orientation of the crystals is not present.

The results of tests are displayed in Figure 4 and in Table 3.

Fig.5. DRMS Cordless in operation

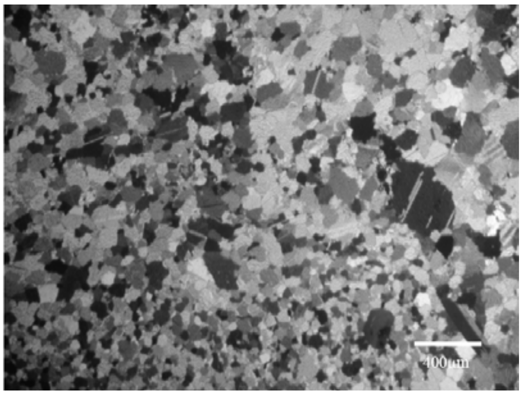

Fig.6. Thin section of Marble sample from Florence Cathedral (6 ×).

| real density $\gamma r$ ($g/cm^3$) | bulk density $\gamma s$ ($g/cm^3$) | water porosity WP (%) | total open porosity P (%) |
|---|---|---|---|
| 2.70 ± 0.10 | 2.67 ± 0.10 | 1.0 ± 0.1 | 1.2 ± 0.1 |

Table 1. Typical physical properties of Florence Cathedral marble (mean values ± standard deviation)

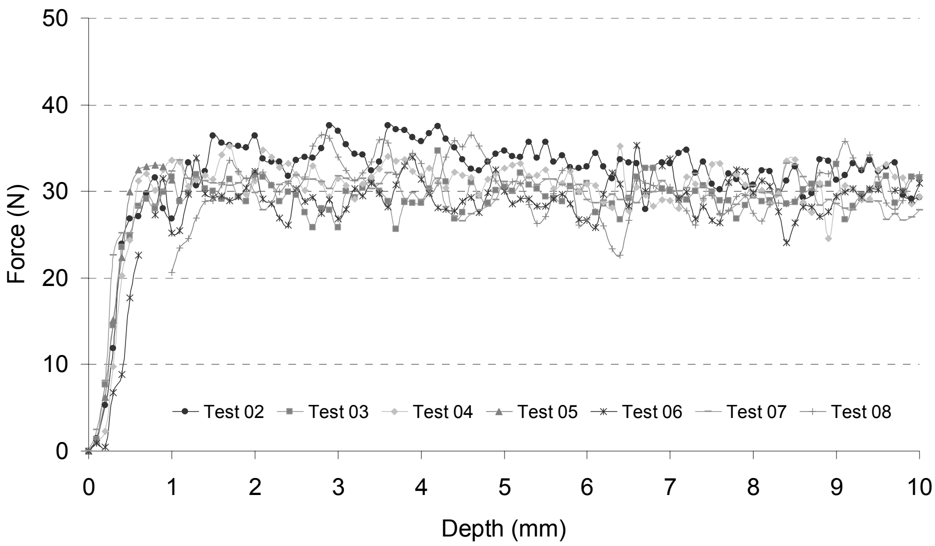


Figure 7. – Florence Cathedral. Plot of the test results

## 4 Evaluation of methodology used

### 4.1 Laboratory Tests

The laboratory tests were conducted by using samples of two materials: ARS (Artificial Reference Stone) and Carrara Marble White P. Figure 8 shows the samples used during the tests. The aim of these tests was primarly to assess the repeatability of the test method.

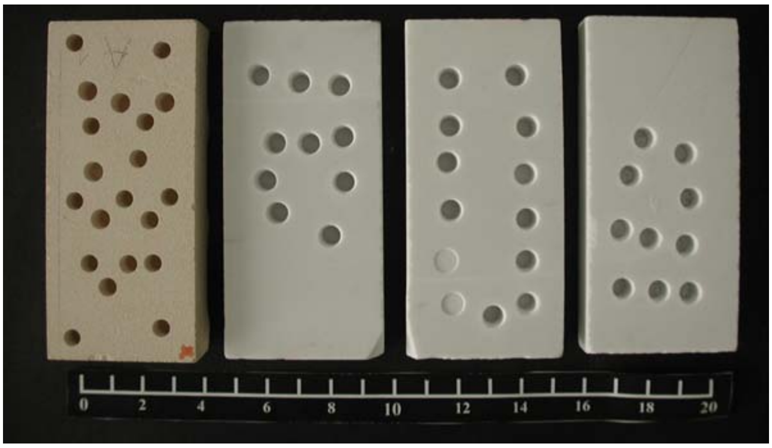


Figure 8: ARS (first on the left) and Bianco P marble samples used in the laboratory tests

| | |
|---|---|
| Specimen | ARS (Artificial Reference Stone) |
| Rotational Speed | 600 rpm |
| Penetration Rate | 10 mm/min |
| Hole depth | 10 mm |
| Hole Diameter | 5 mm |
| Drill Bit | Polycrystalline diamond |

| Hole Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| DR (1,5-10) | 5.3 | 4.9 | 5.1 | 5.1 | 5.1 | 5.3 | 5.3 | 5.3 | 5.2 |
| St.Dev. | 0.19 | 0.21 | 0.23 | 0.22 | 0.23 | 0.15 | 0.20 | 0.28 | 0.24 |
| INHD (%) | 3.6% | 4.3% | 4.5% | 4.3% | 4.5% | 2.9% | 3.8% | 5.3% | 4.6% |
| Hole Number | 10 | 11 | 12 | 13 | 14 | 15 | | | |
| DR (1,5-10) | 5.5 | 5.4 | 5.2 | 5.0 | 5.0 | 4.9 | | | |
| St.Dev. | 0.23 | 0.16 | 0.18 | 0.14 | 0.17 | 0.15 | | | |
| INHD (%) | 4.2% | 3.0% | 3.5% | 2.8% | 3.4% | 3.1% | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Data per hole (m) | 101 | | | | | |
| Discharged data (k) | 14 | | | | | |
| DR (1,5-10) | 5.2 N | Drilling Resistance of the Specimen | | | | |
| Precision Index | 0.2 N | | | | | |
| INHD (%) | 3.8% | Index of Non Homogeneity through Depth | | | | |
| Coverage Factor - k | 2 | | | | | |
| Declaration of results | DR= | 5.2 | ± | 0.1 | N | (95% confidence limit) |

Tab. 2: Measurement results (ARS)

Two ARS samples were used for the tests. On these samples, 17 holes in all were performed, with 2 diamond drills: 11 holes in the first specimen (first diamond drill), and 6 holes in the second (second drill). Table 1 shows the detailed results for each of the 15 holes and the overall results for the specimens.

Taking into account a population of 15 valid data (on 17 overall), the following results were obtained: a) the mean Drilling Resistance measured value is 5.2 ± 0.1 N (95% confidence limit), b) the repeatability standard deviation is 0.2 N and c) the Index of Non Homogeneity through Depth is 3.8%.

Concerning the Bianco P marble, 3 samples were analyzed, with 27 holes in all (9 holes on each specimen). Table 2 shows the detailed results for each of the 25 holes and the overall results for the specimens.

Taking into account a population of 25 valid data (on 27 overall), the following results were obtained: a) the mean Drilling Resistance measured value is 76.1 ± 1.2 N (95% confidence limit), b) the repeatability standard deviation is 2.9 N and c) the Index of Non Homogeneity through Depth is 3.8%.

For all the specimens, the following test conditions were used: hole depth: 10 mm, rotation speed: 600 rpm, penetration rate: 10 mm/min.

| | |
|---|---|
| Specimen | Marble Carrara Bianco P . 18A |
| Rotational Speed | 600 rpm |
| Penetration Rate | 10 mm/min |
| Hole depth | 10 mm |
| Hole Diameter | 5 mm |
| Drill Bit | Polycrystalline diamond |

| Hole Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| DR (1,5-10) | 74.6 | 78.4 | 77.4 | 76.1 | 77.0 | 75.3 | 75.2 | 75.6 | 76.0 |
| St.Dev. | 2.9 | 2.6 | 2.5 | 2.6 | 3.0 | 2.8 | 3.1 | 2.6 | 3.1 |
| INHD (%) | 3.8% | 3.3% | 3.2% | 3.4% | 4.0% | 3.8% | 4.1% | 3.5% | 4.1% |
| Hole Number | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| DR (1,5-10) | 77.5 | 76.1 | 76.0 | 77.3 | 75.3 | 76.5 | 78.0 | 73.5 | 77.8 |
| St.Dev. | 2.2 | 3.1 | 3.3 | 2.8 | 2.6 | 3.1 | 2.3 | 2.6 | 3.2 |
| INHD (%) | 2.9% | 4.1% | 4.3% | 3.6% | 3.4% | 4.1% | 3.0% | 3.5% | 4.1% |
| Hole Number | 19 | 20 | 21 | 22 | 23 | 24 | 25 | | |
| DR (1,5-10) | 76.1 | 75.2 | 76.3 | 76.3 | 75.1 | 76.2 | 74.6 | | |
| St.Dev. | 3.6 | 3.0 | 3.3 | 3.0 | 4.1 | 2.6 | 3.3 | | |
| INHD (%) | 4.7% | 4.0% | 4.3% | 3.9% | 5.4% | 3.3% | 4.4% | | |

| | | |
|---|---|---|
| Data per hole (m) | 101 | |
| Discharged data (k) | 14 | |
| DR (1,5-10) | 76.1 | Drilling Resistance of the Specimen |
| Precision Index | 2.9 | |
| INHD (%) | 3.8% | Index of Non Homogeneity through Depth |
| Coverage factor - k | 2 | |

Declaration of results DR= 76.1 ± 1.2 N (95% confidence limit)

Table 3: Measurement results (Marble Carrara Bianco P)

Before and after the tests on each sample, one hole on an ARS sample was carried out (4 holes in all) to verify the possible drill bit wear on an extremely uniform material. The ARS sample used for this check is different form the 2 ARS samples used for the repeatability tests.

Even if the tested materials are more homogeneous than other natural stones, the influence of the non-homogeneity of the material can't be totally excluded. For this reason it's possible to say that the repeatability standard deviation of the test method (relative only to the parameters independent of the material) is lower than the values above, for the force levels examined.

4.2 Analysis of in situ tests

Having set up the in-lab statistical processing, the data obtained through the *in situ* tests on Florence Cathedral was analysed.

Table 4 shows the detailed results for each of the 7 holes and the overall results for the specimens.

| | |
|---|---|
| Specimen | Carrara Marble. Florence Cathedral |
| Rotational Speed | 600 rpm |
| Penetration Rate | 10 mm/min |
| Hole depth | 10 mm |
| Hole Diameter | 5 mm |
| Drill Bit | Polycrystalline diamond |

| Hole Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| DR (1,5-10) | 33.0 | 29.6 | 31.1 | 34.6 | 29.1 | 29.9 | 30.5 |
| St.Dev. | 2.4 | 1.7 | 2.0 | 2.0 | 2.5 | 1.6 | 3.3 |
| INHD (%) | 7.4% | 5.7% | 6.5% | 5.7% | 8.5% | 5.5% | 10.7% |

| | | |
|---|---|---|
| Number of holes | 7 | |
| Data per hole (m) | 101 | |
| Discharged data (q) | 5 | (10 data for hole n.7) |
| DR (0,5-10 mm) | 31.1 N | Grand Average |
| Standard deviation | 2.0 N | |
| Precision Index | 2.3 N | |
| INHD (%) | 7.1% | |
| Coverage Factor - k | 2.5 | |

Declaration of results DR= 31.1 ± 1.9 N (95% confid. level)

Table 4 - Florence Cathedral. Table presenting the test results.

Taking into account a population of 7 valid data, the following results were obtained: a) the mean Drilling Resistance measured value is 31.4 ± 2.7 N (95% confidence limit), b) the repeatability standard deviation is 2.6 N and c) the Index of Non Homogeneity through Depth is 8%.

Figure 10 presents an example of a statistical analysis of the Drilling Resistance data relevant to the Drilling Resistance profile presented in Figure 9 (Hole n.2)

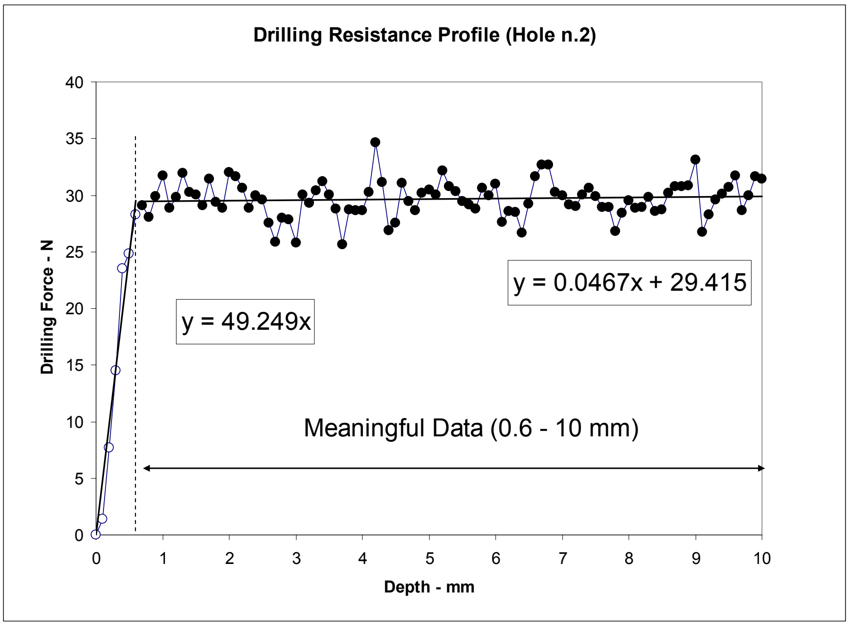


Fig. 9 - Typical Drilling Resistance Profile versus depth (Hole n.2)

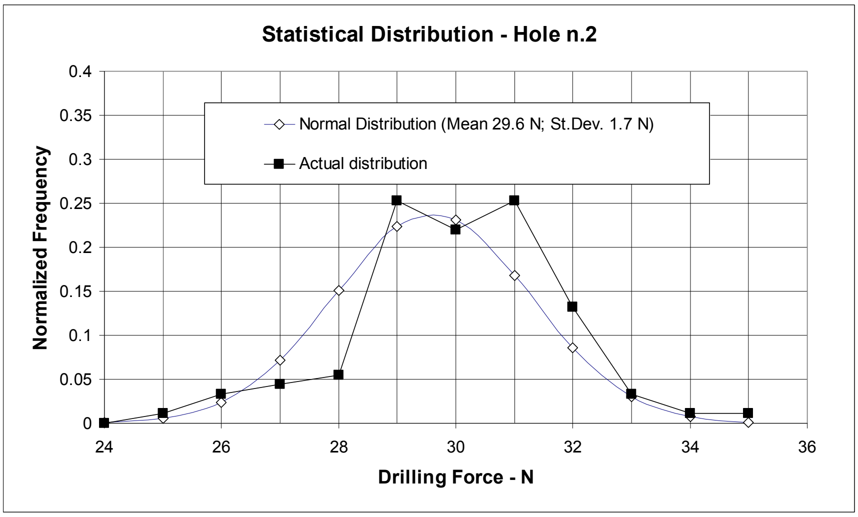


Fig. 10 –. Typical Frequency Distribution compared with Normal Distribution (Hole n.2)

## CONCLUSIONS

The DRMS Cordless is confirmed to be a validated instrument to perform *in situ* quasi non destructive tests on natural stones.

The repeatability of the drilling resistance test method with the DRMS Cordless is determined taking into account the repeatability tests conducted on 2 materials (ARS and Carrara Marble Type P) which show are highly homogeneous with respect to other stone materials. The statistical analysis has been applied for the data processing of the tests conducted on Florence Cathedral ashlars.

This test method can be applied for in situ characterization of natural stones, by measuring both the Drilling Resistance and the index of Non Homogeneity through Depth

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