DIAMOND WIRE CUTTING TECHNOLOGY AND WORKABILITY OF NATURAL STONES: VALIDATION OF A NEW CLASSIFICATION METHOD (EASE R3)

R. Bellopede[1], P. Marini[1], L. Zichella[1], A. Tori[2]
DIATI - Department of Environment, Land and Infrastructure Engineering, Politecnico di Torino, Turin, Italy.
[2] CO.FI.PLAST S.r.l., Lessolo, Italy

ABSTRACT

In the diamond wire stone cutting process the objective is to remove a chip of material or a layer of uniform thickness from the entire length of the cut. The aim of this study is to correlate the cutting performance to the characteristics of the natural stone and subsequently to propose a method of classification strictly connected to stone workability.
Hardness and micro-hardness tests are currently considered important methods for acquiring useful information about the workability of natural stones, but such gathered data alone do not give enough information to establish a satisfying classification. The concept of workability and stone machining has been, for the past thirty years, one of the main area of investigation in national and international researches. This study endorses a method for the prediction of stone-cutting tools interaction (mainly diamond wires) combining the micro-hardness and the UPV measurements, that better represent the mechanical, physical and petrographical stone properties.
This paper studies eight different stones classified according to an "easy-to-cut" scale based on the historical company know-how (HIC - Historical Industrial Classification). This classification is based upon experience and not on explicit or really scientifically quantified parameters, nonetheless, it describes the stones workability completely.
In previous works, however, criteria based on quantifiable parameters (SSC - Scientific Stone Classification) have been pursued and this led to a scientific correlation with the industrial classification. For each stone the following investigation techniques were performed: petrographic analysis, micro-hardness, Schmidt rebound, Ultrasound Pulse Velocity (UPV). Moreover UPV measures in indirect and direct method have been executed on stone blocks in the cutting plant and compared with those performed on slabs. The results of all the performed tests were analyzed and good correlations with the industrial classification were found.

Introduction

The prediction of stone - diamond wire interaction is crucial for the extractive sector, both to improve the productivity and efficiency of quarry work and to avoid dangerous and expensive endeavors of cutting when an unknown stone has to be introduced in the plant.
The diamond wire users themselves determined an empirical classification of the stone (Industrial Workability Classification) mainly taking into account the greater or lesser ease of cutting. However the new classification suggested by Bellopede et al . (2014) [1] has been obtained by means of a scientific approach with easy and expeditious test methods. In particular, while the IWC is characterized by 9 classes, with the new technical classification the classes decrease to 7, thus reducing the case of overlapping and uncertainty due to the intrinsic variability of the materials.
Diamond-wire cutting operations are affected essentially by two different kinds of parameters: partially controlled and non-controlled. The partially controlled ones refer to the properties of the cutting tools and equipment, such as the cutting speed (peripheral speed of the diamond-wire – m/s), the feed rate (cm/h), and the machine absorption (ampere/m). Instead, the non-controlled parameters refer to the stone properties, such as the petrographic and mineralogical composition, grain size, water content, weathering, discontinuities/anisotropy and hardness.
Previous studies demonstrated that the uncontrolled parameters can be measured indirectly by different techniques but the Knoop microhardness and the Ultrasonic Pulse Velocity (UPV) measures best correlate with workability and are therefore more significant [1,2,3,4]. From 1982 Mancini and Morandini [5] and more recently in 2003 Beste and Jacobson [6] have underlined the

importance of the microhardness measurement to study the tool wear. However, very little is reported in the literature on the relationship between the petrographic characteristics and the industrial process involved in the stone cutting and finishing, as pointed out by Riberiro et al (2007) [7]. UPV measures can be considered an expedite and reliable testing of the mechanical properties of a rock (quarry face or block), and gives also available information on the stone slab quality [8,9,10]

This research is part of the EASE-R3 (FoF.NMP.2013-8-608771 -Integrated framework for a cost-effective and ease of Repair, Renovation and Re-use of machine tools within a modern factory – ESS project). It's aimed at developing a novel integrated framework for a cost-effective and easy Repair, Renovation and Re-use of machine tools in modern factories , oriented towards both SME and OEM/end-users, and covering the entire life cycle of the system, from the design stage through the operative life.

The aim of the present work is to validate this scientific classification with new stone categories by means of measurement performed directly on stone blocks and therefore to evaluate the applicability of this methodology to the stone plant.

Materials and Methods

Eight different kinds of stone have been studied. Their names, identification codes and petrographic description are shown in table 1, where the IWC classes and their determining cutting parameters are reported. In fact, as for the granite GRP and RBE, sienite SIE and diorite DIOS, feed rate (cm/h) and machine absorption (A/wire) were recorded in plant in order to compare them with the physical-petrographic properties of the examined stone.

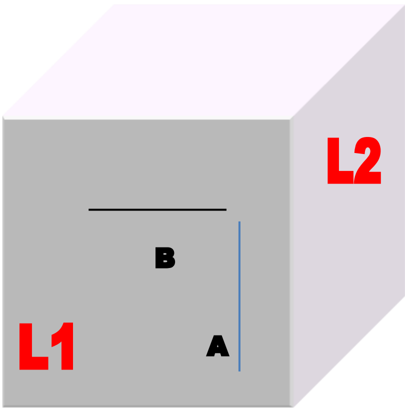
Table1 Mineralogical composition , textural characteristics of the stone tested , IWC and main cutting parameters.

Stone	Rock type	Acronym	Mineralogical composition	Industrial Workability Classification	Feed rate (cm/h)	Machine absorption (A/wire)
SERIZZO	Gneiss	SER	K- Feldspar plagioclase 70% Quartz 20% Biotite + access 10%	1-2	n.a.	n.a.
MONTORFANO	Granite	MON	K-feldspar and plagioclase 55%; quartzs 40% ; biotite 5%	3	n.a.	n.a.
DIORITE SCURA	Diorite	DIOs	Plagioclase 65% Hornblende + Biotite 30% Opaque min 5%	3	16,52	1,43
DIORITE CHIARA (TRAVERSELLA)	Diorite	DIOc	Plagioclase 55% Quartz 10% Hornblende + Biotite 30% Opaque min 5%	3	n.a.	n.a.
SIENITE	Sienite	SIE	Feldspar 50% Biotite + Hornblenda 25% Quartz 15%	3	24,36	1,65
LUSERNA	Gneiss	LUS	K- Feldspar plagioclase 40% Quartz 50% White mica5% opaque 5%	3	n.a.	n.a.
ROSA BETA	Granite	RBE	Plagioclase 25% Feldspar 30% Quartz 35%	3-4	25,00	2,78
GRIGIO PERLA	Granite	GRP	K- Feldspar + Plagioclase 65% Quartz 30% biotie + pyroxene 5%	4	23,8	2,83

In situ measurements of UPV in indirect method and in direct method (figure 1) and Schmidt rebound tests have been performed. In laboratory, Knoop hardness have been measured on the same slabs tested in situ.

Fig 1 – ultrasonic measurements by direct method on DIOs block

In the Figure 2 a general scheme of the measurements carried out on the blocks is reported.



Legend:
L1: Face parallel to the drill holes
L2: Face perpendicular to the drill holes
A and B: Lines followed for UPV

Fig 2 - General scheme of the measurements carried out on the blocks

The indirect method with ultrasonic measurements were performed on two contiguous faces L1 (parallel to drill holes) and L2 (perpendicular to drill holes) along the directions A and B shown in

the figure 2. In the indirect method, according to the EN 14579 (2004) [11], measurements were made using conic 33 kHz frequency transducers and by placing the transmitter transducer on a fixed point and the receiver at progressive distances – 25mm far one from another, up to 175 mm distance – on the same surface. A reference slab of the same kind of stone, provided by the plant's owner, has been tested by indirect method. A specimen for Knoop determinations has been cut from that slab.
The direct method measurements have been carried out by taking the transducers with frequency of 54kHz on two opposite faces of the block up to 3m distance, the maximum dimension of the tested blocks.
Schmidt rebound index has been measured on all the stone blocks except RBE and GRP. The test has been performed by making three rebounds on the same eight points of the UPV alignment, and recording the third one.
The Knoop measurements have been performed according to ASTM E384-11 [12] by a pyramidal diamond point pressed into the polished surface of the test material with a specific load a for a specified dwell time (40 s). The resulting indentation has been measured by microscope.
The rock hardness is determined by the cumulative frequency curve of 40 micro-hardness Knoop (HK) measurements detected. The test results are expressed through the characteristic values of the diagram, corresponding to the 25% (HK25), 50% (HK50) and 75% (HK75) cumulative frequencies, respectively. In this work, HK 25 has been used for the correlations.

Results and Discussion

In the table 2 the results of UPV measures, the in situ Schmidt rebound and the values of HK25 on the same slabs tested in situ are reported. As clearly shown in that table, the Schmidt values are the same for all the rock tested except for DIOS. As a result, Schmidt rebound doesn't give useful information about the technical classification of stone workability.

Table 2. In situ UPV measures by direct and indirect method on stone slabs and block and HK25 values obtained in laboratory.

Rock acronym	UPV indirect method on block B direction (m/s)	UPV indirect method on block A direction (m/s)	UPV indirect method on slab B direction (m/s)	UPV indirect method on slab A direction (m/s)	UPV direct method on block (m/s)	Schmidt rebound on block B direction	Schmidt rebound on block A direction	HK25 –MPa-
SER	1801	1801	1927	1737	3931	60	60	2109
MON	1714	1752	1628	1704	3490	60	60	2789
RBE	2387	2310	2754	2430	3530	n.a	n.a.	4049
LUS	2024	2154	2230	1756	3960	61	60	4358
DIOs	2287	2352	2708	2443	5450	53	53	2789
DIOc	2197	2482	2511	2420	5550	61	59	3260
SIE	2482	2172	2449	2299	4730	61	60	3602
GRP	2601	2510	2785	2780	4500	n.a.	n.a.	5234

As shown in table 2, there is a ratio from 2 to 2,2 between the UPV measures by direct method and those performed by indirect method.
In figure 3, the mean values of the UPV data obtained by direct and indirect method on blocks are reported: a linear correlation, with a good regression coefficient, has been computed and drawn.

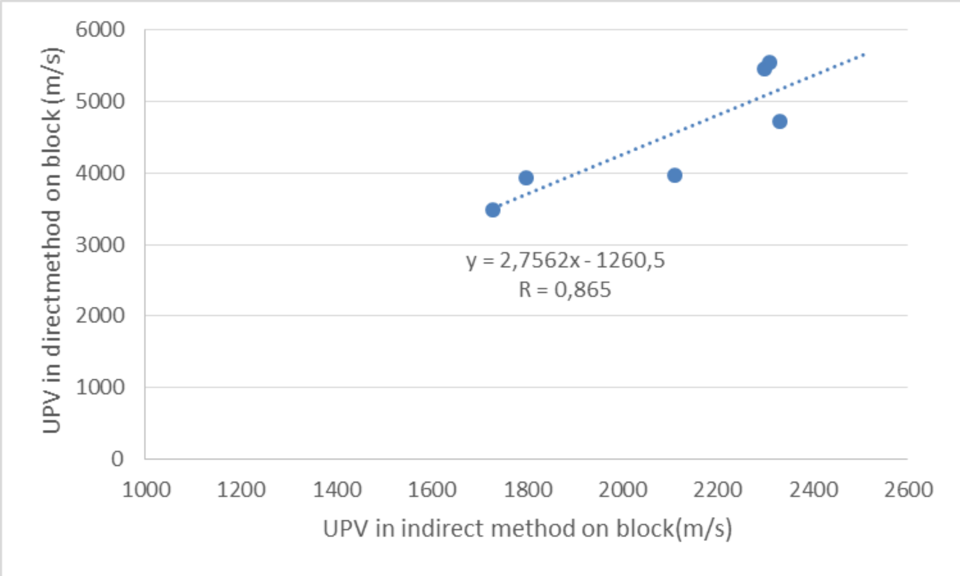


Fig. 3. Correlation between UPV by direct method and UPV by indirect method on block performed in plant

Moreover, taking into account that the of the UPV measurements is about the 3-5%, it is possible to assert that there is no difference between the results obtained on the B direction and those on the A.
Another important result of this investigation is the good correspondence between indirect measurement on blocks and the indirect ones performed on slabs, - in situ on the same day – figure 4.

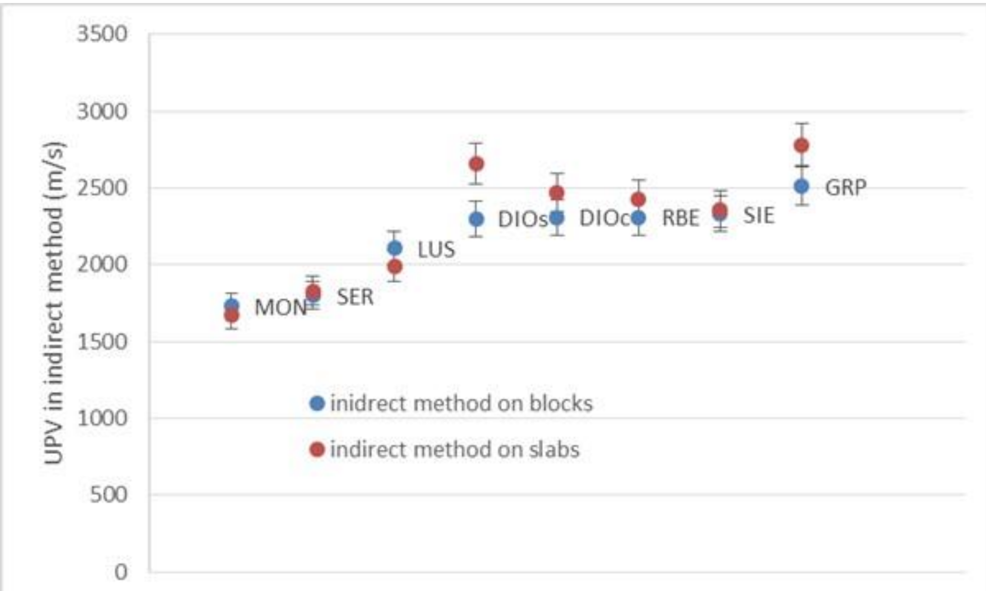


Fig. 4. Comparison between UPV by indirect method on blocks and on slabs

The petrographic characterization of the tested stone (table 1) show the lack of a direct relation between the workability classification and the mineral composition. For example granite GRP with a 50% of quartz content is in classes n. 4 while gneiss LUS, with the same content in quartz is in class n. 3.

There are, therefore, other factors that affect the workability of natural stone, as previously asserted, and they can be well represented by Knoop hardness and ultrasonic pulse velocity data and by the graph of figure 5 where the new data have been plotted on the graph proposed in previous work.

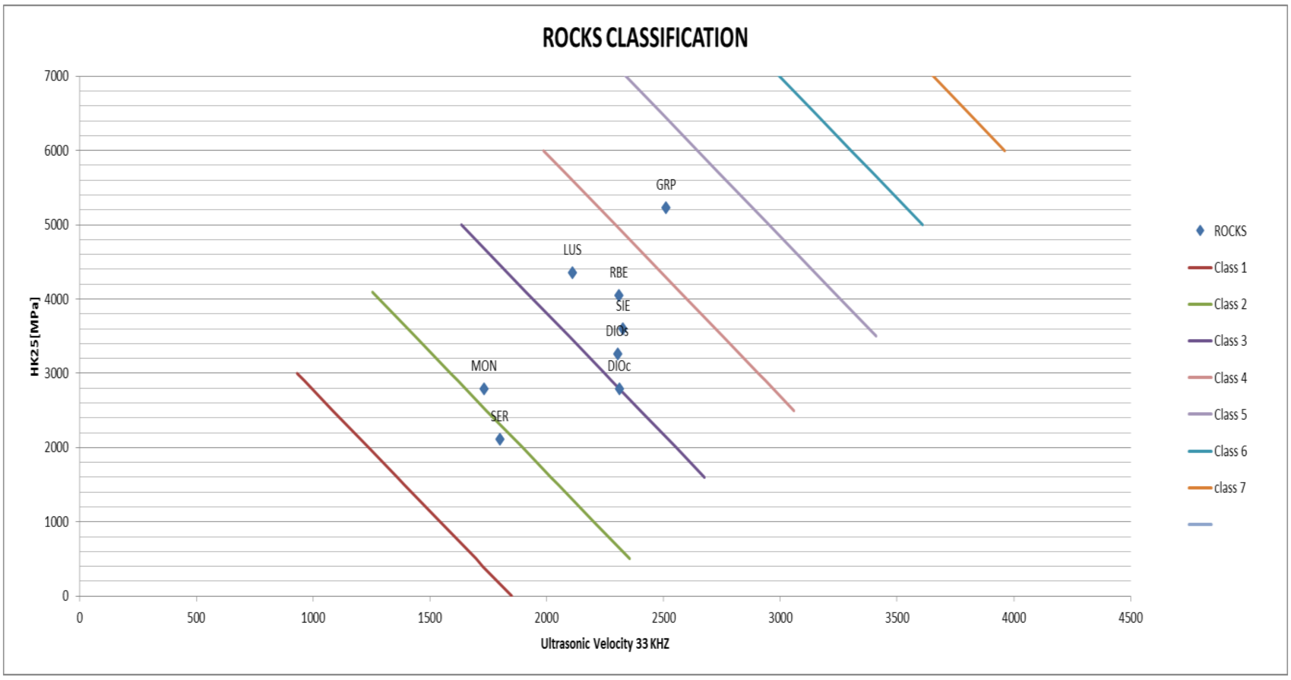


Fig. 5 Scientific classification of the tested stone.

On the basis of the recently scientific classification [1], the eight tested stone are all classified in class no.3, except the GRP which is placed in class no.4 , MON in class no.2 and SER in class no.1 (see figure 5). The scientific classification corresponds to the industrial classification (IWC) based on the experience. UPV values obtained by indirect method on blocks have been used for the correlation.

Concerning the relation of cutting parameters with quartz content, as described in figure 6, the machine absorption is well correlate with to the quartz content of the tested stone. However, the cutting parameters weren't measured for all the stones, consequently it not possible to demonstrate the full correlation with quartz content. From the table 1, in fact, there wasn't a direct correspondence between IWC and quartz content for all the different kinds of stone. This could be due to the different content of feldspar and their degree of alteration in the analysed stones and it should be further studied in the next researches.

In the figure 7 the correlation among machine absorption and HK25/UPVind (as mean values of UPV performed by indirect method on the block) is reported. The exponential regression has a correlation coefficient of 0,91. The correlation between KH25, UPV and workability class demonstrated in the previous research [1] has been confirmed here.

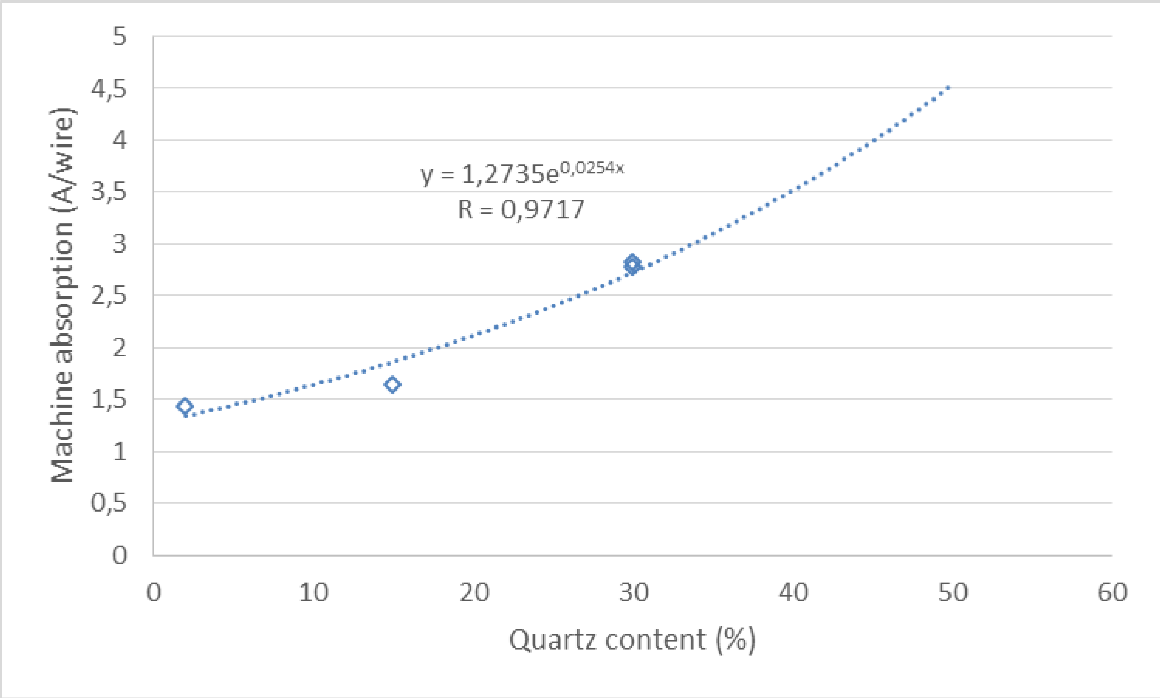


Figure 6. Machine absorption vs quartz content for RBE, SIE, DIOs and GRP.

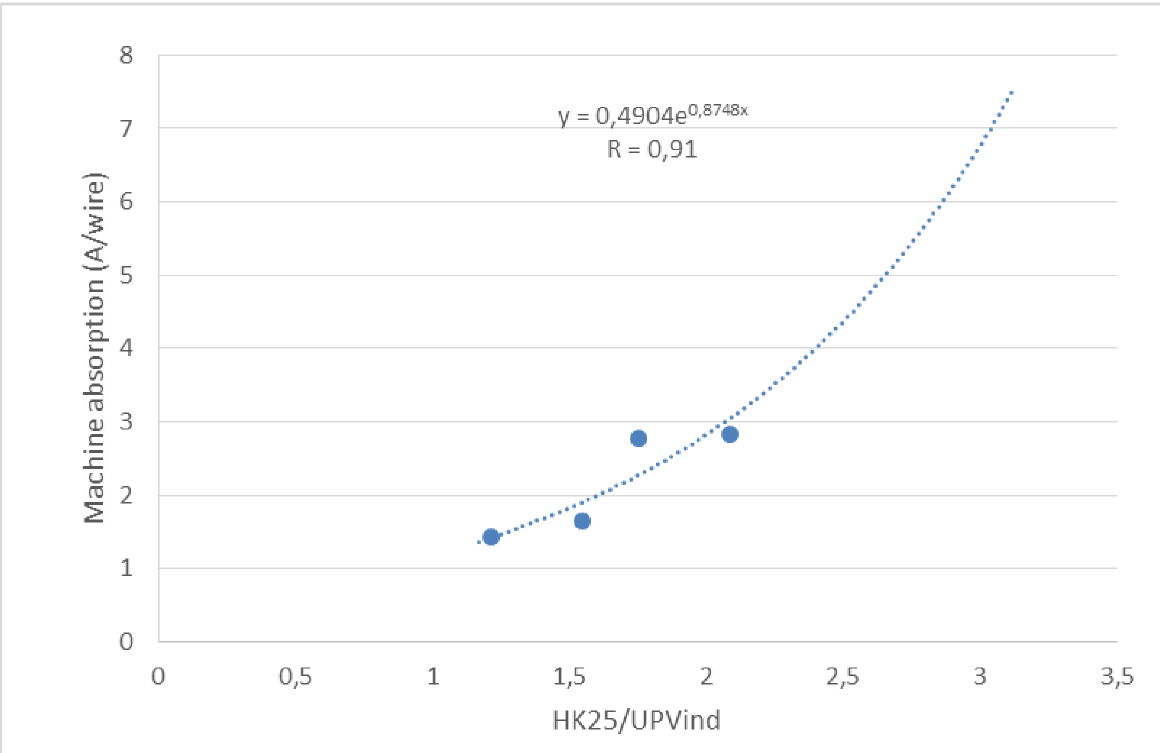


Figure 7. Machine absorption vs H25/UPVind for RBE, SIE, DIOs and GRP.

Conclusions

The in situ measurements on blocks on eight different types of stone allowed to verify the reliability of the different measurement techniques used and to validate a new scientific classification for the workability of natural stones.
From the result analysis, itis possible to confirm that the Schmidt test doesn't discriminate the workability of the rock and therefore it isn't a useful method for this technological classification. Instead, the ultrasonic measurements on blocks are well correlate with those performed on the slabs on the same stone. Moreover, the UPV measurements by indirect method can be considered reliable because they match with those by direct method.
The combination of ultrasonic measurements by indirect method with the index HK25 allowed to order the stones in classes of workability that correspond to what the owners of the plant used to give to such stones. The correspondence with the in situ cutting parameters has confirmed the reliability of this scientific methodology.
With the proposed classification, technical and scientific criteria, have been applied, so to help the choice of the diamond wire and of the cutting parameter,

Acknowledgements
This research has been developed within the European Project EASE - R3 under the Seventh Framework Program under grant agreement no. 608771.

References

[1]Bellopede R., Marini P., Tori A., Zichella L. (2014). Proposal of a new methodology for stone classification in diamond wire cutting technology (EASE R3). Diamante A & T, edizione 79, anno XX, dicembre 2014, pp. 19-26
[2] Amaral, P., Cruz Fernandes, J., Frisa, A., Guerra Rosa, J., Manfredotti, L., & Marini, P. (2000). Evaluation of the workability by means of diamond tools of a series of portuguese commercial granites.pp.323-329.
[3] Ersoy, A., Buyuksagic, S., & Atici, U. (2005). Wear characteristics of circular diamond saws in the cutting of different hard abrasive rocks. Wear, 258(9), 1422-1436. DOI:10.1016/j.wear.2004.09.060.
[4] Gokhan Aydin, Izzet Karakurt , Kerim Aydiner (2013). Wear Performance of Saw Blades in Processing of Granitic Rocks and Development of Models for Wear Estimation. Rock Mech Rock Eng (2013) 46:1559–1575. DOI 10.1007/s00603-013-0382-y.
[5] Mancini and Morandini 1982 Mancini R, Frisa Morandini A (1982) Applications of microhardness tests to the technical evaluation of dimension stones. Fourth Congress International Association of Engineering Geology, New Delhi, p 321–331
[6] Beste U., Jacobson S., (2003) Micro scale hardness distribution of rock types related to rock drill wear. WEAR 254: 1147:1154
[7] Ribeiro R. P., Paraguassú A. B., Rodrigues J. E. (2007) Sawing of blocks of siliceous dimension stone: influence of texture and mineralogy. Bull Eng Geol Env 66:101:107
[8]. Bellopede R., De Regibus C., Manfredotti L. & Marini P., 2005 *Natural stone diagnosis with the means of non-destructive tests: case studies* in MPES05, Canada, CD-ROM
[9] Vasconcelos, G., Lourenço, P. B., Alves, C. A. S., & Pamplona, J. (2008). Ultrasonic evaluation of the physical and mechanical properties of granites. Ultrasonics, 48(5), 453-466. DOI:10.1016/j.ultras.2008.03.008.
[10] Khandelwal M., Ranjith P.G. (2010) Correlating index properties of rocks with P-wave measurements. Journal of Applied Geophysics. Volume 71, Issue 1, May 2010, Pages 1–5
[11]EN14579: 2004 Natural stone test methods - Determination of sound speed propagation CEN-European Committee for Standardiza
[12] ASTM E384-11e1, Standard Test Method for Knoop and Vickers Hardness of Materials , ASTM International, West Conshohocken, PA, 2011, www.astm.org

AKNOWLEDGEMENTS

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 608771 - Project EASE-R3 (Integrated framework for a cost-effective and ease of Repair, Renovation and Re-use of machine tools within modern factory).