Performance and issues of diamond wire in ornamental basalt quarries

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The University of Cagliari (Italy) has carried out extensive research on the use and application of diamond wire in basalt quarries, with the objective of assessing the effectiveness of sawing. The focus of the research has been on time-measurements, in order to produce better data about sawing speed rather than what has already been highly documented by diamond wire builders. Net, technical, commercial and gross sawing speeds are calculated, explained and assessed in close context with the sawed parts. The paper gives also an overview of many issues occurring during block squaring, by offering an interpretation of their cause.
Keywords: *dimension stone, basalt, diamond wire, sawing speed, breaking of the tool.*

Prestazioni e problematiche dell'uso del filo diamantato nelle cave di basalto a uso ornamentale. *L'Università di Cagliari ha intrapreso un ampio studio volto alla valutazione delle prestazioni del filo diamantato impiegato nelle cave di basalto a uso ornamentale, durante le operazioni di segagione dei blocchi. Grande attenzione è stata data allo studio dei tempi, in modo da restituire migliori informazioni sulle velocità di segagione rispetto i dati comunemente forniti dai produttori di filo diamantato. Sono state calcolate e spiegate le velocità nette, tecniche, commerciali e lorde di segagione; esse sono state messe quindi in relazione con le aree segate. Lo studio fornisce anche una panoramica dei cedimenti dell'utensile che avvengono durante le operazioni di segagione e riquadratura del blocco, cercando di individuare le ragioni di tali rotture.*
Parole Chiave: *rocce ornamentali, basalto, filo diamantato, velocità di segagione, rottura dell'utensile.*

1. Introduction

Diamond Wire (DW) technology has established itself as the cutting technology in hard and abrasive dimension stone quarries for over 20 years. This is due to the fact that it provides a way to make precise and non-destructive cuts in the rock mass. Previous barriers pertaining to the costs of the tool have solved themselves over time, thanks to the ever-increasing availability and affordability of industrial diamonds as well as the improvement of diamond-metal alloys' sintering technology (Careddu and Cai, 2014). The use of DW has been particularly common in granite quarries, and and extremely successful commercially (Careddu et al, 2017a).

On the other hand, the use of the DW wire in other hard and/or abrasive (silicate) stone quarries, such as sandstones, trachytes and basalts, is fairly recent. The profit margin of economical stones (which were typically extracted, processed and sold for the local market) could not cover the costs of the consumption/wear and tear of the tool until recently. However, the current increase in demand following the extensive use of local stone for the recovery of many historical town-centres, has made DW technology more economically viable (Careddu et al, 2017a).

The above-mentioned lack of references about the use of DW on these hard and abrasive stones has added to a generally insufficient systematic study into sawing time-measurements and DW "failures".

This study aims to clarify these points and provides substantial data for future research and development. It was necessary to constantly monitor the block-squaring operation on the floor of the same basalt quarry where the blocks are extracted for ornamental use.

2. State of art

The interest of the market towards ornamental stones which are commercially known as "stones" has increased in recent years (expecially basalts) (Careddu *et al.*, 2017b). The request of rocks such as basalt has now strongly increased (Montani, 2016) because of the planned recovery of several public buildings and historic town centers, alongside a greater demand for stone materials intended for street furniture.

Sardinia is currently the main production area of raw basalt in Italy; however, the Island is characterized by a greater planning of quarrying sites and by greater uniformity of the chemical composition of its stone deposit (Primavori, 2011), when compared to other areas where basaltic rocks are quarried (Sicily, Lazio and Campania).

The blocks quarrying process takes place essentially in two ways: the first involves the complete classic cycle, from the isolation of large volumes, from which commercial blocks are obtained

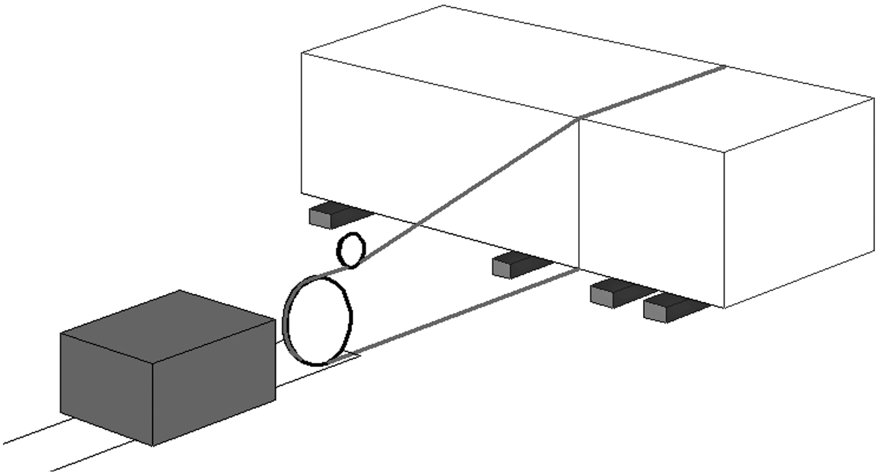

Fig. 1. Block shortening/squaring by diamond wire with "closed loop" configuration (from Cai personal archive).
Riquadratura/riduzione delle dimensioni del blocco mediante la configurazione "a cappio" del filo diamantato (Cai, archivio personale).

by tipping, splitting and squaring the single portion. This procedure is the best method that is used in stone deposit which are kept in good conditions, i.e. characterized by a significant thicknesses of lava flow and a less intense fracturing. The main technology for separation of banks is precisely the diamond wire, possibly supplemented by drilling and/or splitting devices.

If on the other hand, we are dealing with adverse conditions of the stone deposits, a selective quarrying method consisting of the separation of boulders, can be used instead.

In this case, from a technological point of view, a greater usage of earth-moving machinery is necessary for a better assessment of the total volume of stone which has to be quarried. These are flanked by the DW and usually drilled to be squared into different sizes.

However, the current trend is toward the use of the diamond wire as the main technology. At the same time, drilling will gradually become less and less popular (it will likely only be used to create the passage hole for the wire), due to the increased risk of scraps and consequent production decrease in commercial volumes.

The continuity provided by the wire is guaranteed by its closing feature by means of a joint (in copper or steel), pressed on both ends of the cable, by means of a hydraulic clamp. Diamond wire sawing machines for quarry use a closed loop configuration, which gives access to different production methods, all of which would only require the drilling of holes to facilitate the sawing by the diamond wire around the perimeter (Careddu and Mulas, 2003) as shown in figure 1. In that case, and only when the diamond wire is used in quarry by a sawing machine, i.e. with a single flywheel, the wire is always "open". However, it is possible to pass the closed wire around the block before putting the supports that hold the block. It should to be noted that the use of a closed wire after the block wrapping is less common than the open wire solution.

3. Equipment and Materials

3.1. Basalt

Basalt is one of the most common effusive igneous rock It typically features a very dark colour and is relatively poor in quartz; it consists mainly of calcic plagioclase, pyroxene and olivine.

The most exploited basalt formations are located in the western part of Sardinia, specifically in the area of Monte Arci and Giara di Gesturi, in the highlands of Abbasanta and Campeda and in the historical regions of Montiferru and Barigadu (Piras, 2000).

These formations arise primarily from the cycle of subsidence and the associated igneous activity related to the formation of Campidano's Graben. This relaxing tectonic, with faults in NW-SE direction, affected Sardinia during the Pliocene-Pleistocene era, about four million and up to one million years ago (Grillo *et al.*, 2009).

Because of the rapid cooling, basaltic matrix has a very fine grain or, in some cases, often amorphous, crossed by fractures. Minerals cannot be recognized at the naked eye. The minerals that constitute basalt are rich in iron and manganese, which is the reason why the rock has a very dark colour and it more rarely it shows a reddish-vinaceus colour (Careddu *et al.*, 2015) caused by a deterioration by oxidation.

3.2 Basalt quarry

The basalt quarry where the study was carried out, is located in the area called "Su Inzale" in the municipality of Santu Lussurgiu (OR), between the plateau of Abbasanta and the massif of Montiferru as shown in figure 2.

The mineral-petrographic analysis by thin sections showed similar features all over the stone deposit. The basalt generally shows a porphyritic structure with intersertale texture in basaltic rock. The olivine phenocrystals and clinopyroxens are immersed

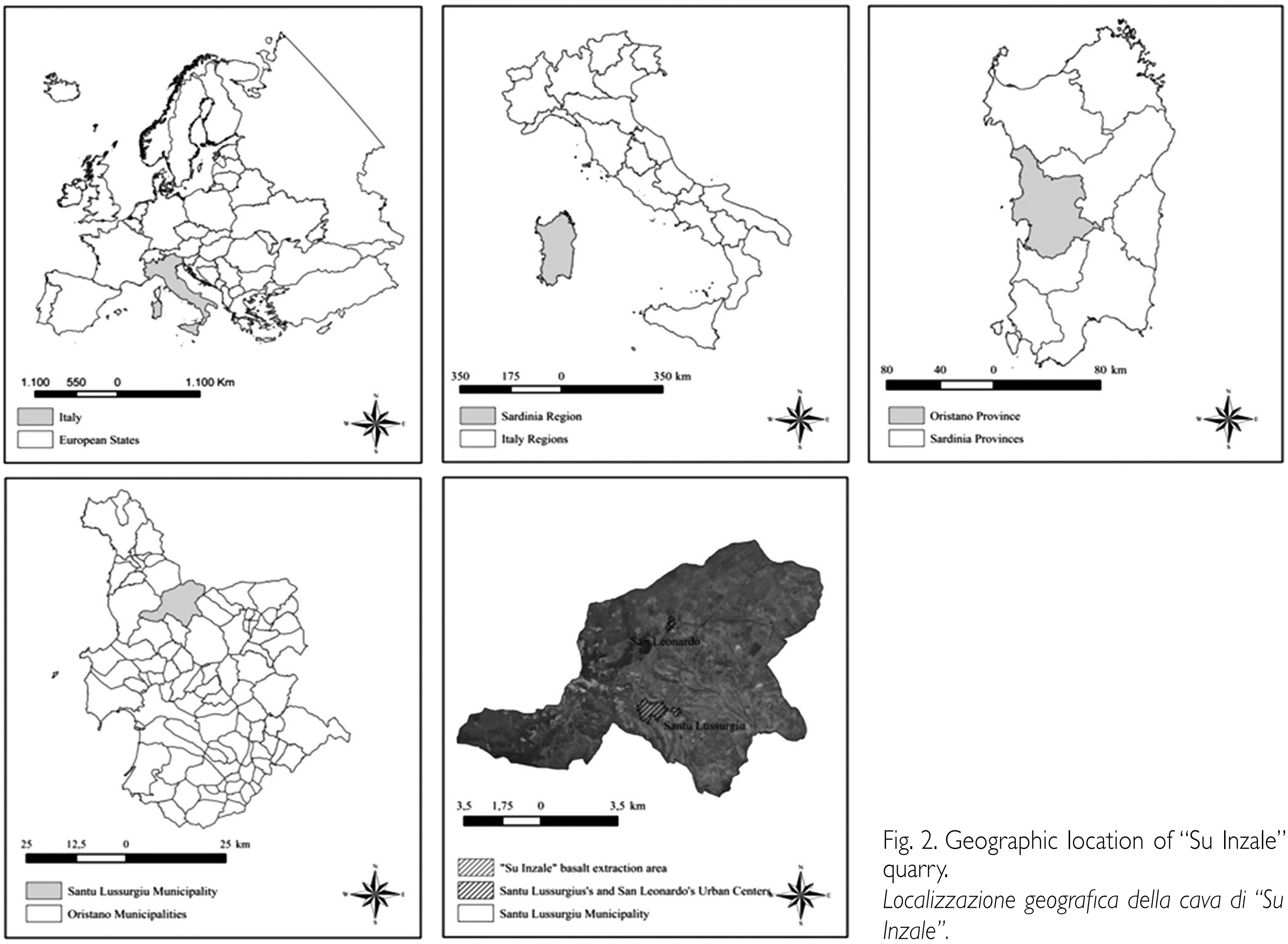

Fig. 2. Geographic location of "Su Inzale" quarry.
Localizzazione geografica della cava di "Su Inzale".

in a matrix of calcic plagioclase. Olivine is often from reddish borders altered to hiddingsite.

Some of the physical and mechanical properties of the basalt are given in Table 1. The physical and mechanical properties were determined by a whole range of laboratory tests which were carried out in accordance with CEN-EN standards.

The basalt rock mass takes a parallelepiped-shape, with rounded edges and vertices larger than 2 m, which are naturally found in the quarry area. Sometimes it is possible to find even much bigger blocks, up to 4 m in the longer side.

Vertical stripes in one step is the excavation method adopted in the quarry; blocks are distanced from the quarry-face by excavator.

The quarry-face is not homogeneous; the blocks that gradually emerge in the face are in fact already isolated by rock-mass discontinuities which are filled with fine materials resulting from basalt degradation.

The first step is to remove the topsoil over the block to be extracted; topsoil is often a few decimetres thick; it is totally absent in some areas. The block which will be sawn will be placed on a bed of debris which would have been prepared in advance; it is then conveniently placed on other rocks (rubble) to avoid using the

Tab. 1. Physical and mechanical properties of the basalt quarried at "Su Inzale".
Proprietà fisiche e meccaniche del basalto estratto a "Su Inzale".

Physical-mechanical properties	Eu standard	Unit	Values
Petrographic examination	EN 12407:2007	-	Olivinic basalt
Apparent density	EN 1936:2007	kg/m^3	2,711 ± 2
Water absorption at atmospheric pressure	EN 13755:2008	%	0.82 ± 0.03
Flexural strength under concentrated load	EN 12372:2007	MPa	9.26 ± 0.10
Compressive strength	EN 1926:2007	MPa	127 ± 0.76
Compressive strength (after 48 freeze – thaw cycles)	EN 1926: 2007 + EN 12371:2003	MPa	140.50 ± 0.91
Abrasion resistance	EN 14157:2005	mm	18.3 ± 0.2
Slip resistance	EN 14231:2004	-	69.80 ± 0.84 (dry)

drilling machine. In this way, it is not left on the ground on the free passageway where DW must be inserted. In case this is not possible, the tradesman must drill a passage hole.

Once moved from the quarry-face, the blocks are shortened by diamond wire sawing (they are sawed in two or more parts) until they reach the maximum volume of 7 m^3 (about 20 tons), due to the lifting limit (safety restraint) of the crane located in the stone-processing plant.

The current quarry yield is about 35%.

3.3. *Diamond wire*

A DW with injected vulcanized rubber was used to saw the basalt blocks; this DW has 40 sintered beads per meter, the beads have an external diameter of about 11.4 mm. The initial length of the DW was 30 m.

Given that the beads must have a homogeneous wear along their lateral surface, a 1.5 twists/m is given to the tool in the tightening direction of the strand; this is done manually by the operator before "loop" closing of DW with joint pressed by hydraulic crimping (Cai *et al.*, 2007).

The operator draws a red line on the block in order to highlight where the DW will start its sawing process; the sharp edges are eliminated with a hammer, because they will strongly wear out the tool.

The diamond wire sawing machine used in the quarry is a S625EGT provided by Italy's based Dazzini Macchine. The peripheral speed of the wire can be adjusted electronically at any time during the process and it may range from 0 to more than 30 m/s. The optimal value on this type of rock is of about 28 m/s.

The tension of the wire is the result of the withdrawal of the sawing machine on its tracks; the backwards-and-forwards movement and speed are controlled by an inverter.

During the sawing process, the DW is constantly supplied with water – about 7-8 L/min – which is necessary to cool down and keep clean the tool and the fluting; this detail is a very important, but hardly ever mentioned in any bibliography. The body of water should not exceed to avoid aquaplaning. The water hose is placed on the block above the saw-line.

4. *Experimental*

Before describing the experimental plan, it should be noted that this study illustrates a part of a research aimed to estimate the efficiency of the diamond wire in the basalt stone quarries from an economically as well as environmentally aspect (Careddu *et al.*, 2017a]. During the sawing operations, the following data were collected: 1) wire length and number of beads, 2) decrease of the diameter of the beads, 3) characterization of both stone and sawing sludges, 4) gross and net sawing times, 5) sawed areas. Because of the above-mentioned reasons, the data in 1), 2) and 3) were not used in the present study, but already discussed in (Careddu *et al.*, 2017a).

Time measurement allows to assess both gross and net sawing times. In fact, gross time is strongly affected by early and final sawing stages (for the slow speed which feeds the tool) and accidents (breakings, blockages, sliding out from joint, etc.).

The time needed to carry out all operations was measured during the sawing process: DW preparation (skinning, junction, twist), marking line for block squaring and machine positioning, start sawing, sawing steadily, possible pauses, final stage.

The cut surface has been assessed with the following methodology. A photograph of each surface was taken perpendicularly to each same surface obtained by sawing, with a tape measurer alongside as a reference; the photographs were then processed with ImageJ software, provided by the U.S. National Institute of Health (fig. 3).

225 sawing operations were monitored in quarry during a period of about 7 months.

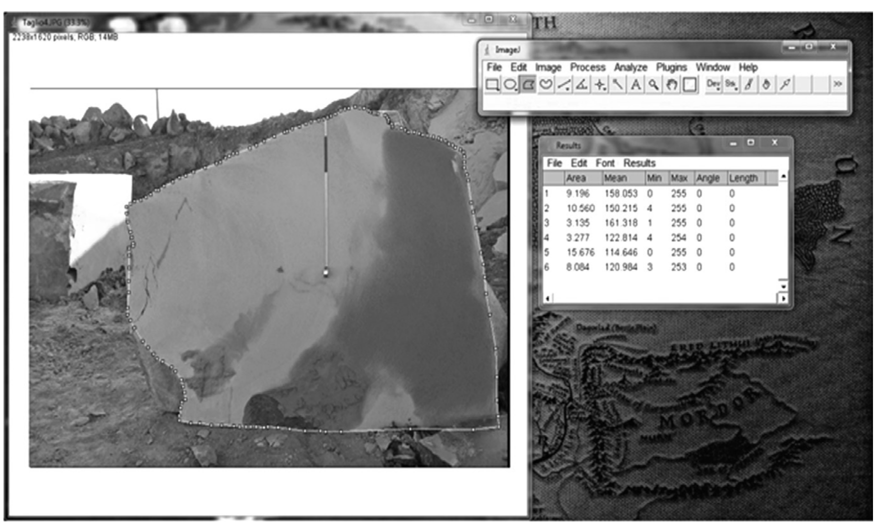

Fig. 3. Sawed area measurement by using software ImageJ 1.47v.
Misura della superficie segata mediante il software ImageJ 1.47v.

5. Discussion and results

5.1. Time measurements

The average sawing speed S_a can be defined as the total time T (measured in hours) necessary for the machine to separate the area A (in m^2). Consequently, S_a will be also a gross sawing speed S_g:

$$S_a = S_g = \frac{T}{A} \tag{1}$$

The net sawing S_n does not take into account any dead-times (also called down-times) such as those related to accessory operations, wire breakage, other accidents, etc. Therefore, S_g takes into account the total time T which can be described by the equation (2):

$$T = T_n + T_s + T_f + T_{down} + T_{set} \tag{2}$$

where:

T_n = net sawing time; it is the time during which the machine is really sawing the block in steady conditions;

T_s and T_f are respectively the time needed for the sawing machine to reach the steady condition and time of the final phase of the sawing process. In both cases, the sawing speed is reduced to avoid an excessive wear of the DW due to the high curvatures;

T_{down} is the time spent for repair (or replacement) of the DW and/or sawing machine;

$T_{set} = T_w + T_{aux}$: is time needed to set up the sawing machine. It is total of T_w, time needed for DW preparation (positioning, skinning, junction), and T_{aux}, which takes into account the auxiliary times for block marking and machine positioning.

By this way, the following sawing speeds can be both recognized and defined:

$S_a = S_n$ = net sawing speed, when $T = T_n$;

$S_a = S_t$ = technical sawing speed, when $T = T_n + T_s + T_f$;

$S_a = S_c$ = commercial sawing speed, when $T = T_n + T_s + T_f + T_{down}$;

$S_a = S_g$ = gross sawing speed, when $T = T_n + T_s + T_f + T_{down} + T_{set}$.

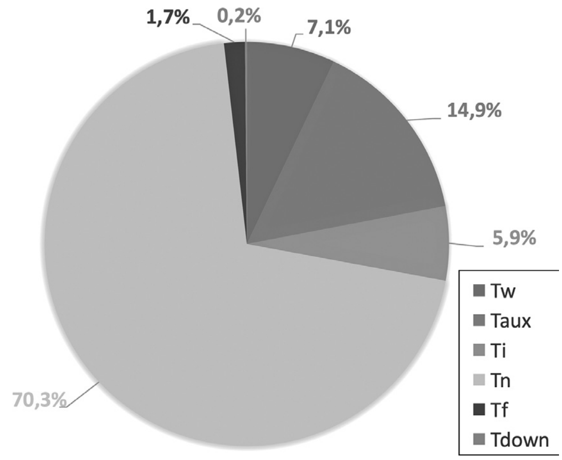

Fig. 4. Subdivision of the total time T in the different sawing phases (average).
Ripartizione media del tempo totale T nelle varie fasi che costituiscono le operazioni necessarie per i tagli

The pie chart in figure 4 shows the average subdivision of the times spent during the different stages of the sawing process

The variation of the percentages is summarized in Table 2 by the mean square deviations of each phases.

Data analysis shows that more than 70% of the total time T is spent on block sawing under steady conditions (T_n). The analysis also clearly shows a greater variability during T_w and T_{aux} (and, consequently, T_{set}).

During sawing, T_w has varied from a minimum of 0 minutes (when it was not necessary to cut and re-joint the wire) to a maximum of 30 minutes when, passing to another block to be sawed, the wire had to be necessarily cut, repositioned and re-jointed. In one particular case, during the passage of the wire under the rock by the probe, one end of the wire was damaged and it needed to be cut by three centimetres. The operation had to be repeated. Statistically, the wire did not require cutting in 1 out of 3 sawing operations, when it was positioned directly around the block to be cut.

T_{aux} is closely dependent on the moving operation of the sawing machine in the quarry and its subsequent setting of the operating parameters. When sawing, T_{aux} has varied from a minimum of 6'51", because it was not necessary to move the sawing machine, nor change its parameters and the only auxiliary operation was the line marking for block squaring, up to a maximum of 43'33" when the auxiliary operations were more complicated.

In percentage terms, both T_i and T_f have not varied substantially; however, in absolute terms the length of time necessary to reach the steady speed since the beginning of the sawing was timed with a minimum of 3'40" to a maximum of 23'50" since the geometry of the initial block was more complicated and the beginning of sawing needed more precision.

T_f (ending deceleration phase) has varied little; in some cases, it was null, because the block has broken itself suddenly in the surface yet to be cut.

Tab. 2. Mean square deviations (in %).
Scarto quadratico medio (in %).

	T_w	T_{aux}	T_{set}	T_i	T_n	T_f	T_{down}
σ	6.15	8.02	6.27	2.62	6.03	1.77	0.46

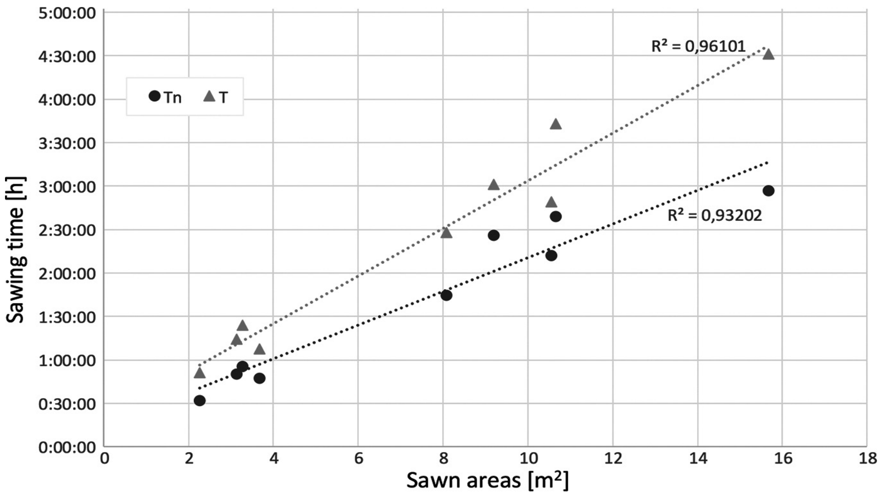

Fig. 5. Correlations between net (Tn) and gross (T) sawing times and sawed areas.
Correlazioni tra i tempi di segagione netto (T_n) e lordo (T) e le aree segate.

Anyway, the T_{down}, times to stop for wire and or sawing machine, were few and very fast. For example, in some cases a sawing stop was necessarily in order to pull DW under a pulley so as to allow the machin to gain rail; those breaks lasted an average of just over 2 minutes.

T_n has varied in percentage terms (61.7% and 80.7%) and, especially, in absolute terms, because it is strongly linked to the size of the sawed surface (fig. 5). In any case, the sawing time – net and gross – show a linear correlation with the sawing area.

The different sawing speeds on basalt, measured in m^2/h, are summarized in table 3. S_n ranges from 3.55 and 5.32 m^2/h. These differences are related to the block geometry, which sometimes requires more caution during operations. Moreover, with the wear and tear of the DW (and its loss of beads), S_n decrease.

S_n average is 4.31 m^2/h, comparable with the net sawing speed measured in a granite quarry of II-III of sawability classes.

Tab. 3. Minimum, maximum, average and mean square deviation values of the sawing speeds (in m2/h).
Valori minimi, massimi, medi e scarti quadratici medi delle velocita di segagione (in m^2/h).

	S_n	S_t	S_c	S_g
min	3.55	3.14	3.14	2.35
max	5.32	4.76	4.76	3.75
average	4.31	3.89	3.88	3.02
σ	0.59	0.57	0.57	0.46

5.2. Problems of diamond wire during sawing

Different types of issues may occur during on-site sawing, due the iteration between rock and diamond wire. Such problems damage the DW; this can take place in different ways; a number of cases were detected during the sawing operations (see below).

A "classic" case would be the totally unexpected cracking of the rock (latent fracture): in this case, the falling rock squashed the wire and damaged it in two points. (see figure 6). We noticed that the tool stopped suddenly for a split second (the machine is meant to pause automatically for safety reasons), during which some rubber spacers presumably got loose and got too close to the diamond beads (fig. 7). This kind of dynamic is very frequent in

Fig. 6. Fracture opening (a) and rock falling (b) during sawing.
Apertura della frattura e crollo della parte di roccia interessata.

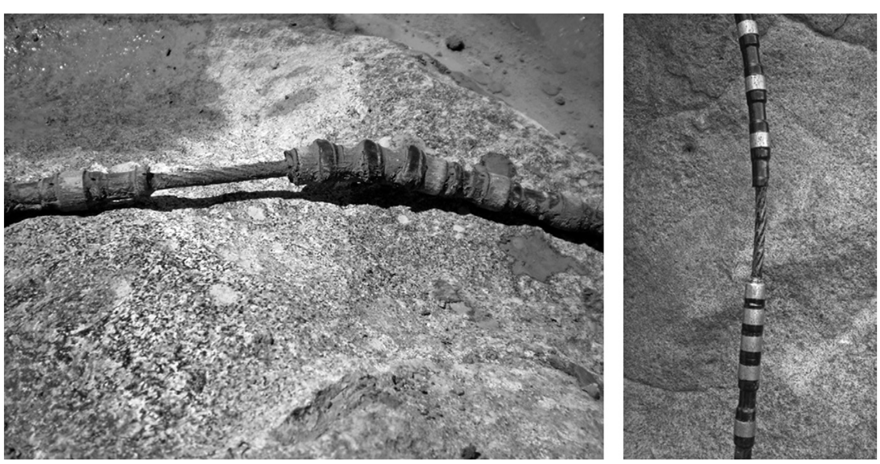

Fig. 7. Same cases of segments of DW damaged by the settlement of the spacers.
Esempi di tratti di filo danneggiati per lo slittamento dei distanziali.

cases like this that are described here.

Figures 7a and 7b show a classic accident due to the spacers settlement. On left side of the DW (fig. 7a), it's possible to note the regular distance of the beads; so, the first bead on the right is the one that surrendered and then dragged the other two against the fourth that has resisted. The same considerations could be done with respect to the segment of wire shown in Figure 7b.

Figure 8 shows an example of wire breaking for "pinch", and swiping and tearing of the tool, when its section was intact.

The DW often continues to saw with uncovered segments of wire which are too long; in other words, some segments can be uncovered (without rubber/plastic cover) and have no beads. The outer wires of this segment begin to be eroded by the abrasive sawing sludge at some points, until the whole section no longer has a sufficient tensile strength: at that point, the breakage of the diamond wire happens.

Figure 9 shows a diamond bead which was damaged during the sawing. It is sintered directly on a spring (which during heat treatment loses its springing features whilst maintaining the same shape); this method (which is almost no longer in use) is twofold:

1. to make flexible the internal support of the diamond bead;
2. to facilitate the gripping of plastics/rubber during injection; however, as we can see in figure 9, that does not seem to have been set up correctly.

The sintered bead appears to have broken because its inner support was not rigid enough. However, it should be noted that irregular sawing forces sometimes resulted in fracture of the diamond segment (Ucun et al, 2008).

An unusual case of DW failure is shown in figure 10.

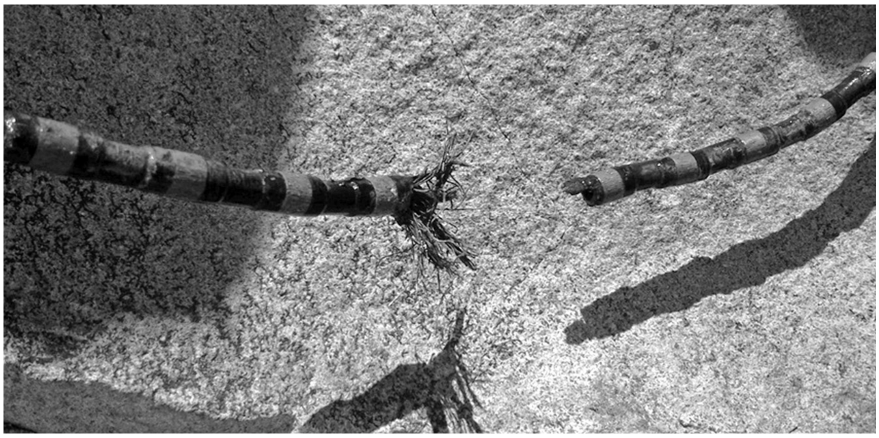

Fig. 8. Case of wire breaking for "pinch" and swiping and tearing of the wire.
Caso di rottura per "pizzicamento" e strappo del cavetto.

In fact, if the basalt block produces a "pinch" on the bead at point A (as illustrated in figure 11), the force due to the kinetic energy of the diamond wire (which is related with DW peripheral speed) moves the beads towards the left, due to the spacers settlements, while the diamond beads on the right did not show any stress and would remain in their place.

In this case, the failure of the spacers may have occurred for other reasons, such as the lack of adhesion of the bead wire or an erosion (especially on that DW segment) caused by friction with rock debris.

However, a cable which deformed over the limit of elasticity remains harder to explain. If we rule out the possibility of a hard impact of the DW at the entrance to the block, due to malfunctioning

Fig. 9. Broken bead.
Perlina rotta.

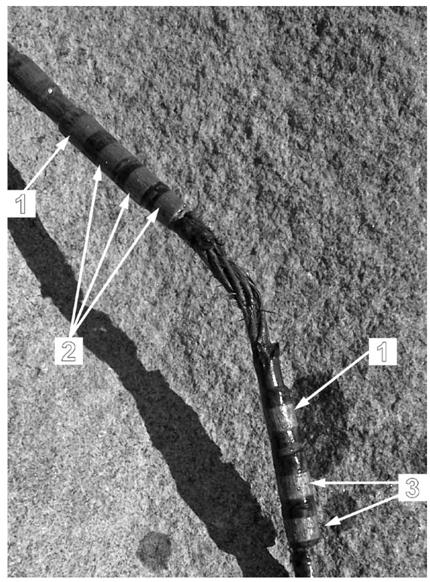

Fig. 10. Unusual deformation of diamond wire. 1) Diamond beads which have resisted; 2) diamond beads whose injected plastic spacers did not resist and are slipped along the steel cable; 3) diamond beads whose spacers did not resist.
Particolare deformazione del filo. 1) Perline che hanno resistito; 2) perline il cui distanziale di plastica iniettata non ha resistito e sono slittate lungo il cavo di acciaio; 3) perline il cui distanziale non ha resistito.

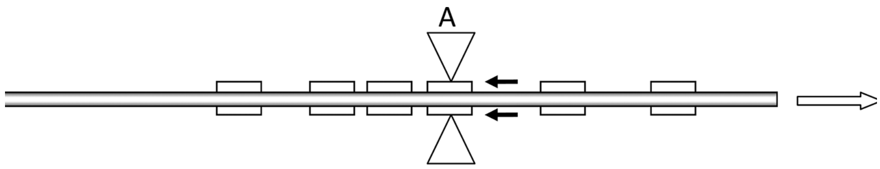

Fig. 11. "Pinch" of the diamond bead due to rock failure. The DW is moved in the direction of the white arrow; when the DW is blocked a certain number of beads are moved according with the direction of the black arrows (from Cai personal archive).
"Pizzicamento" della perlina nel punto A dovuto al cedimento della roccia. Il filo diamantato è mosso in direzione indicata dalla freccia bianca; quando esso è bloccato, un certo numero di perline scorrono nella direzione indicata dalle frecce nere (Cai, archivio personale).

of the sawing machine, it is possible that the deformation is related to a sudden failure of the general support of the block on the side opposite to the feed of the DW; in this case, the settlement of some spacers may have suddenly stalled. The aging of steel cable, its wear and tear (Huang and Xu, 2006), can certainly amplify the problems described above.

Whenever these problems occur, it is necessary to remove, i.e. cut away, the unusable segments of the diamond wire and re-joint their ends. This implies a shortening of the DW, a loss of beads (at least two for junction) and an increase of the junctions (which does not contribute to sawing). Therefore, the wire underperforms (due to the decrease of the number of beads per meter) and lasts less (fast aging of the tool) as specified in Careddu *et al.* 2017a.

6. Conclusions

The study showed how the different phases of block squaring in quarry by diamond wire can affect the sawing speed. The causes which slow down the sawing operations are not typically defaults of the tool during its processing (T_{down}). Many issues happened during the setting and preparation of the DW (T_{set}) or before sawing; T_s and T_f affect surely less than T_{set}.

The problems found in the tool are mainly related to the fact that after so many sawings (225!) the steel cable ages to "fatigue" and experiences a sudden breakage. The probability of a tool breakage is further increased by the blockage and/or the contraction of DW, due to its impact on the sliding rock, which cause breakage or cracks the beads and/or settlement of the spacers. As a consequence, the steel cable sheds its cover, which is eroded by the abrasive sawing sludge until it completely loses its tensile strength and breaks down.

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