Araştırma Makalesi

Rock Characterization and Wire Performances for Dimension Stone Cutting by Diamond Wire Saw

Elmas Tel Kesme ile Boyutlu Taş Kesimi için Kaya Karakterizasyonu ve Tel Performansı

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Abstract

A joint research between Italy and India was conducted in 2 marble quarries to compare the characteristics of the diamond wires used, through the analysis of their performance. The research had also the aim to exchange the know-how on the quarrying methods and cutting techniques: tests were carried out both on site and in laboratory, and the necessary data were collected. The sites under investigation were Carrara (Italy) and Ambaji (India). In both quarries the mixed technique "diamond wire saw and cutting chain" is used, but research has focused mainly on the performance of the wire. The following data were collected on the diamond wire saw to outline the performance of the system: installed power, cut geometry, cutting speed, wire length, tension applied to the wire, diameter of wire and beads, number of beads/meter. Moreover, samples both of marble and of overburden waste rocks were collected, needful to carry out the mechanical laboratory tests. Therefore, a characterization of the rock at different laboratory scales was done, to obtain data on rock-tool interaction, to evaluate the beads consumption and to develop guidelines for dimension stone cutting with diamond wire saw.

Keywords: Marble; Diamond wire saw

Özet

Italya ve Hindistan'da 2 mermer ocağında kullanılan elmas tellerin performans analizleri ile özelliklerini kıyaslayan bir bütünleşik bir araştırma yapılmıştır. Bu araştırma aynı zamanda kesme teknikleri ve taşocağı işletme teknikleri ile ilgili bilgi değişimini de amaçlamaktadır. Hem laboratuvarda hem de sahada testler yapılmış ve gerekli veri toplanmıştır. Çalışma sahaları Italya'da Carrara ve Hindistan'da Ambaji taş ocaklarıdır. Her iksinde de hem elmaslı tel testere hem de zincirli kesme makinası kullanılmıştır. Ancak çoğunlukla araştırma tel performasına odaklanmıştır. Sistemin performansını incelemek için elmas tel testere ile ilgili kurulu güç, kesme geometrisi, kesme hızı, telin uzunluğu, tele uygulanan gerilme, telin ve boncukların çapı ve metre başına düşen boncuk sayısı ile ilgili veri toplanmıştır. Buna ek olarak, mermer ve üst örtü malzemesinden numuneler alınmış ve mekanik laboratuvarında test edilmiştir. Böylece kaya-zemin etkileşimni ile ilgili veri alabilmek ve boncuk tüketimini değerlendirmek ve elmaslı tel testere ile taşın kesilmesi için rehber geliştirilmesi için kayanın farklı laboratuvar ölçeklerinde karakterizasyonu sağlanmıştır.

Anahtar Kelimeler: Mermer, Elmas tel kesme

1. Introduction

The attention has been initially focused on the types of materials exploited in the two sites of Carrara (Italy) and Ambaji (India), and a laboratory characterization of the two marbles has been then made, through the employment of the following tests: Brittleness Test (S20), Cerchar Abrasiveness Test (CAI), Knoop Micro-Hardness. The procedure of the different tests and the results obtained are shown below.

Being the purpose of the study to provide a better understanding of the benefits of diamond wire cutting on the above quoted marbles, an experimental investigation at the quarry sites has been carried out, in order to obtain data pertaining to the cut, both primary and secondary (reshaping of blocks). It was therefore created a database to facilitate the retrieval of data related to the diamond wire type, to the machines employed, to the type of cut and to the geometry of blocks.

During the experimental campaign, important data were collected useful for the characterization of the behavior of the diamond wire, such as the cutting speed. It was also considered of great importance the correlation between the cutting speed and power and amperage of the wire that are applied to the cutting machine.

Laboratory tests were then performed to evaluate the tensile strength of steel cable (with and without beads), that is the core of wire. Through the correlation of data derived from Indian and Italian samples, it has been determined that the cables used in Carrara perform better than others. This is due not only to the type of material to be cut, but also to the constitution of the wire, especially in the case of assembled wire.

Finally, as a possible starting point for future studies related to diamond wire, the problems of bending strength to which the wire is subjected during cutting have been exposed. For these problems, in fact, were never conducted tests to determine the behavior of the steel cable, although this is constantly subjected to bending efforts.

2. Location of quarries under study

2.1. Carrara quarry

Data were collected on the execution of primary and secondary cuts; the activity was carried out in the quarry "I Campanili" (Figure 1), which is located in the basin of Colonnata, that includes 29 active quarries and is the easternmost of the three Carrara basins (Torano, Fantiscritti and Colonnata). The area took its name from two high spurs of rock residues of the work undergone from the ancient crest of the watershed and recently shut down for safety reasons, because of their instability, which created a danger of falling on the yards of the quarries below.

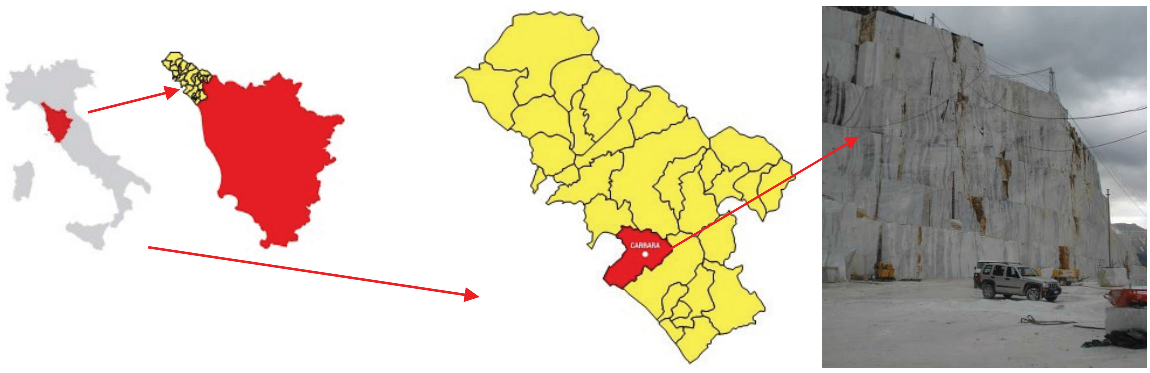

Figure 1 - Framework of the Marble Quarry "I Campanili" (Italy).

***Şekil 1 -** Mermer ocağının çalışma alanı "I Campanili" (Italya).*

2.2. Ambaji Quarry

The quarry where the activities were carried out for data collection is one of the most beautiful white marble quarries in India and is located at Ambaji, in the federal state of Gujarat (Figure 2).

The current production amounts to about 15000 m2/month of polished marble slabs. The quarry is characterized by the presence of a thick overburden, which must be removed to provide access to the underlying marble benches (Figure 3). Currently, the removal of the waste material is carried out by means of the drilling & blasting technique, and blasts are sized to cause the least damage to the underlying rock. However, the spread of unwanted fractures due to the use of explosives is not completely excluded, so it is partially compromised the integrity of the ore body. The use of explosives is still the cheapest and fastest, because of abrasiveness and the hardness of the overburden, largely made up of microcrystalline silica.

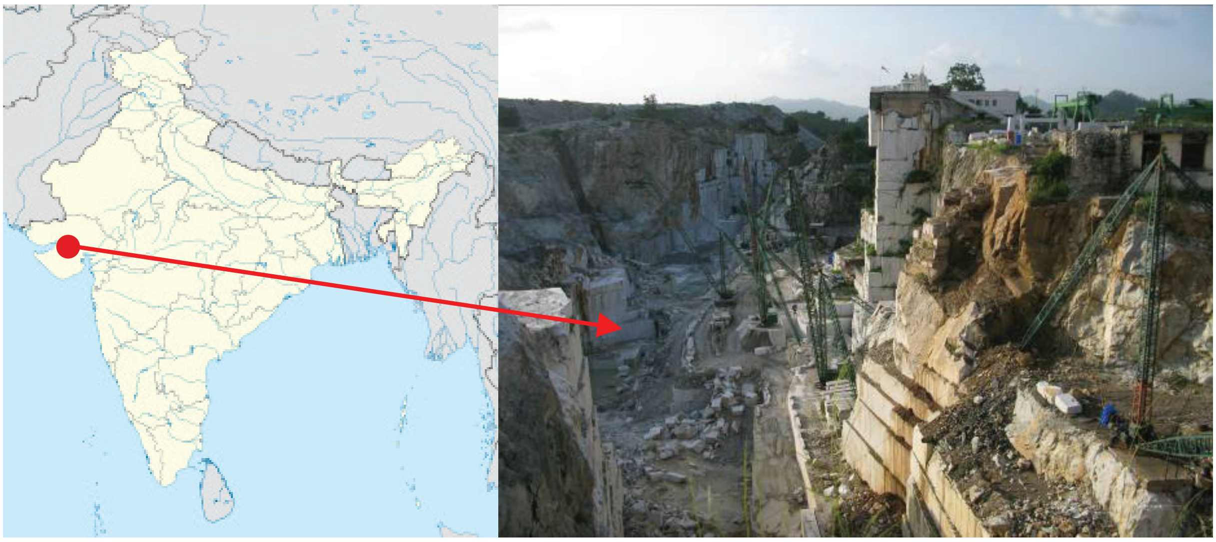

Figure 2 - Location of the Ambaji quarry, Gujarat (India).
***Şekil 2** - Ambaji ocağının yeri, Gujarat (Hindistan).*

Figure 3 - Waste material to be removed to carry out the exploitation of the white marble underneath, Ambaji quarry, Gujarat (India).
***Şekil 3** - Waste material to be removed to carry out the exploitation of the white marble underneath, Ambaji quarry, Gujarat (India).*

3. Laboratory tests

3.1. The Brittleness Test

The test gives a reliable measure of the capability of a rock to resist to crushing after a number of repeated impacts. According to its definition, the brittleness value (S20) equals the percentage of rock fragments that pass the 11.2 mm mesh after the original amount of material has been hit 20 times by a hammer (14 kg) in a mortar (Dahl 2003). The final S20 value characterizing a rock type is given by averaging the values obtained from at least three tests performed on the same rock type. S20 is the first value needed in order to assess the Drillability Rate Index (DRI).

In order to collect at least three samples per rock type (around 500 g per sample), 15 kg of raw material or more were crushed in the jaw crusher and, then, collected and sieved with squared meshes of different sizes: 16 mm, 11.2 mm, 8 mm, 4 mm and 2 mm. By calculating the percentages of material of the other sizes, a first approximate behaviour of the rock type can be predicted.

The rock was then crushed with the mortar. The test requires twenty impacts from an average height of 25 cm (the distance between the top of the lid and the tip of the hammer). After that, the fragments of rock were removed from the cylinder and, then, sieved using all the meshes employed before, except the 16 mm one. The percentage of material passing through the 11.2 mm mesh is the one yielding S20 (Table 1).

Rock	Brittleness (S20)
Carrara Marble	62.06
Marble M0 (Ambaji)	35.31
Marble M1 (Ambaji)	38.27
Marble M2 (Ambaji)	53.52
Marble M4 (Ambaji)	58.99
Overburden OB-1 (Ambaji) Gray	36.30
Overburden OB-2 (Ambaji) Green	35.34
Overburden OB-2 (Ambaji) Green	39.09

Table 1 - Results of Brittleness test (S20) (Shukla, 2011).

Çizelge 1 - *Results of Brittleness test (S20) (Shukla, 2011).*

3.2. The Cerchar Abrasiveness Test

The Cerchar abrasiveness test is meant to characterize a rock specimen in order to evaluate its diggability and to predict tool wear and performance. This test has gained much popularity, being very easy to do. It consists of scratching a steel pin with a 90° conical point on a rock sample for a length of 10 mm. The steel pin has to be pressed down on the rock's surface with a 70 N force. The Cerchar abrasiveness index, commonly referred to as CAI, is the measured wear flat of the pin, given in tenths of millimetres (Cerchar 1986). Up to date, there is no universally accepted standard procedure for this test: there are mainly two devices with which the test can be performed. The difference between them is the way the steel pin is scratched on the rock: in the original machine, designed when the test was developed, there is a lever to which the steel pin connected directly; the scratch is done by pulling the lever.

The testing procedure was quite simple: the rock sample is placed on the sliding support and fastened with the surface that is going to be scratched upwards; then, the steel pin is put in place, being sure that the top of the cone touches the rock's surface. Once the pin is positioned, the 70 N force can be applied on top of it.

The scratching test is then ready to begin, and the crank has to be turned 5 times in order to move the rock sample 10 mm. Once the scratching procedure is completed, the pin can be removed and taken to the optic microscope in order to measure the wear flat. Every pin has to be photographed two times, so that the wear flat in two perpendicular directions can be measured, yielding an average value. The results of tests are given in Table 2.

Rock	Cerchar Abrasivity Index CAI
Carrara Marble	0.86
Marble M0 (Ambaji)	0.83
Marble M1 (Ambaji)	0.62
Marble M2 (Ambaji)	0.98
Marble M4 (Ambaji)	0.65
Overburden OB-1 (Ambaji) Gray	2.75
Overburden OB-2 (Ambaji) Green	2.5
Overburden OB-2 (Ambaji) Green	2.6

Table 2 - Measured of Cerchar Abrasivity Index (CAI).
Çizelge 2 *- Measured of Cerchar Abrasivity Index (CAI).*

3.3. The Knoop Micro-Hardness Test

Hardness tests are meant to evaluate the response of materials under point-concentrated loads, meaning thereby that the load is applied on a very small surface.

The Knoop test is a typical micro-hardness test with obtuse indenter, well suited for fragile or hard materials, as the mark left by the indenter is easily recognizable and measurable. The indenter is an elongated rhombohedral pyramid with apical angles of 130° and 172° 30', and the weight applied is 200 g. In the standard Knoop test, the longest diagonal of the indented on the sample is measured, and the Knoop hardness (HK) is expressed by the formula:

$$HK = 14230 \cdot P \cdot l^{-2}$$

where: P is the load applied on the indenter, expressed in grams, l is the length of the longest diagonal measured on the sample, expressed in micrometers. The HK value is expressed in MPa. Previous studies (Mancini et al.,1993; Cardu et al., 1994) have shown how the HK value decreases as the load increases.

Table 3 and Figure 4 supply the microhardness values. It is noticeable that the trend of the microhardness of the Indian overburden is significantly higher, compared to marbles. Moreover, it has to be underlined that the trend of hardness is approximately the same both for Italian and Indian marble.

Rock	Microhardness [MPa]			
	25%	50%	75%	mean
Carrara Marble	1248	1354	1542	1371
Marble m0	1168	1291	1475	1352
Marble m1	1124	1248	1354	1305
Overburden OB-1 Grey	1785	3602	5456	3686
Overburden OB-2 Green	5533	6501	7496	6511

Table 3 - Percentile microhardness of the rocks analyzed.

Çizelge 3 - *Percentile microhardness of the rocks analyzed.*

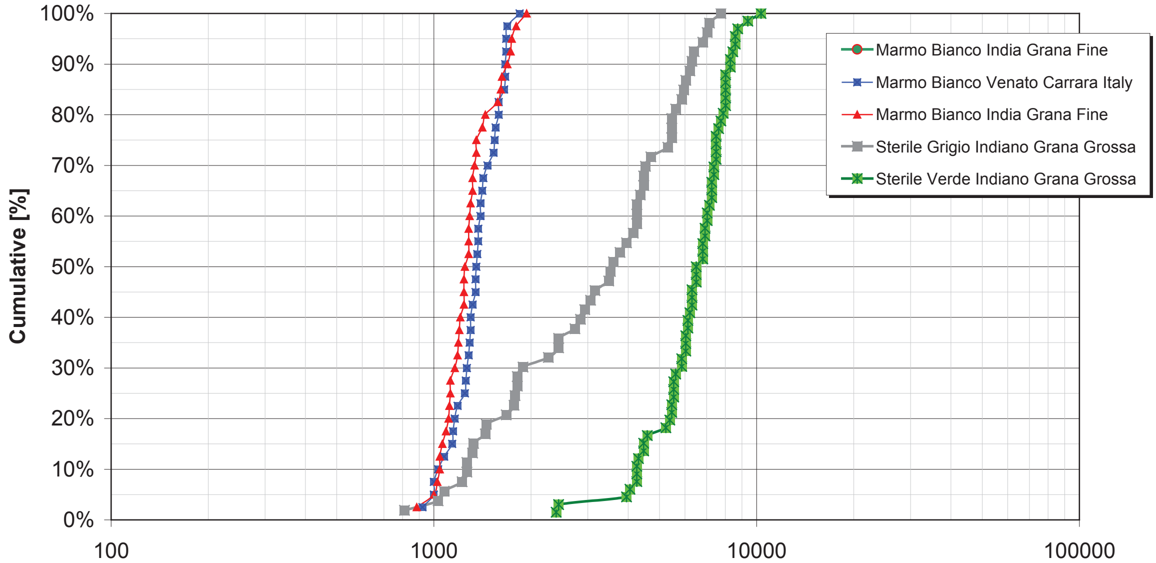

Figure 4 - Microhardness frequency distribution diagrams of the rocks analyzed.

Şekil 4 - *Microhardness frequency distribution diagrams of the rocks analyzed.*

4. The cutting machine

The use of diamond wire involves the creation of a closed loop within the rock mass to be cut, by which the wire runs at high speed (approximately 30 – 40 m/s), always sprinkled with water for its cooling, so as to gradually affect the stone and create an ever deeper groove (Figure 5).

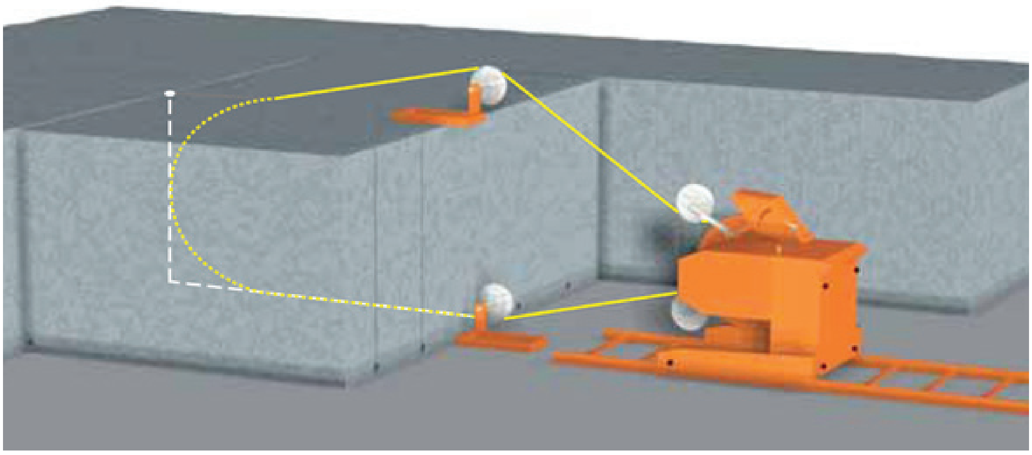

Figure 5 - Scheme of a block cut in a quarry bench.

Şekil 5 - *Scheme of a block cut in a quarry bench.*

The realization of the circuit, in the simplest "loop" case, consists in the drilling of two holes pre-coplanar and convergent (Figure 5), that will be virtually positioned along the edges of the real portion of the rock to be isolated.

Within this path is then inserted the wire, which then is closed in a ring around the outer edge of the pulley driven by the engine of the saw.

During the cutting the machine recedes, usually on a sliding track and thereby maintaining continuous tension in the wire in contact with the rock, producing a planar cut through progressive wear of the rock body.

The machines used in the Carrara quarry have a power of 75 HP (55.2 kW), weighs 2100 kg and have a flywheel with a diameter of 900 mm (Figure 6).

Figure 6 - An example of diamond wire saw employed in the Carrara marble quarry "I Campanili".
Şekil 6 *- An example of diamond wire saw employed in the Carrara marble quarry "I Campanili".*

The rate of retreat of the machine varies from 1.5 mm/s to 3 mm/s, depending on the size of the block to be cut and on the amperage required by the operator: the more it is lower, the speed of retraction decreases and increases the time needed for the execution of the cut.

The data collected in the quarry included the observation and detection of block sizes, ranging from a few m^2, in the case of squaring (1.5 m^2 to 15 m^2), to tens of m^2 for primary cutting (20 m^2 to 100 m^2).

From these informations, it was possible to derive the speed of the diamond wire cutting in the rock, which varies from 6.2 m^2/h to 14.3 m^2/h, in the case of squaring, and from 12.7 to 17.8 m^2/h in the case of primary cutting. These data are therefore been linked with power (Figure 7) and amperage (Figure 8) of the machine and compared with data relating to the speed cutting in the quarry of Ambaji and those found in the literature.

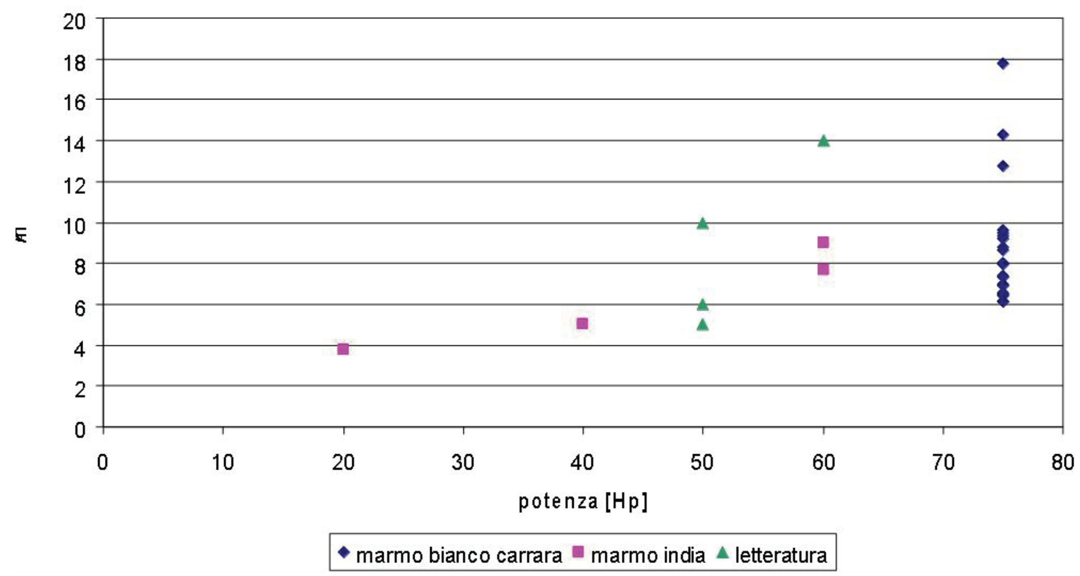

Figure 7 - Cutting rate against the power installed on the diamond wire saw.

***Şekil** 7 - Cutting rate against the power installed on the diamond wire saw.*

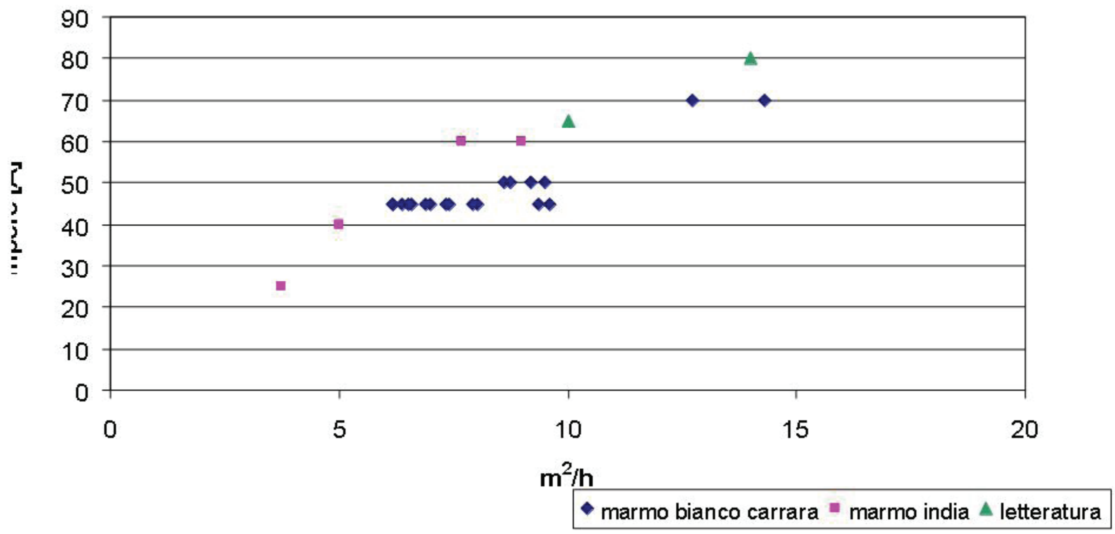

Figure 8 - Cutting rate of the machine according to amperage required.

***Şekil 8** - Cutting rate of the machine according to amperage required.*

As it can be seen, the cutting rate tends to increase with the increase of installed power, and, at the same power as in the case of data relating to the quarry in Carrara, the speed increases with the amperage, always taking into account both the size of blocks and their nature and the type of cut performed.

5. Tests performed on the wire

The study has provided a sampling of diamond wire, both from the quarry of Carrara and from that of Ambaji, in order to perform tests of tensile strength of steel cable in the laboratory.
To perform the tests, reference was made to UNI 3171, which requires a minimum cable length of 30 cm (Figure 9).

The minimum length of the cable must be calculated as shown in Table 4, taken from the same UNI 3171.

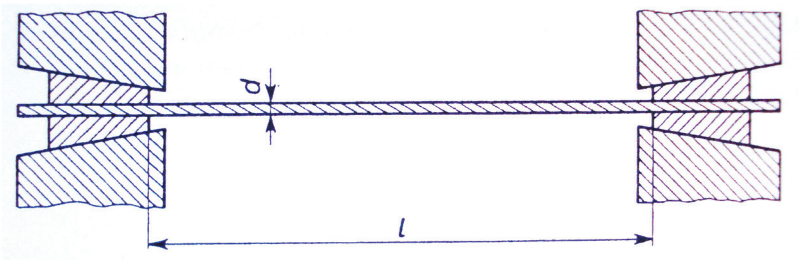

Figure 9 - Conditions for carrying out the test and example of the equipment
Figure 9 - *Conditions for carrying out the test and example of the equipment*

Minimal diameter of the cable [mm]	Minimum length of the cable [mm]
d < 6	300
6 < d ≤ 20	600
d > 20	30 d

Table 4 - Criteria to determine the minimum length test.
Çizelge 4 - *Criteria to determine the minimum length test.*

The test was performed using a press equipped with two coaxial clamps, connected to a dynamometer to record the load imposed, and to a strain gauge, which records the lowering of the lower grip. This instrument is connected to a computer and allows to evaluate the displacement, in millimetres, between the two clamps, which results in lengthening of the cable until its failure, at the maximum permissible load.

The test was performed on samples of wire cable both new and used, and on samples in the central part of which had been set up a joint (Figure 10).

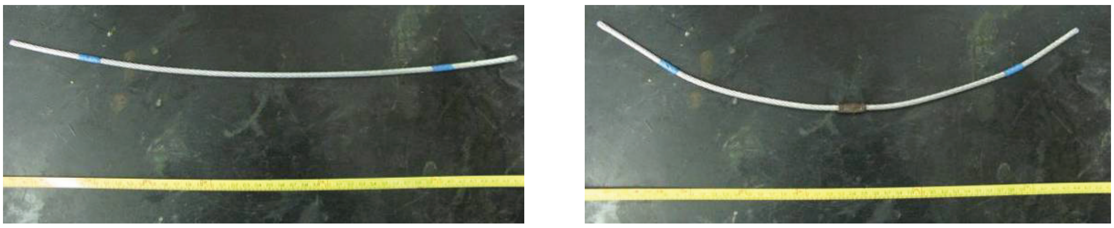

Figure 10 - Cable segments on which the test was performed (on the left, bare wire; on the right, cable with joint).
Şekil 10 - *Cable segments on which the test was performed (on the left, bare wire; on the right, cable with joint).*

The following Table 5 shows the data of the tensile strength of the wires without the joint. As can be noted, the Italian cable has a far superior resistance to that of India, whether new or used.

Wire n.	Conditions of the cable	Origin	Tensile strength [kg]
1	New	India	1720
2	New	India	1620
6	New	Carrara	1940
10	End of life	Carrara	2150
12	Mid-life	Carrara	1690
13	New	Carrara	1650

Table 5 - Tensile strength of steel cables.
Çizelge 5 - *Tensile strength of steel cables.*

The break, however, is achieved because of the progressive stripping of the strands that make up the cable. In particular, one can state that, on samples characterized by the presence of all other components of the wire, ie, beads, springs, spacers and fasteners, the break occurs in portions of bare wire and not along the line "covered" (Figure 11).

Regarding the tests performed on cables with joint, the results are shown in the Table 6 below.

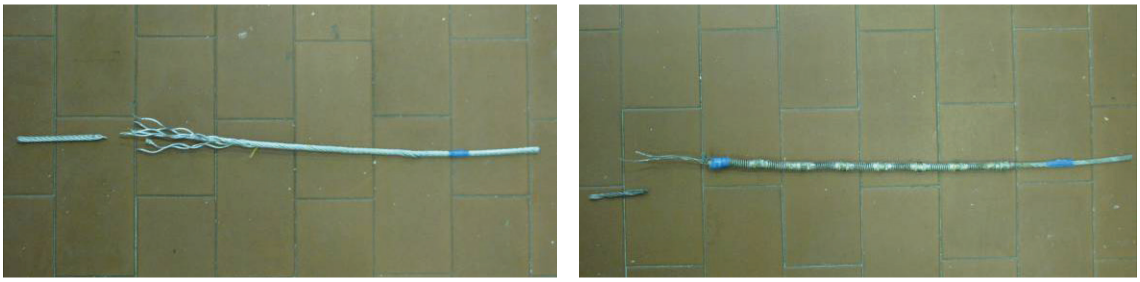

Figure 11 - Samples of wire after fracture (bare wire on the left, the cable "covered" on the right).
Şekil 11 *- Samples of wire after fracture (bare wire on the left, the cable "covered" on the right).*

Wire n.	Conditions of the cable	Origin	Tensile strength [kg]
3	New with joint	India	210
4	New with joint	India	260
5	Almost new with joint	India	400
7	End of life with iron joint	Carrara	1130
8	New with joint	Carrara	1020
9	End of life with copper joint	Carrara	1270
11	Mid-life with copper joint	Carrara	1220
14	New with joint	Carrara	900

Table 6 - Tensile strength of steel cables in the presence of the joint.
Çizelge 6 *- Tensile strength of steel cables in the presence of the joint.*

Again it is evident that the tensile strength of the diamond wire used in Carrara is significantly higher than that of India. It should be underlined, however, that the coupling used in India differs from that of Carrara both for the size (it is on average 2.3 cm long, up to 3 cm in Carrara) and the kind of pressing. In the Indian quarry hydraulic presses are used, while in Carrara manual presses are the most widely used.

The tests performed show that the most common breakage, in the case of diamond wire with joint in a central position, occurs at the joint itself or directly through breakage of the strands in its vicinity, or is due to pull-out.

In the case of Indian wires, the fracture was always due to pull-out, suggesting that the joint type is not suited to withstand high tensile loads: in fact, on average, the failure is obtained for load values of 290 kg, against 1160 kg recorded for samples of Carrara.

For these, however, the break did not happen just for pull-out, but also for breaking of the strands close to the joint (Figure 12), as in the case of a sample (No. 7) that consisted of a piece of diamond wire used, in the central part of which was located an iron joint, which was also used.

Figure 12 - Diamond wire breakage at the iron joint.
Şekil 12 *- Diamond wire breakage at the iron joint.*

The data obtained from the tensile strength tests were then processed, resulting in the trend of the displacement, expressed in mm versus time in seconds. The displacement was detected by using a strain gauge connected to the equipment, thus given the informations related to the lowering of the bottom vice as a function of the load application. The displacement then results in an indication of elongation suffered by the steel cable during the test, before reaching the failure. Diagrams have therefore been carried out, from which it is easy to identify the instant when the cable is broken. An example is given in Figure 13.

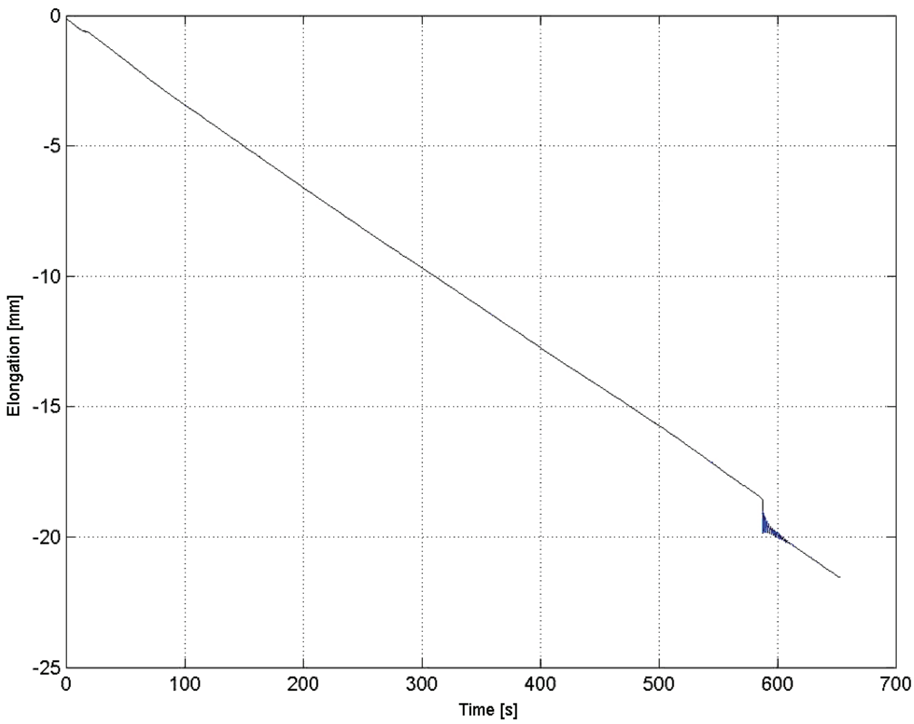

Figure 13 - Representation of the tensile strength test on the Indian sample No. 2.
Şekil 13 *- Representation of the tensile strength test on the Indian sample No. 2.*

The cable was "naked", without a joint. The fracture occurred after 587 s, following a stretch of about 19 mm. The performance of the cable elongation as a function of the load has also been analyzed, to better understand the behaviour of the steel subjected to tensile test. An example, referring to the same Indian sample No. 2, is given in Figure 14.

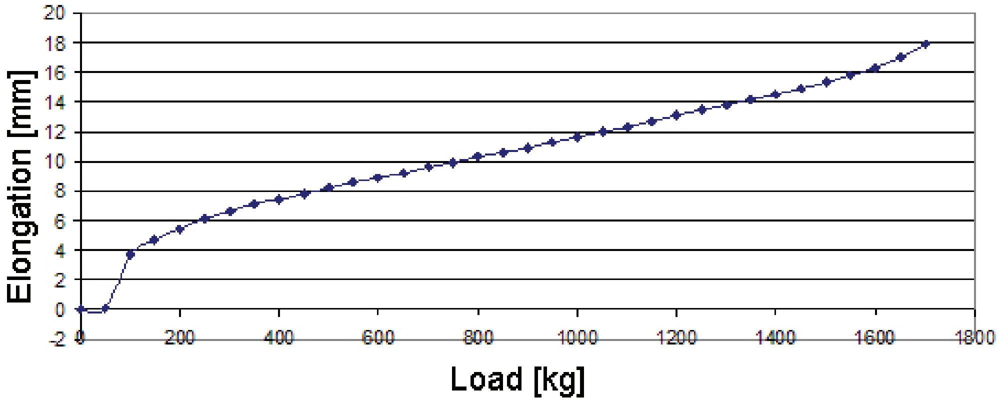

Figure 14 - Elongation of the cable as a function of load for the sample No. 2.
Şekil 14 *- Elongation of the cable as a function of load for the sample No. 2.*

6. Conclusions
The tests performed in this study allowed to find the tensile strength of the steel cables, representing the soul of the diamond wire.

Through the correlation of data from Indian and Italian samples, it was found that the cables used in Carrara perform better than others. This is due not only to the type of material to be cut, but also to the structural characteristics of the cables, especially in the case of assembled wires.

In addition, the data were compared to those provided by the manufacturer and supplier of steel cable at the quarry of Carrara: the results obtained have provided a tensile strength of the cable of 1800 kg. Two of the tests have provided much higher values, even in the case of cable at the end of life, and then in the case of diamond wire next to the regeneration. This indicates that the cable maintains excellent tensile strength throughout its life. The rupture, however, is obtained by gradually pulling out the strands of the wire: in particular it can be said that, on the samples characterized by the presence of all other components of the wire, such as beads, springs, spacers and fasteners, the break occurs in portions of bare wire and not along the line "covered". In samples of diamond wire with a joint in a central position, however, the rupture occurs at the joint itself or directly through breakage of the strands in its vicinity, or is due to pull-out.

In the case of Indian wires, the fracture occurred always because of the pull-out, suggesting that the joint type is not suited to withstand high tensile loads: in fact, the breakage is on average obtained at loads of the order of 290 kg, compared to 1160 kg recorded for samples of Carrara. This can be explained by the fact that the coupling used in India differs from that of Carrara for the size (it is 2.3 cm long on average, compared to 3 cm in Carrara), and for the kind of pressing.

Moreover, thanks to the analysis of data obtained from the tensile strength tests, it was found that the tensile strength in the case of assembled wire is greater than the simple bare wire, which could suggest that the presence of components of the wire gives a greater rigidity and tensile strength to the steel cable.

As for the diamond beads, one can say that their different duration in India and Italy is due to the composition of the matrix: the Italian one is more durable and allows a more gradual adjustment in consumption, since only a certain number of diamonds is simultaneously involved in cut, as is logical, but these diamonds show greater cutting efficiency, through better sealing of the matrix.

Other important data from the study were provided by the correlation of the cutting speed as a function of installed power, and depending on amperage. The rate of retreat of the machine varies from 1.5 mm/s to 3 mm/s, depending on the size of the block and on the amperage imposed by the operator: the more it is low, the lower the rate of retreat, and the greater the time required to execution of the cut. The cutting speed tends to increase with the installed power and, at the same power, as in the case of data relating to the quarry in Carrara, the speed increases with the amperage, always taking into account both the block size and their nature, and the type of cut performed.

It was therefore possible to hypothesize a trend in the same cutting speed as a function of the power of cutting machine, defining a range of values based on experimental data: by increasing the installed power in the machine, the cutting speed increases: for example, by adopting cutting machines with a power of 100 HP, the cutting rate could achieve values between 11 m2/h and 25 m2/h, whereas at present it is only 18 m2/h, with a power of 75 HP.

7. Acknowledgement

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