ROCK EXCAVATION EFFICIENCY IMPROVEMENT BY MICRO-WAVE TREATMENT

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Abstract
The paper deals with an overview of the state of art on using microwaves for assist hard rock cutting with mechanical means. The information provided consist on actual findings from the literature review, and the results of researches performed in this field by the team of the University of Petroșani. Tests have been carried out to determine the physical-mechanical characteristics of three types of rock, in the dry and saturated state, mainly uniaxial compressive strength, tensile strength by splitting (Brazilian test), apparent density (volume), apparent porosity, water absorption. On the basis of field research and laboratory analyses, the macro-level cracking state and the continuity/discontinuity of the massif were followed. These results represent the start elements in the further research in recently started MIWACUT project in the frame of ERAMIN-2 programme, financed jointly by EU and Romanian National Research Agency (UEFISCDI).

Keywords: *microwaves, excavation, rock, microwave assisted rock destruction*

1. Introduction

In order to make possible the mechanised excavation of hard rocks with mechanical means, other than Tunnel Boring Machines (TBM), or to increase its productivity and reduce the wear of the excavating device, in past years some innovative methods, such as microwave-assisted (MWA) rock destruction, has recently drawn the attention of the professional community.

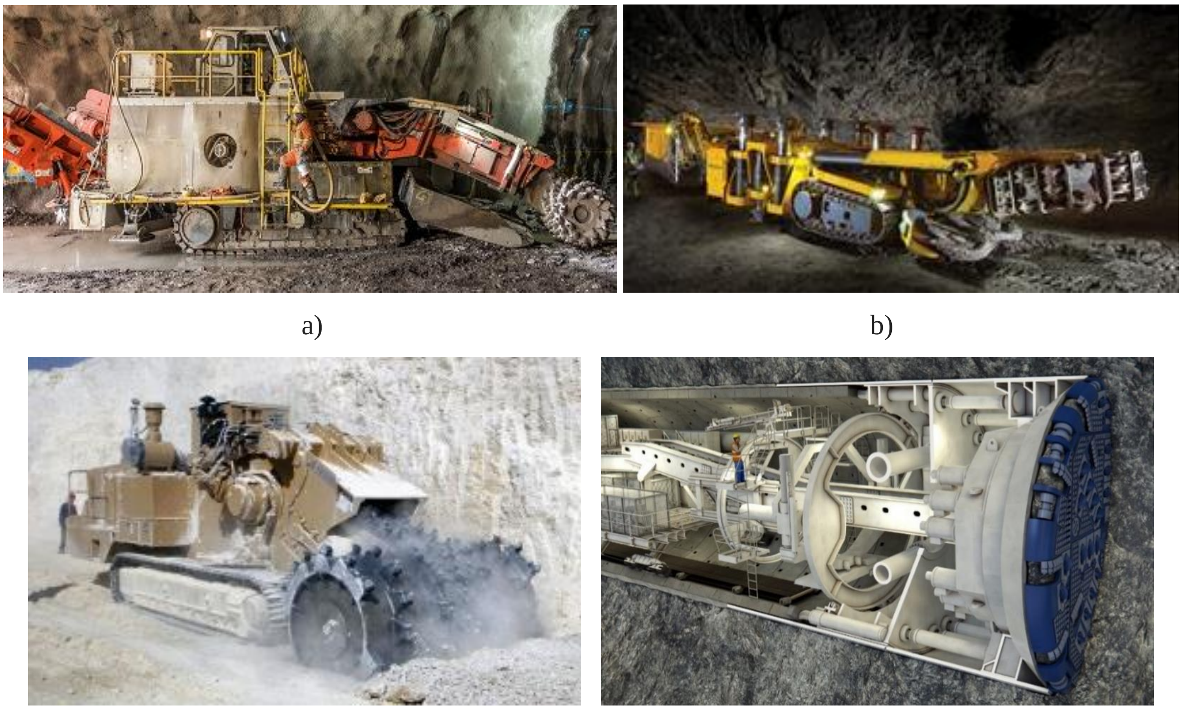
Currently, the wining of hard (high-strength) rocks in open-pit mines is carried out exclusively by drilling-blasting method. As far as underground mining is concerned, the use of tunnelling machines (TBM) which is the only mature alternative technology for hard rocks, is limited in its application due to several disadvantages.

The purpose of the excavation of rocks is not only to drill tunnels or roadways, but also to extract recoverable rock, and mechanized wining proved to be the most suitable for this, but the hardness of the rock also represents the limits of applicability for the machines used for this purpose.

The recently developed Surface Cutting Machines (SCM) can be an alternative to the open pit mechanised extraction of hard rocks, but also for this kind of machines, the upper limit of rock hardness limits their applicability.

In the past decade, several development results have been obtained in connection with the improvement of the theoretical and operational parameters of the aforementioned machines, but no industrial application has yet taken place with acceptable results, which shows that the extensive and intensive development reserves of this technology have been exhausted.

These alternative machines (equipment) are presented in Figure 1. for illustrative purposes.



a) b)

c) d)

Figure 1. *Various hard rock winning machines: (a) Roadheader (RH), b) Continuous Miner (CM) c) Surface cutting machine (SCM), d) Tunnelling machine (TBM),*

Another approach, which is the topic of the present paper, is to reduce the hardness of the rock, and in this respect microwave treatment is one of the most promising solutions.

Several researchers examined the effect of microwave treatment on the mechanical properties of rocks, in order to make possible the use of this phenomenon in the microwave-assisted rock winning (Peinsitt et al., 2008).

These researches have not yet provided a microwave-assisted rock winning machine for use in a laboratory or on site. Previous research has mainly focused on granite and similar rocks, regarding mainly the microwave produced loosening prior to breaking (Hartlieb et al., 2017).

The aim of the present paper is to study the cuttability of carbonate rocks with an integrated MWA linear cutting machine, which may result in the development of an MWA roadheader machine.

Currently, carbonate rocks are produced by drilling and blasting, mainly but not exclusively in opencast mines, which is a great challenge for the development of the mechanical extraction method, because at the present moment the mechanical winning of carbonate rocks is usually impossible or, if possible, inefficient.

The aim of the cited project is to study the cuttability of carbonate rocks with microwave-assisted cutting machines. Previous studies have either not addressed the MW-assisted winning of these types of rock, or they have recorded that their MW absorption rates are very low and are not suitable for MW-assisted cutting. Thorough and systematic clarification of this lack of research is the main topic of the research to be performed.

The first planned experimental procedure, linear cutting tests, using microwave-assisted and without microwave treatment on samples from Romania and Turkey, and in this way the determination of specific cutting energy (Figure 2.).

Based on this, the performance of a CM will be estimated, using the properties of specific energy and rocks, to compare the results of microwaves and traditional comings.

Finally, the specific costs (economy) of the two mechanised processes and the current drilling explosion are compared.

2. Presentation of preliminary research

Microwaves are a type of electromagnetic radiation with a wavelength ranging from 1 mm (frequency 300 GHz) to 1 m (frequency of 300 MHz).

Several studies, using numerical and laboratory methods, have confirmed that microwave energy heats the rock according to the specific properties of its composing minerals (Jacob et al., 1995).

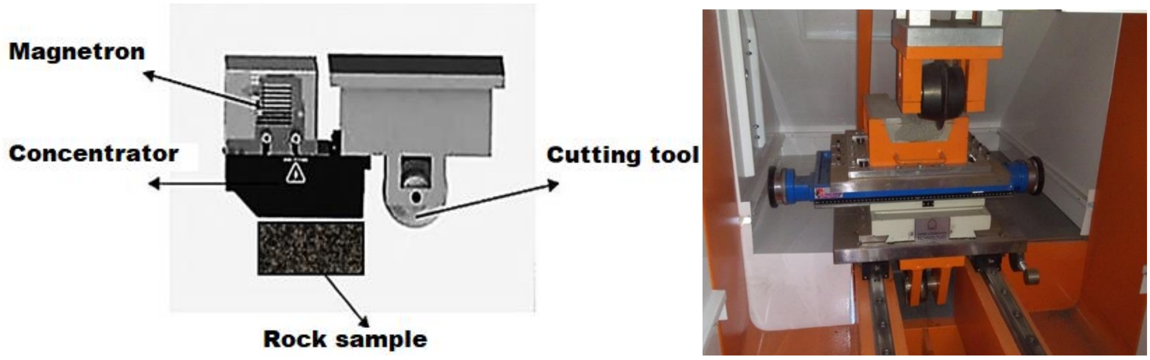


Figure 2. *Linear cutting test machine with dynamometer and integrated microwave equipment (Kahraman S. et al., 2018)*

Heat causes thermal expansion of various minerals, and these differentiated thermal expansion of minerals cause internal stress in the rock. As a result of these stresses, microfractures are formed in the rock, thus reducing its strength (Kingman et al., 1998).

This phenomenon can lead to the development of microwave-assisted mechanical drilling or rock-winning machines (Maurer, 1968).

The effect of microwave treatment, in terms of reducing the strength of rocks, depends on the energy used, the duration of radiation and the composition of the mineral (Figure 3.), (Kahraman et al., 2018).

It can be said that the type of minerals in the rock and their proportions are the most important parameters that affect the degree of warming under the same treatment conditions (Motlagh, 2009). In order to clarify this aspect, further studies must to be carried out, with various mineral rocks with different mineral characteristics.

The effects of higher microwave power should also be investigated for lower radiation duration.

The use of microwave energy for deep drilling was briefly examined in the 1960s (Lindroth et al., 1992) (Figure 4.), but at the time it was not considered economical or further investigated due to technical problems.

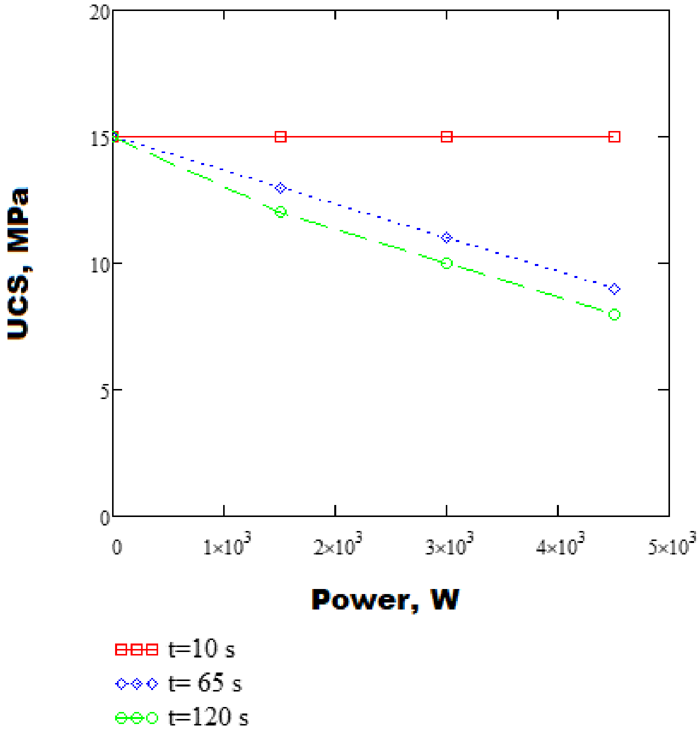


Figure 3. *Reduction in rock strength as a function of power and radiation duration (Hassani et al., 2016)*

Microwave applications have been studied primarily for mineral processing (Hassani et al., 2008, 2011) in order to reduce the energy demand for ore comminution by microwave pre-treatment and to increase the release of mineral particles for increased separation.

Among the many available winning methods, the mechanical rock cutting proved to be the most economical and therefore the most commonly used method (Hassani et al., 2016). With the development of current technologies and the shrinking and increasing value of raw materials, the importance of developing innovative rock cutting methods is increasing, and one solution to this may be the MW-assisted one.

The use of microwaves in rock cutting was introduced in the 1960's. Since then, microwaves have been widely and increasingly used in the food industry (Metaxas et al., 1983) and also in the pharmaceutical industry (Saxena et al., 2011) and for the processing of minerals (Znamenackova et al., 2003).

In mining and civil engineering, microwave pre-treatment methods may be used to avoid the influence of factors limiting the performance of mechanical equipment such as tunnelling machines (TBM) (large-scale tool wear and maintenance needs).

This include, for example, a plan for TBM assisted by flame torches (Lauriello et al., 1974) which was considered economical in terms of equipment, but its feasibility was limited by high fuel consumption and smoke emissions.

In contrast, pre-treatment with microwave energy offers many advantages because the power source is available on the machine, does not generate harmful emissions and is easy to control.

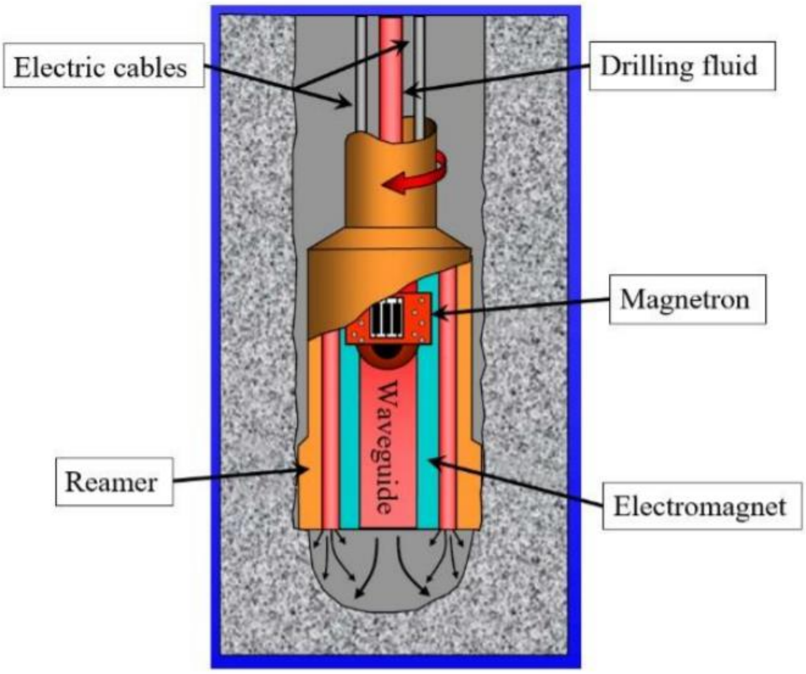


Figure 4. *Drawing of a drill bit for deep drilling assisted by microwaves 1960s (Lindroth et al., 1992)*

The microwaves used in the studies described in the literature power of 150 W to 5 kW range, different durations (up to 240 s) were used and different hardness reductions, crack formation and local melting were observed depending on the type of rock, microwave power and duration of radiation.

Applying higher microwave power (25 kW) to some hard rocks, basalt, diabase and gabbro, the temperature reached 270 °C in 6 seconds. (Hartlieb et al., 2017)

The temperature of sandstone and granite rise to 240 °C in 30 seconds. Important macro cracks were observed on the samples used. (Figure 5.)

A preliminary study has also been carried out on the effect of microwave treatment on the strength of marble. Although the temperature of some samples reached above 350 °C, the temperature of most samples was less than 300 °C, after 6 kW MW, after 5 minutes of treatment, and showed that the decrease in strength was about 20% in the uniaxial compressive strength and 38% in case of traction strength (Kahraman et al., 2018).

In the literature there is a very limited number of studies on MWA winning. A patent was issued for the MWA hard rock cutting equipment (Lindroth et al., 1991) which presents the basic plans for microwave treatment of the rock block during cutting (Figure 4.), but the method was not applied in practice yet.

The same author also presented a theoretical comparison between the roadheader machine using MW and its traditional version, showing that with the MWA roadheader, the unit cost was 34% lower than with the conventional one.

In the papers (Lindroth et al., 1991) they reviewed studies on the effects of microwave energy on the mechanical properties of some general hard rocks and presented the possible schematic design of MWA-TBM (Figure 6.).

Figure 5. *Cracks and melts in granite (a) and iron ore (b) with a power of 6 kW after treatment of 360 s. (Hartlieb et al., 2017)*

A cut with a 24 kW open-ended waveguide on a granite block irradiated for 30 seconds with a linear cutting machine showed that the reduction in cutting forces was about 10% (Hassani et al., 2016). In this study, the microwave system and the cutting machine are separate systems.

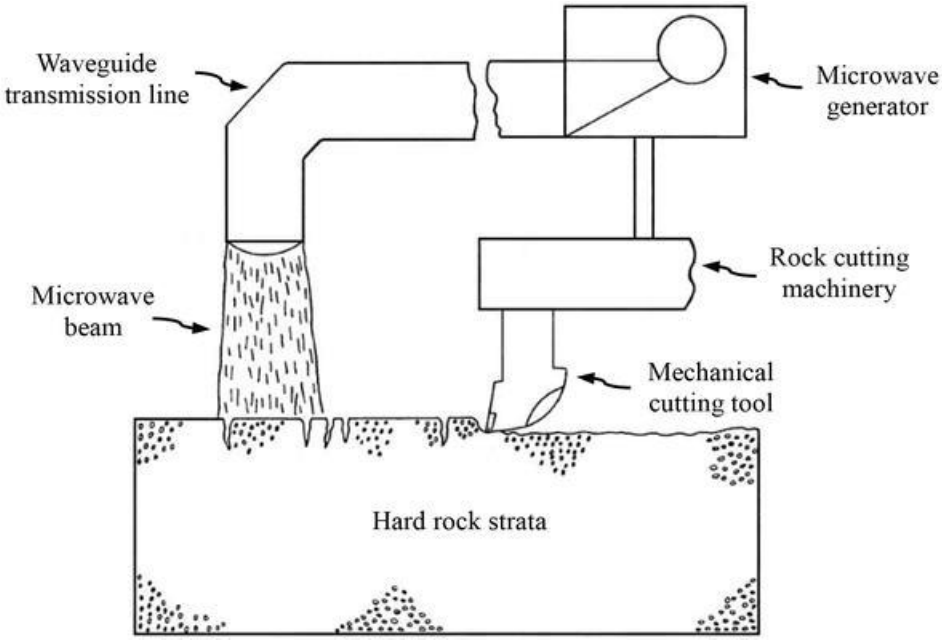


Figure 6. *Theoretical drawing of MWA cutting machine (Lindroth et al.1991).*

In order to simulate the actual cutting conditions, both systems must be integrated and the rock sample must be cut during microwave heating. The manufacturing of such an MWA linear cutting machine (Figure 2.), in which the microwave system is integrated into the cutting machine is underway.

The microwave power of this system will be 9 kW. Carbonate stones are less sensitive to microwave energy than other rocks because they are transparent for microwave radiation, 150 W power, 5 minutes of radiation duration (Hassani et al., 2008), but less transparent for high-performance resources such as 3 kW or 6 kW. (Hassani et al., 2008)

In these cases, however, the duration of radiation is high (4-5 minutes), but under the actual cutting conditions the microwave radiation duration should be less than 10 s.

Pre-treatment before cutting cycles may be an alternative to its short radiation duration, but then the overall cutting efficiency will be low. Therefore, the performance of the MWA linear cutting machine is designed for 25 kW.

3. Performed work

From what has been shown, it can be concluded that the numerous physical, mineralogical and structural parameters of the rocks and the characteristics of MW (frequency, energy, duration of exposure) which influence the effects of MW treatment contribute to a wide variety of results, difficult to generalize, requiring experimental, laboratory and in-situ tests in order to validate the feasibility and eco-effectiveness of the proposed mechanical dislocation process.

Because carbonate rocks have mineralogic, petrographic, chemical, physical-mechanical characteristics, different from other types of medium to high strength rocks, which have been treated in literature, but similar within their typology (limestone, marble, travertine, etc.) and because MW's influence on them has been little studied, it is necessary to a-priori know the physical-mechanical characteristics (compressive strength, tensile strength, porosity, water absorption, etc.) as well as the mineralogic composition and their micro and macro crack state.

It is known that these rocks are generally compact and isotropic, have a high cutting resistance, and are generally transparent to MW. Physical-mechanical and mineralogical-structural characteristics are to be repeated after microwave treatment at different powers, frequencies and durations in order to determine the influence of MW on these properties.

To this respect, cores (test pieces) of the same samples were marked and sent to the partner from Turkey to carry out tests on the test rig, with and without microwave assistance, using punctual attack bits, in order to determine the specific energy values of the cutting.

Based on these, the performance of CM machines, with and without MW assistance, will be estimated and the results will be compared.

This will demonstrate the applicability and eco-efficiency of MWA-CM excavation in a quarry, using a prototype CM with MWA.

Mechanical cutting excavation of MW-assisted rocks will also facilitate the process of crushing - further grinding, by the fact that the grain size of the mined-out mass will be lower, without agabarits, specific to the drill and blast cutting, and the mechanical resistance of the mining mass will be reduced due to the MW effect, which will also reduce post-extraction processing costs.

In this respect, the geological documentation of the deposits were analyzed on field (the location of the respective quarries and the owners premises) and on this basis the locations for the collection of samples were established, taking into account:

- their destination (types of tests);
- representativity for the deposit, from structural and quality point of view;
- not to be included in the operating activity in the near future, so that they can be visited later for further in-situ tests.

The following three carbonate rock-carrying perimeters were considered:

- limestones from Podeni (Moldovenesti), Cluj County
- Marble from Ruschița, Hunedoara County
- the limestone from Bășchioi, Tulcea County

These deposits are in operation at quarries owned by S.C. Marmosim S.A.

The collection and shaping of the samples in prismatic blocks and their preparation for transport to Petroşani was ensured by MARMOSIM S.A., their transport being carried out by the contractor's own means. (Figure 7.)

From these samples, the test pieces necessary for the tests and analyses provided for in the research plan, cylindrical in shape, with a diameter of 54 mm, coefficient of slenderness 2-3 for the compression test in question 0,5-1 for the Brazilian test, were made by coring. (Figure 8.)

For this purpose, diamond coring heads suitable for the type of rock, adaptable to the sample-making machine available at Geotechnical Laboratory and diamond armored discs (for cutting irregular blocks), were purchased.

Figure 7. *Samples prepared for transport.*

Figure 8. *Samples made by coring.*

In drawing up the specifications to produce the coring bits, it was taken into account the shape, dimensions, matrix material, density and granulation of the synthetic diamond abrasive particles a.s.o., in order to ensure high productivity, cut quality (low roughness), reduced wear intensity, corresponding cooling, taking into account the appreciable quantity of cores to be made.

The preparation of cores and the conduct of tests and analyses was carried out according to the recommendations of ISRM (International Society of Rock Mechanics) - Suggested Methods for Determining Compressive Strength and Deformability, respectively Suggested methods for the quantitative description of discontinuities in rock masses.

Some of the prismatic samples were kept as blank specimens and a number of 12 of each assortment were prepared to be transported to the Turkish partner for testing on the Linear Cutting Rig, with and without treatment with MW.

Figure 9. *Coring bits purchased. (author's photo)*

For each harvesting perimeter, a detailed report was carried out on the basis of field research, on the basis of the study of existing geological documentation and laboratory analyses. In particular, the macro-level cracking state and the continuity/discontinuity of the massif were followed. (Figures 10, 11, 12)

Tests have been carried out to determine the physical-mechanical characteristics of all three types of rock, in the dry and saturated state, as follows:

Uniaxial compressive strength, tensile strength by splitting (Brazilian test), apparent density (volume), apparent porosity, water absorption.

The results were recorded in analysis bulletins, then synthesized for statistical processing in tables.

The petrographic and mineralogical analysis was carried out in the laboratory for each type of rock, and analysis bulletins were drawn up. The analysis bulletins revealed by macroscopic and microscopic analysis the petrographic and mineralogic parameters of the rocks in the three perimeters, using thin sections obtained from the samples taken.

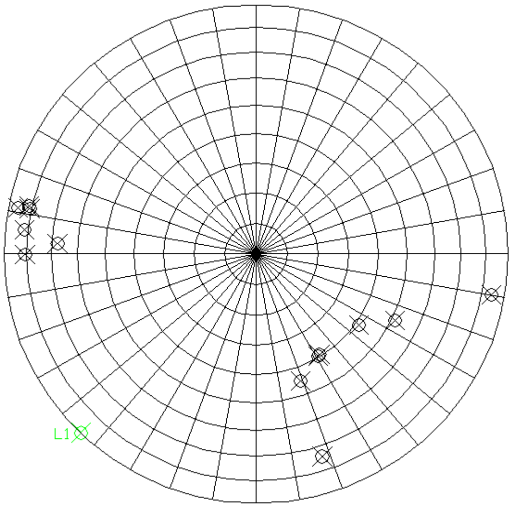


Figure 10. *Stereographic diagram of cracks.*

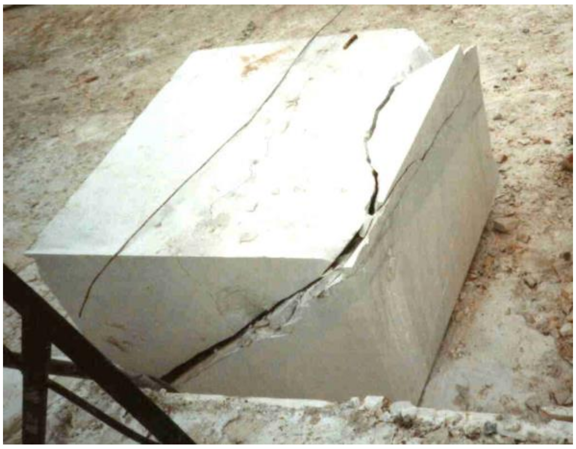


Figure 11. *Fragmentation of a block due to cracks.*

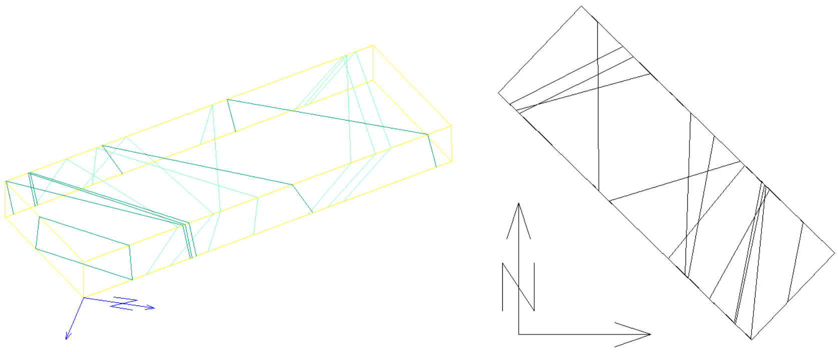


Figure 12. *Spatial and planar representation of discontinuities obtained by modelling*

Figure 13. *Details about mechanical tests (author's photo)*

4. Summary

With the aim to study the cuttability of carbonate rocks with an integrated MWA linear cutting machine, which may result in the development of an MWA roadheader machine. to make possible the mechanised excavation of carbonate rocks with mechanical means, to increase its productivity and reduce the wear of the excavating device, in the frame of MIWACUT project financed jointly by EU and Romanian National Research Agency (UEFISCDI) through ERAMIN-2 programme, a research has been started in order to find out the suitability of MWA cutting in Romanian carbonate rock carries.

The project being in progress, preliminary research work has been presented, regarding the physical, mechanical, mineralogical and other characteristics of two kind of rocks (marble and limestone), from three deposits, including the assessment macro-level cracking state and the continuity/discontinuity of the orebodies.

The project, through the anticipated results, has the potential to produce a positive overall impact in terms of knowledge advancement, technological, economic, environmental and social effects.

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