The effect of microwave irradiation on hard rock as pre-treatment to increase the efficiency of underground mining

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Abstract. Due to the euphoria of people to make the impossible possible, increasingly complex construction projects are being planned and implemented. As a rule, projects are currently carried out under high cost and time pressure. This results in the need to optimize known processes in order to save additional time and costs and to continue to do justice to dwindling resources and the growing world population in the future. In the course of population growth and the shortage of space, the urbanized areas of the cities must be connected or expanded underground. Depending on the type of soil, solid rock in the mountains can pose a challenge due to its high strength. This increases the demand for pre-treatment of solid rock. A possible solution is the use of microwaves.

Keywords: Microwave radiation, mining, rock mechanics

1 Idea and description of the research work

1.1 Electronic waves and microwaves

Around 1864, the Scottish physicist James Clerk provided the first mathematical description of electromagnetic waves, which had been partly carried out by the physicist Ernst Lecher some years earlier through experiments (Pehl 2012). The experiments proved that electromagnetic waves consist of oscillating magnetic and electric fields that propagate at the speed of light. These waves are divided into different categories according to their wavelength. All electromagnetic waves are summarized as electromagnetic spectrum as shown in Figure 1.

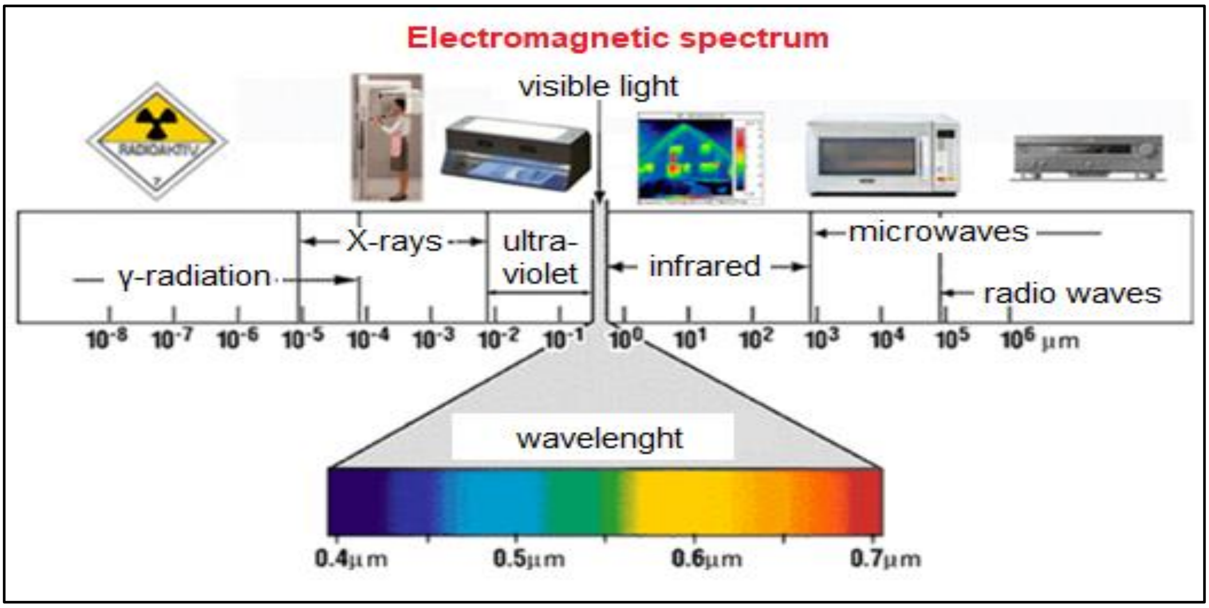

Fig. 1 Wavelength spectrum from teaching material "Experiments with microwaves" FU Berlin (2016)

Electromagnetic waves oscillate perpendicular to their direction of propagation. During these oscillations an electric and a magnetic field meet. The order of magnitude of the wavelengths is between 1 m and 1 mm and the frequency range is 300 MHz to 300 GHz (Pehl 2012).

Percy Spencer developed the first microwave oven in 1950 (Spencer 1950). It worked with a magnetic field tube that converts electrical energy into electromagnetic waves and emits them. The mode of action of microwave energy is determined only by the dielectric properties of the food inside the microwave oven. Each substance or state is characterized by its relative dielectric coefficient. Water has a pronounced dipole character and high dielectric coefficients due to its angled molecular structure and its binding polarity, whereby microwaves are particularly well absorbed. In general, there is a high water content in food. Due to the high frequencies during the irradiation with microwaves, the molecules cannot follow the field changes fast enough due to their rotational movements, a phase delay occurs compared to the electromagnetic field. As a result, field energy is transferred to the molecules, i.e. electrical energy is converted into kinetic or thermal energy (Bloomfield 2015). This conversion results in an almost uniform heating of e.g. food.

1.2 Application of microwaves

But microwaves can also do more than just heat food: They enrich our everyday lives with wireless communication systems such as mobile radio, Bluetooth, WLAN or radar technology (Pehl 2012). In particle accelerators, electric waves accelerate charged particles to the speed of light. Electromagnetic sensors are expected to detect cancer early in the future (Serway et al. 2004). However, what makes life easier can also have the opposite effect and destroy life or existing structures, since electromagnetic weapons are relatively easy to produce and can pose a threat to many states (German Federal Ministry of the Interior 2001).

For microwave irradiation of solid rock, first theoretical simulations exist to simplify known drilling, blasting and digging techniques. Challenges such as high wear due to abrasiveness, high material consumption, cost-intensive and time-consuming processes or high dust emissions can be positively influenced or controlled. Therefore, pretreatment with microwave radiation is an efficient component, since the microwaves cause stresses in the rock compound and thus exceeds the critical load limit (Hartlieb et al. 2011). When the load limit is reached, cracks appear in the rock, which reduce the strength of the rock and thus facilitate mining.

1.3 Formation of rock and rock mechanics

The distinction of the rocks is made according to the type of formation. The hardest naturally occurring rocks are e.g. granites or basalts, which are called solidification rocks or magmatites (Figure 2, right). These rocks are formed by solidified magma on the earth's surface (effusive rock) or inside the earth (deep rock). Sandstones and sand-lime bricks, on the other hand, are called sedimentary or sedimentary rocks (Figure 2, left), which were deposited in the earth's crust by weathering and transport and subsequently solidified by pressure from superimposed masses. If existing solidification and sedimentary rocks are further influenced by forces such as foliation, uneven pressures, compression or rolling, the coarse structure can change and a granite, for example, becomes gneiss. These are called transformation rocks or metamorphites.

Fig. 2 Sandstone in Killesbergpark, Stuttgart (left), former granite quarry Schleifmühle near Metten (right)

For irradiation with microwaves, the properties of a coherent rock, especially discontinuities and the influence of water, have to be considered. In order to be able to represent an entire rock mass, it must be examined for intact rock, i.e. rock that does not have any continuous interfaces, and for the actually existing interfaces using laboratory and field techniques. Only then can a statement be made on the overall behaviour of the rock through the interaction between rock, parting surfaces and mountain water. An illustration of this can be found in Figure 3.

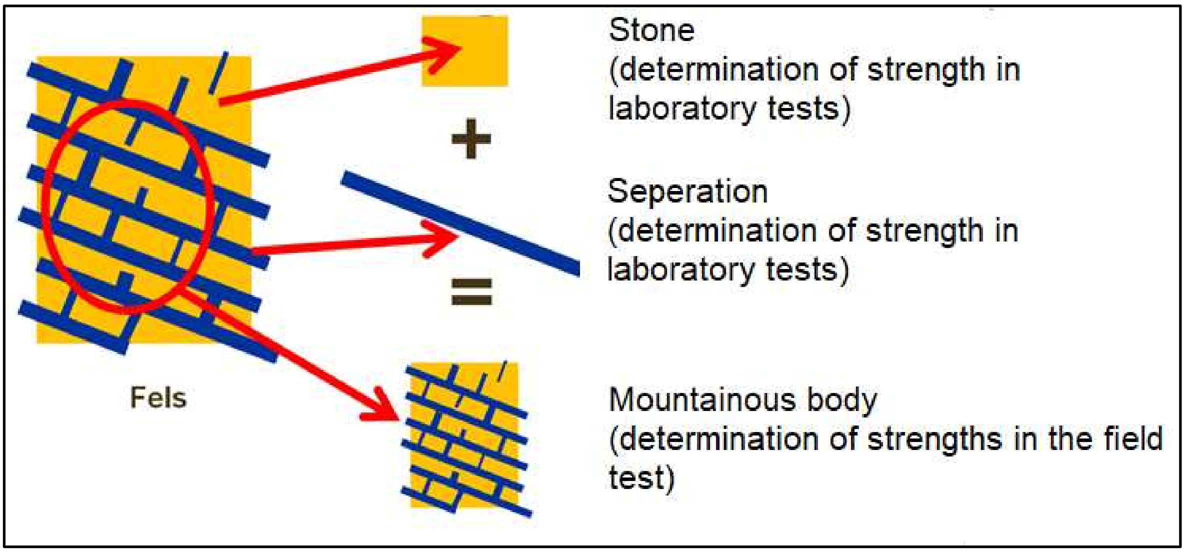

Fig. 3 Behaviour of the mountains as a function of rock and interfaces according to Schmitt (2015)

Based on these findings, it becomes clear that the strength of the rock is influenced by the rock-mechanical interaction between the compact rock and the rock faces. However, the separating surfaces can have different properties depending on their type. Here the degree of separation (possibly existing material bridges and the thickness of the parting surface), parting surface distances and spatial orientation of the parting surface distance and the parting surface covering play a decisive role.

Sandstone is an example of a rock with a high degree of separation and a small separation surface distance. In sandstone, the strength properties of the interface result in lower strengths compared to a rock with a low degree of separation and larger interface spacings, e.g. granite. For the example of granite, higher rock strengths can be assumed, since the rock mechanical influence of the parting surfaces is smaller.

A factor not to be neglected which has not yet been mentioned in Figure 3 is the influence of water. With compact rock in the mountains it can be assumed that no water can penetrate. However, separation surfaces with a high degree of separation and a small separation surface distance offer sufficient space to be able to collect water. Existing water plays a decisive role in the irradiation of microwaves and this has to be investigated by the boundary conditions of the interfaces.

2 The state of the art in research and technology

The technique of "pretreating" the solid rock was used until the 16th century for "setting fire". The rock was heated by fire in order to loosen the dressing due to the different thermal expansion of different types of rock (Agricola 1556). With the first blasting techniques of Giovanni Battista Martinengo (Wild 1992) the preparation of the rock by heat input before the actual mining was forgotten.

Microwaves have been used to heat food since 1960. The water molecules in food are set in motion or a torque is caused, whereby the atoms start to rotate from their resting state and kinetic energy is released, thus increasing the temperature of the environment (Kumar et al. 2014).

At the beginning of the 21st century, microwaves were used to measure moisture in buildings. Here the relative humidity content between water and building material is measured without affecting the condition of existing buildings. The electromagnetic alternating field applied to the component from the outside causes the molecules of the component to rotate. Which molecules are set in motion can be controlled by power and frequency (Wilfried et al. 1997).

The research of Hartlieb et al. (2017) investigated the forces that occur when cutting microwave irradiated and untreated granite. The treated area of the granite showed that pronounced crack networks run through the rock. Irradiation with microwaves at 2,450 MHz with 24 kW significantly reduced the measured peak and average forces of the treated granite (Hartlieb et al. 2017). When cutting the granite through treated and untreated areas, cutting forces of varying magnitude are shown. Figure 4 shows the linear cutting of the granite, the X and Y axes indicate the surface of the granite and the Z axis the cutting direction. It was found that the forces in the treated area are 10% lower than in the untreated area of the granite.

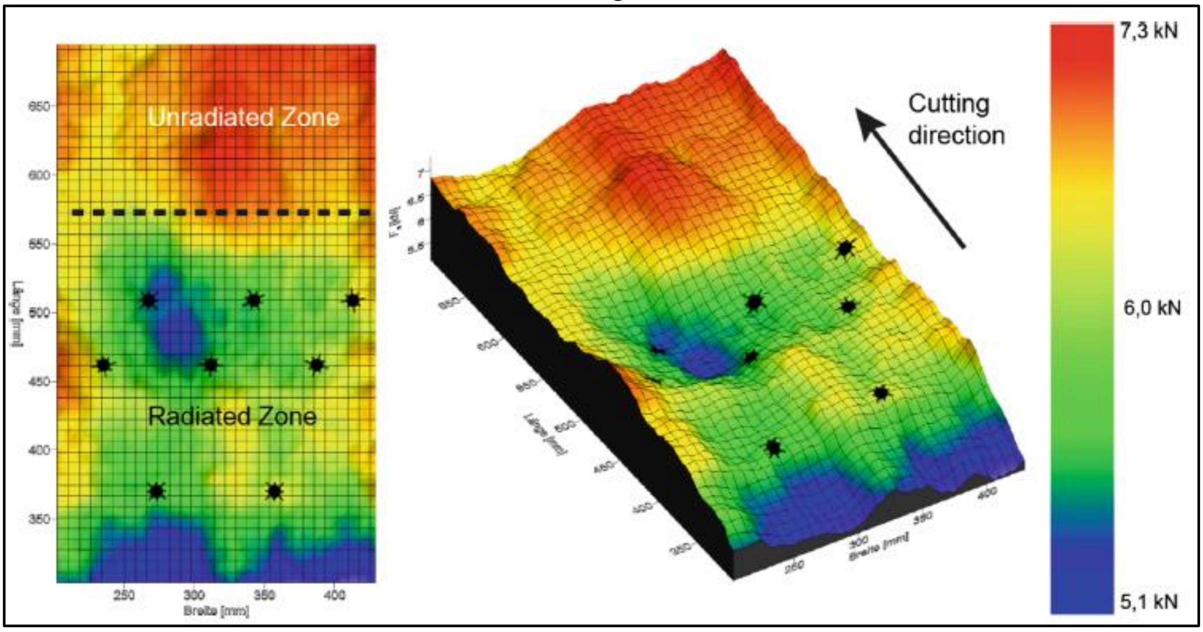

Fig. 4 Cutting wheel forces in granite differentiated according to untreated and treated area by microwave irradiation according to Hartlieb et al. (2017)

Following on from these research results, there are further open questions, e.g. how granite and other solid rocks behave at different frequencies and powers and whether the expansion of solid rocks in the large structure can have a positive effect on crack formation when heated.

Some investigations were limited to crack formation by irradiation of microwaves on Austral Black Gabbro, which has similar properties to granite and basalt. The rock warmed up and the compressive strength was reduced as a function of time and intensity. Using basalt as an example, four cylinders with a height of 40 mm and a diameter of 38.1 mm were exposed to a power of 750 W and a frequency of 2,450 MHz. The temperatures after irradiation were between 14 °C and 115 °C (Satish et al. 2006). Figure 5 shows the crack formation after 360 seconds on the left, which is already clearly visible to the naked eye, and the change in compressive strength over time on the right.

Similar studies in Australia show that higher power and shorter irradiation times can heat up the rock more quickly or cause it to partially melt (Zheng et al. 2017). The Austral Black Gabbro was tested here with a power of 2 kW and a frequency of 2.45 GHz.

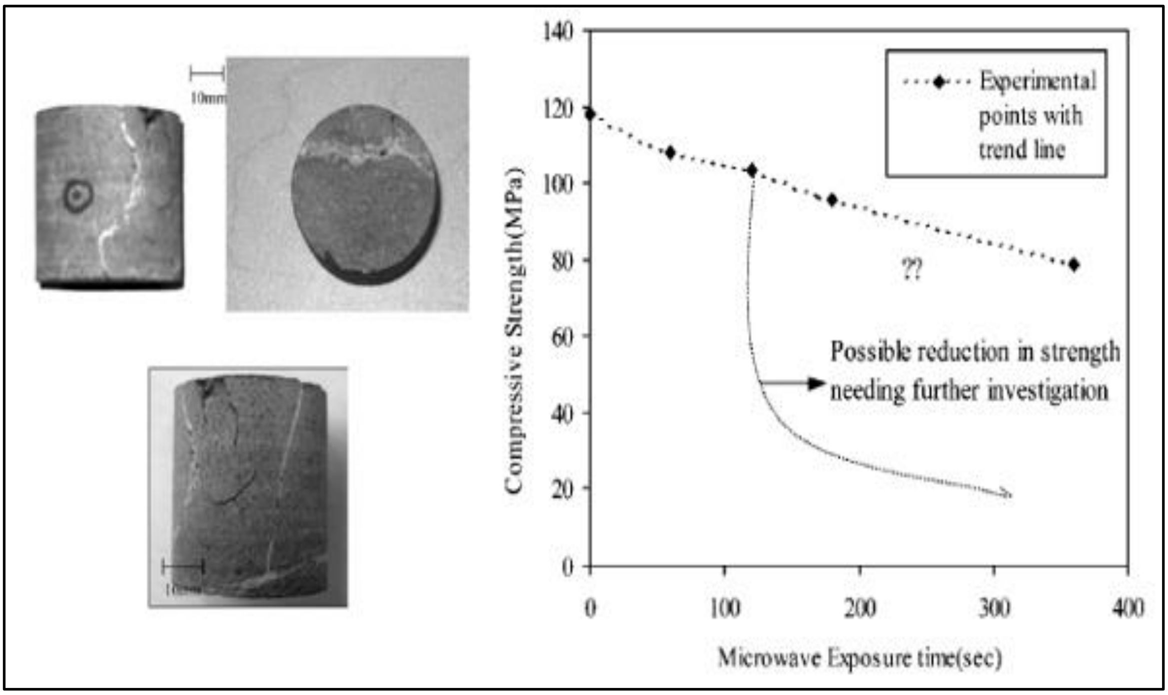

Fig. 5 Cracking after 360 seconds (left). Decrease of compressive strength over time (right) according to Satish et al. (2006)

In the investigations by Zheng et al. (2017) it was found that a basalt sample at a power of 3.2 kW can be heated up to 330° C after only 60 seconds. The same can be said for granite. In the available research by Zheng et al. (2017), Hartlieb et al. (2017) or Kumar et al. (2014), the samples generally consisted of only one type of rock under laboratory conditions. This is not the case in situ, anisotropic conditions are present here.

3 Aim and contribution of the research work

In previous research work, only magmatic and metamorphic rocks have been investigated, which as a rule have only a very low degree of separation and in which the interfaces play only a minor role. The influence of microwave irradiation on sedimentary rocks, for example, where the interfaces are the decisive factor, has not yet been investigated. The irradiation itself and the resulting thermal expansion is carried out similarly to Hartlieb et al. (2011).

The aim of the dissertation is to analyse and evaluate the effects of microwave irradiation on solid rock or rock that is difficult to dissolve in accordance with Class 7 of DIN EN ISO 14688-1, both qualitatively and quantitatively. The interaction of irradiation duration and intensity and the differentiated investigation of material and composition of the solid rock are the key points of this dissertation. Furthermore, further findings on the properties of heated solid rock with the effect on the bond and the influence of interfaces occurring in the rock can be investigated. The result of this work in a scientific sense is the knowledge regarding altered rock mechanical properties of solid rock. Based on this, a recommendation for a more effective mining method can be developed.

The assessment of the changed rock mechanical properties, in particular in connection with interfaces of solid rock, is in the foreground here. Since in tunnelling and mining the compressive strength is particularly relevant for the mining and loosening of rock material, special attention is paid to the reduction of compressive strength by microwave irradiation. The dimensioning of tunnel boring machines or conventional excavation methods is determined to a large extent by the compressive strength of the rock, whereby better results can be achieved in the execution phase in terms of cost savings and environmental compatibility.

4 Research methodology

4.1 Structure

The work includes a theoretical and an experimental focus. The theoretical part contains the basics of electromagnetic waves and how they can be applied in building practice and how they can be refined in the future. Separated from this, an introduction to rock mechanics is given, whereby rock and rock properties, existing interfaces, stresses in the rock and the influence of water are dealt with in more detail. In the experimental section own model experiments are carried out and solid rocks in their input and output state are analytically investigated, i.e. before, during and after irradiation with consideration of heat development, change of strength and stress development.

4.2 Literature research and evaluation

The first step is to prepare the state of the art and research. The basis for this are publications on the basics of microwave technology and the definition and differentiation of solid rocks within their soil class. In particular, the problems of foundation engineering and tunnel construction will be dealt with. A further focus will be the representation of natural interfaces in solid rock. Furthermore the consideration follows, to what extent laboratory tests with microwaves were accomplished by third parties and these play a role for own methods. The publications are compiled, evaluated and general questions concerning the mining of hard and solid rock are clarified.

4.3 Laboratory tests

At the beginning of the laboratory experiments an analytical recording of different rock types and the differentiation or problem of the laboratory conditions in comparison to the natural occurrence is carried out. The central task here is to what extent the experiments can be investigated or reproduced as realistically as possible. In order to limit the deviations, a large number of specimens and tests are required. In order to distinguish themselves from works such as Satish et al. (2006) and Hartlieb et al. (2011), sedimentary rocks and metamorphites are increasingly used as rocks.

First, the specimens are obtained in standardised sizes from regional quarries, adapted to the irradiation equipment and the subsequent laboratory tests. A microwave with up to 3.2 kW power is used as the irradiation device. The selection of solid rocks with uniform and different microstructures is determined in advance. The samples are analysed according to their grain and large structure in order to record the characteristic values and fluctuation ranges within the rock groups. Since the electric field in the microwave will react particularly to water components in the rock structure, the water content must be determined in advance. Some selected samples are subjected to a rock analysis by thin section or X-ray diffraction. This allows the qualitative and quantitative evaluation of the mineral content to be verified.

In the case of solid rocks with pronounced interface structures, e.g. sedimentary rocks, standardized specimens, such as those required for uniaxial compression tests, can only be obtained to a limited extent. More often only specimens with non-standardized dimensions are available. Therefore, in the next step, non-standardized samples of different geometries are collected and evaluated accordingly. It can be assumed that the heat propagation will be distributed unevenly. Here the question is clarified to what extent the geometry and composition of e.g. sedimentary rocks with high discontinuity behave in contrast to magmatic or metamorphic rocks with a low degree of separation.

In order to measure the heat development on the surface and in the core of the sample, the specimen is cut along the core, reassembled for irradiation in the microwave and after irradiation the temperature is measured at various points, in particular the surface and core temperature. The procedure is analogous to Hartlieb et al. (2011). Infrared cameras are used to measure the temperature. After irradiation, they illuminate the interior and exterior of the rock and thus provide information about the temperature distribution. Since the temperature distribution will behave differently depending on the type of rock, this process must be repeated several times. Therefore, an alternative measuring method is to be developed within the framework of the experiments, so that the temperature measurement can be carried out without affecting the sample beforehand, e.g. by cutting or drilling. Conventional temperature sensors will influence the electric field in the microwave, which is why, for example, fiber-optic temperature measurement can be used. Optical sensors can be used to measure intensity, spectral distribution of the wavelength, time dependence due to frequency, pulse duration and decay and, if modified accordingly, strain changes. These can be analytically investigated in the following process.

After irradiation, the specimens are examined in the laboratory. Special attention is paid to a possible decrease of the compressive strength. The tests are carried out according to Mutschler (2004) in order to implement the requirements of the test equipment, test specimens, procedure for the execution and evaluation of uniaxial compression tests in standardized procedures. Less interesting for the construction industry, but relevant for the general scientific consideration of changes in the rock mechanical properties of solid rock, is the point load test according to Thuro (2010) and the splitting tensile test according to Lepique (2008).

Subsequently, the results are evaluated and the tests carried out with different input values are compiled. It can be assumed that the different variants of the temperature measurement and the choice of geometries will influence the output values accordingly.

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