Microwave heating of rocks with different water content

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The heating of rocks with low to medium microwave absorption strength and its dependence on the water content is investigated in a 3kW microwave oven operating at 2.45 GHz. Sandstone, granite, and basalt are chosen as the rock materials where basalt has the relatively highest absorption strength in the dry state. The effect of the microwaves is investigated by optical microscopy and by measurements of the uniaxial compressive strength and ultrasound velocity. The latter one is more sensitive to structural changes in the irradiated rocks. The largest effects due to the water saturation are observed in sandstone.

1. Introduction

The heating of rocks and minerals by microwaves has been investigated during the past 50 years in laboratory and field tests. The main purpose is to assist mechanical methods for breakage, cutting, and comminution. The investigations prior to the late 1980s are reviewed by Santamarina (1989). More recently, laboratory tests mainly concerning comminution have been performed in microwave ovens (e.g. Walkiewicz et al. (1991), Kingman and Rowson (1998), Amankwah et al. (2005)) and in a single-mode cavity (Kingman et al. (2004)). Substantial weakening of the rocks has been observed whereupon the energy consumption was significantly lower in the single-mode cavity. Lindroth et al. (1993) investigated microwave-assisted hard-rock drilling. Microwave irradiation increased the drilling rate by a factor of up to 6.5 at the highest temperatures achieved. Satish et al. (2006) reported on the possibility of a space mining application.

The absorption of microwave radiation depends on the high-frequency dielectric properties of the constituents of a rock. More strongly absorbing constituents are selectively heated leading to temperature gradients and differential volumetric expansion. As a consequence internal compressive and shear stresses are built up that can cause cracks, which are responsible for a reduction of rock strength and further on a reduction of mechanical energy required for fragmentation or even a fragmentation solely due to the microwave absorption.

The dielectric properties of a solid are described by the complex dielectric constant (permittivity): $\varepsilon = \varepsilon_r + i\varepsilon_i = \varepsilon_0 (\kappa_r + i\kappa_i)$. κ_r is the real part, κ_i the imaginary part of the relative dielectric constant, ε_0 is the permittivity of free space. At microwave frequencies κ_r values of most rocks are between 2 and 10, κ_i values between 10^{-3} and 50; both depend on frequency and temperature (Santamarina (1989)). For $\kappa_i < \kappa_r$ the reflection is mainly determined by κ_r, the absorption or losses by κ_i. A useful quantity for characterizing the absorption is the penetration depth D_p. It can be defined via the decrease of the microwave power P with depth x in a material: $P = P_0 \exp[-x/D_p]$ (another definition uses the electric field strength $E \sim P^{1/2}$). 67% of the energy is absorbed within the penetration depth. The penetration depth D_p (= inverse of the absorption coefficient α) depends mainly on κ_i. Penetration depths vary from millimetres to tens of meters. As an example at 2.45 GHz, a widely used frequency, for $\kappa_r \approx 10$ D_p is about 5 m with $\kappa_i \approx 0.01$ and 0.01 m with $\kappa_i \approx 5$. The κ_i range useful for rock breakage is approximately 0.1 – 2 corresponding to $D_p \approx 0.5$ m – 2 cm. Strong microwave absorbers are magnetite, chalcopyrite, water, poor microwave absorbers are feldspar, quartz, marble, and ice [1-3]. κ_i varies with the content of water and salt. Metallic constituents in a rock reflect microwaves into non-metallic constituents.

In this work heating experiments on weakly absorbing rocks (granite, basalt, sandstone) and the dependence on water content are performed in a microwave oven. The purpose is (a) to understand the effect of the water content of rocks which varies in a natural environment and (b) to investigate the change of properties of rocks, which are currently at the limit of economical cuttability by means of mechanical cutting methods. These are typically minerals with high compressive strength and high abrasivity (Fig. 1).

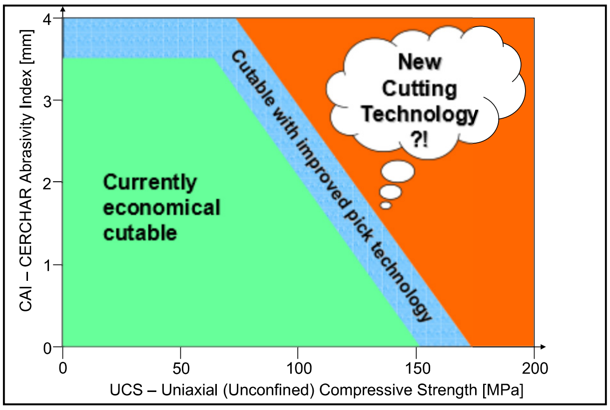

Fig. 1 Economical ranges for current pick technology in solid rock mass

2. Experimental arrangement

The microwave irradiation experiments are performed in a 3 kW multimode microwave oven at the frequency of 2.45 GHz. The samples are of cylindrical shape with 5 cm diameter and height. They are positioned in the centre of the oven by means of glassware which is a very weak microwave absorber. Depending on the material and the temperature to be reached the irradiation time is from seconds to minutes. The general intention was to observe weakening effects but not a fragmentation of the samples due to the microwave irradiation only. Nevertheless, this was achieved in two cases described in section 3.

The samples are cylindrical, 5 cm in height and diameter. They are prepared in a way to obtain the two extreme conditions regarding water content, i.e. they are either dried in a drying oven for at least 48 hours or saturated in a water bath for 48 hours (no change in the weight increase was observed after 96 hours). Relative to the as-received state the decrease and increase, resp., in weight are measured to be 0.37 and 0.29% (granite), 0.55 and 0.37% (basalt), 0.56 and 0.96% (sandstone). The irradiations in the microwave oven are performed with five different durations (three for water-saturated sandstone). For each rock type and duration five samples are investigated. This should present a good average of the rock properties with respect to structural variations between the samples of the same rock type.

The effect of the irradiation is investigated by measurements of sample temperature, modifications on the surface (optical microscopy), uniaxial compressive strength (UCS), and ultrasound velocity. The *surface* temperature is measured on each of the samples by an infrared camera. On some of the samples also the temperature of the *interior* is measured by inserting a thermocouple into a hole. Both types of temperature measurements are performed within a few seconds after the end of the microwave irradiation and after opening the window of the oven. The UCS is measured with the force applied parallel to the axis of the cylinder after the specimen has been cooled down to ambient temperature. The propagation of the ultrasonic wave is measured in the same direction.

3. Results and discussion

The highest *surface* temperatures reached with nominally 3 kW microwave power are given below. The irradiation times were chosen so that surface temperatures up to about 300°C were reached:
(a) for the dried samples: basalt: 330°C after 60 s, granite: 220°C after 300 s, sandstone: 255°C after 300 s,
(b) for the water-saturated samples: basalt: 325°C after 60 s, granite 295°C after 300 s, sandstone: 125°C after 30 s.
The different heating rates of the dried samples can be qualitatively understood by considering the values of κ_i (Sanatmarina (1989)). They are 0.08 – 0.88 (basalt), 0.03 – 0.2 (granite). Sandstone has high quartz content and therefore is a weak microwave absorber. Its heating rate is similar to that one of granite. The water-saturated sandstone heats four times faster than the dry one; the samples burst before reaching temperatures higher than those given above (further details see below). Granite heats twice as fast in the water-saturated state, whereas no difference was observed for basalt. The observation for basalt is consistent with results of κ_i measurements by Ulaby et al. (1990) that showed no difference for natural and dried samples.

The trend of the rock properties with increasing irradiation time is generally the same for the three rock types in the dried state: a decrease of the ultrasound velocity but the value of the uniaxial compressive strength (UCS) being constant within the experimental uncertainty beside a weak increase at short irradiation times for dried sandstone (Fig. 2). All the results shown here are for a nominal power of the microwave oven of 3 kW.

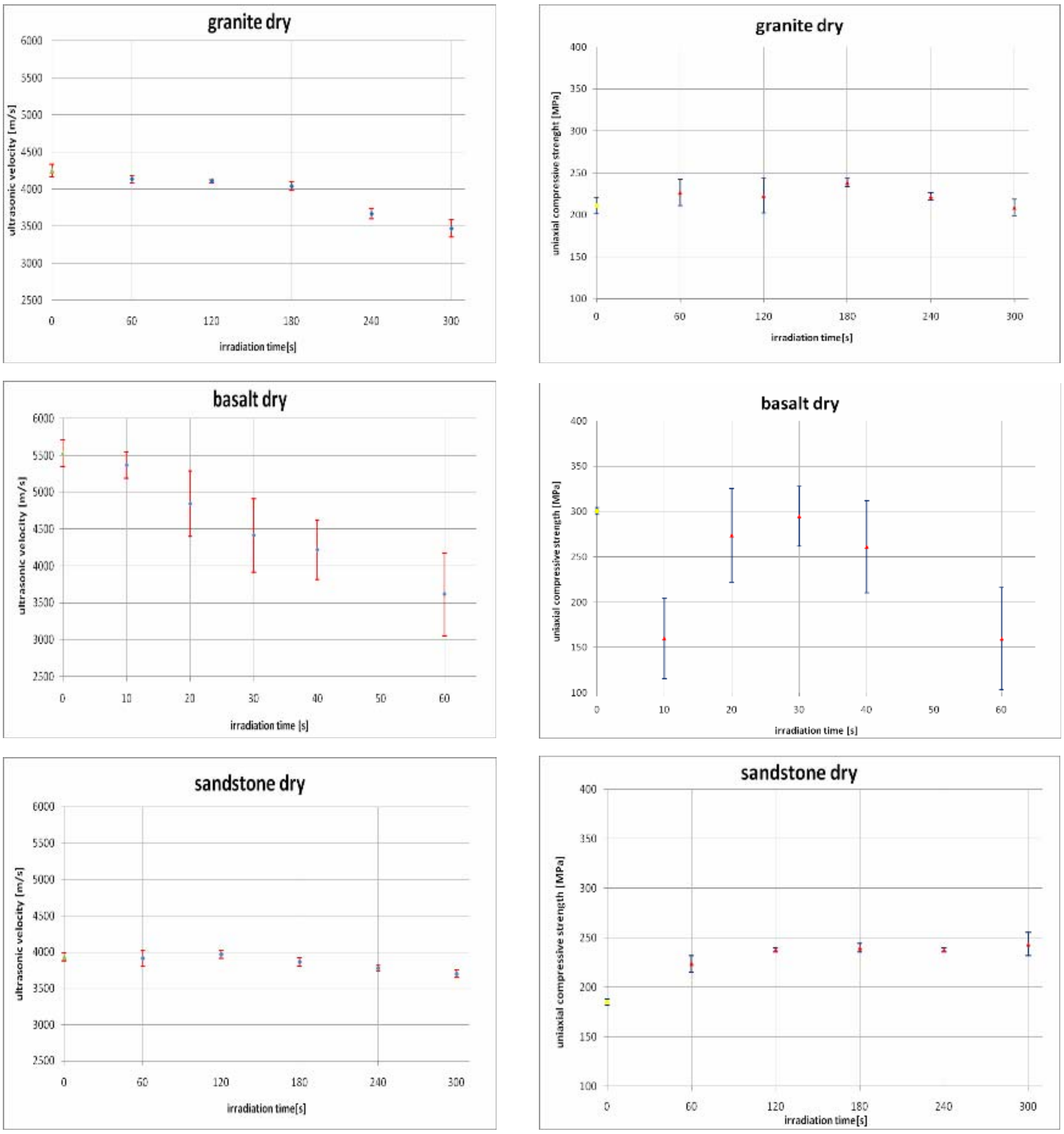

Fig.2 Ultrasound velocity (left) and UCS (right) of the dried samples as a function of microwave irradiation time. The dots on the vertical axes indicate the values without irradiation (average of 10 samples). The vertical bars give the standard deviation of the data taken on five samples (10 non-irradiated samples).

For water-saturated basalt and granite the trend is similar but with the decrease of the sound velocity being stronger than in the dry state. At the longest irradiation times cracks appear primarily in planes vertical to the axis of the cylindrical samples. This is assumed to be the reason for the insensitivity of the UCS measurements which are performed with the force parallel to the axis. Contrary to the UCS, the ultrasound velocity is very sensitive to cracks perpendicular to the direction of propagation (parallel to the sample axis). In the water-saturated sandstone large cracks appear after 20 - 30 s and the samples burst within a few more seconds. The sound velocity strongly decreases with irradiation time (Fig. 3). The ultrasound data are from samples not burst at 30 s irradiation; however, no reliable UCS data could be taken because of the large cracks generated.

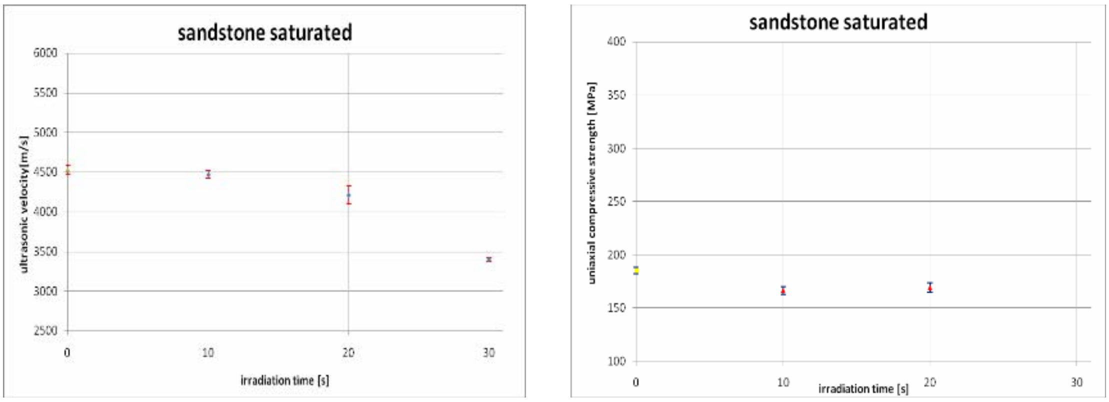

Fig.3 Ultrasound velocity (left) and UCS (right) of water-saturated sandstone as a function of microwave irradiation time. Details as in Fig. 2.

The highest surface temperatures reached after the maximal irradiation times have been measured to be between 200 and 320°C (apart from water-saturated sandstone). After switching off the irradiation a small initial increase of the surface temperature has been observed which indicates that the interior is hotter than the surface. Figure 4 shows the results for granite. The cooling rate after the initial increase (approximately 0.07°C/s) is much smaller than the heating rate during irradiation (0.7°C/s). Therefore, we assume that structural changes are essentially a consequence of the microwave heating and not of strong temperature gradients generated by the cooling of the surface after the irradiation. The results are qualitatively similar for basalt and sandstone.

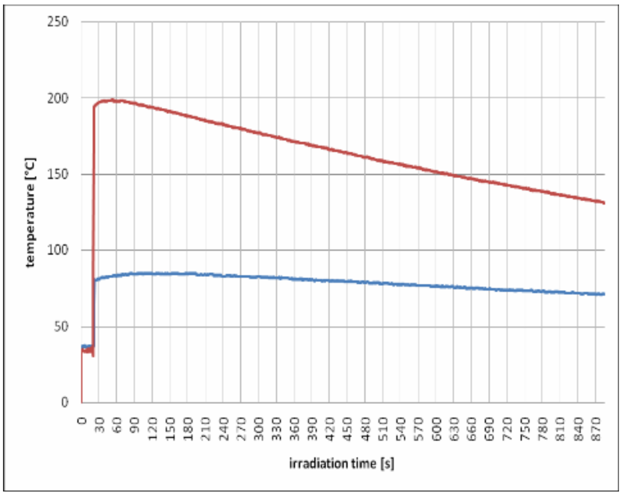

Fig. 4 Temperature of the surface of a granite sample irradiated for 120 seconds. The initial steep increase is during the switch-on period of the infrared camera. The following slow increase indicates a temperature of the interior being higher than that one of the surface. Upper curve: water saturated, lower curve: dry.

To elucidate this observation basalt samples with a hole for inserting a thermocouple have been prepared. Extending the irradiation time to 5 minutes led to a melting of the central part. The temperature measured on the surface and in the interior differed by a factor of more than 2 after the end of the irradiation (580°C and 1220°C, respectively). 1220°C is within the range of melting points reported for basalt.

4. Conclusions

The microwave heating rates in dried and water-saturated samples of basalt, granite, and sandstone are largely different which can be understood from the differences in the imaginary part of the dielectric constants. Compared to the dried samples the heating rates in water-saturated ones are unchanged for basalt, doubled for granite, and increased fourfold for sandstone. The measurement of the sound velocity is well suited to detect structural changes due to the microwave irradiation. Together with the appearance of cracks its decrease indicates a weakening of the rocks. The saturation with water enhances the weakening particularly in sandstone, to a smaller extent in basalt and granite. Due to the microwave absorption being stronger in basalt than in granite, the weakening occurs in basalt after shorter irradiations. In sandstone the water saturation leads to very large cracks and even bursting of the samples solely due to the microwave irradiation. In naturally occurring rocks the water content will be within the two extremes studied in this work. It will be of limited importance for the microwave assistance of mechanical mining techniques in the case of basalt and granite, but particularly effective in the case of sandstone. The potential of the microwave irradiation will be investigated for more rock types in the future to be able to quantify the feasibility of irritation of rock mass by microwave irradiation with the goal of increasing the cuttability.

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