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Original Article

Mechanical property and cutting rate of microwave treated granite rock

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Abstract

The purpose of this study is to investigate the effect of microwave treatment, especially at low power level on compressive strength and cutting rate of granite rock by using multimodal cavity. The power level and cooling rate of treated samples were found to have an effect on the compressive strength, and the cutting rate. This effect is due to the induction of the plastic zones and micro cracks in the rock matrix, especially at the grain boundaries induced by the thermal stresses of rock forming minerals which have the difference in dielectric properties after microwave heating for a certain exposure time together with the thermal-shock treatment after the heating. It was found that the strength of treated granite is less than 60% of the original after 30 minutes of exposure.

The dry heated samples with a water quenching seem to be the most affected samples. They exhibit a significant decrease in compressive strength up to 70% and cutting rate up to 38% after 30-minute treatment at the power of 850W, and after 10-minute treatment at the power of 600W respectively. Prolonged treatment causes the relaxation of induced thermal stresses in the rock mass, leading to a slight increase in compressive strength, and a slight decrease in cutting rate. For dry samples, the cutting rate can be enhanced because of a decrease in hardness of rock mass dropped from 61.5 to 55.4 HRC after the 10-minute heating at 600W with thermal shock treatment.

The absorbed water in the pores of rock mass also has an effect on a decrease in compressive strength. Because micro cracks developed by the water vapor generated by heat which escapes through open pores. However, it seems to have less effect on the cutting rate because it causes a slight decrease in the hardness.

Keywords: microwave treated granite, compressive strength, cutting rate, hardness

1. Introduction

The use of thermal energy to assist mineral liberation and ore grinding has been studied since the early nineteen century (Yates, 1919; Holman, 1927). Because the constituents of ores typically have very different thermal and dielectric properties, e.g. large differences in thermal expansion coefficients, so that stresses of sufficient magnitude to create fractures can be developed during heating or cooling (Salsman *et al.*, 1996; Kingman and Rowson, 1998). It is actually the difference in dielectric properties which control the process as it is the dielectric response of the materials which controls its ability to be heated. The induced power density in the individual mineral phase is then responsible for the heating and then expansion (Kingman *et al.*, 2000). Therefore, significant increases in grindability were possible for heat-treated materials. As it is known that mechanical size reduction in a mineral processing is extremely energy-intensive. It is reported that less than 1% of the total energy requirement is utilized effectively to generate new surfaces while the rest of energy is absorbed on impact and dissipated as heat or noise (Jones *et al.*, 2005). The potential of thermal treatment has been recognized in the past (Veasey and Fitzgibbon, 1990). Main benefits have been reported for thermal treatment of minerals such as increased mill capacity, reduced wear per ton of ore, better control of mill

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product size and improved liberation (recovery) and reduction in slimes production (Jones *et al.*, 2005). Veasey and Fitzgibbon (1990) concluded that "if cheaper, and more efficient, methods of heating can be employed the process might become profitable". Microwaves have been selected for this purpose because they have several advantages over standard heat application methods namely that only responsive phases are affected by the incoming energy leading to no energy is wasted in bulk-heating the sample, and heating rate in responsive phases are much higher (Jones *et al.*, 2005; Kingman *et al.*, 2000).

The basic concept of microwave heating is that microwaves cause molecular motion by immigration of ionic species and/or rotation of dipolar species. Microwave heating a material depends to a great extent on its 'dissipation' factor, which is the ratio of dielectric loss or 'loss' factor to dielectric constant of the material to retard microwave energy as it passes through; the loss factor is a measure of the ability of the material to dissipate the energy. In other words, 'loss' factor represents the amount of input microwave energy that is lost in the material by being dissipated as heat. Therefore, a material with high loss factor is easily heated by microwave energy (Hague, 1999). In fact, ionic conduction and dipolar rotation are the two important mechanisms of microwave energy loss (Kinston and Jassie, 1985). Hague (1999) concluded that microwaves are reflected from the surface and therefore do not heat metals (conductor). Conductors are often used as waveguide for microwaves. Materials which are transparent to microwaves are classed as insulators which are often used in microwave ovens to support the material to be heated. Materials which are excellent absorbers of microwave energy are easily heated and are classed as dielectrics. Chen *et al.* (1984) reported that most minerals could be divided into two groups when microwave heating is applied. Group one is those for which little or no heat was generated and mineral properties remained essentially unchanged and the second group is those for which heat was generated and the mineral were either thermally stable or decomposed/reacted rapidly into a different product. The test result also indicated that most silicates, carbonates and sulphates reported to group one, whilst most sulphides, metal oxides, sulphosalts and arsenide reported to the second group. Ores with a coarse grain size gave the best response (Kingman *et al.*, 2004). Rapid heating of ore minerals in a microwave transparent matrix generates thermal stress of sufficient magnitude to create micro cracks along mineral boundaries. The micro cracking has the potential to improve grinding efficiency as well as leaching efficiency (Hague, 1999). For example, ilmenite which is overexposed to microwave radiation for varying times showed reduction in the Bond Work Index up to 90% (Kingman *et al.*, 1988). In addition, the reduction of up to 50% of the work index can be achieved by microwave exposure of some coals (Marland *et al.*, 2000).

The aim of this study is to investigate the effect of a low-power microwave treatment on compressive strength and cutting rate of granite rock.

2. Experimental methods

2.1 Sample preparation

The granite sample used in this research was Kao Tone granite rock of Thailand. The polished slab samples were cut into tetragonal shape with a dimension of 16 mm x 16 mm x 30 mm for determining the compressive strength. While the orthorhombic shape samples with sizes of 15 mm x 50 mm x 70 mm were cut for determining the cutting rate before and after microwave treatment. Figure 1 shows rock forming minerals of granite sample used in the test. In order to observe the effect of water absorption and thermal shock of rock specimens on compressive strength and cutting rate of microwave-treated samples, the tested samples were classified into 4 groups as followings:

1) The D-D sample refers to the dry specimen and air cooled after microwave treatment

2) The D-W sample refers to the dry specimen and water quenched after microwave treatment

3) The W-D sample refers to the water absorbed specimen (soaking in water for 60 minutes before treatment) and air cooled after microwave treatment

4) The W-W sample refers to the water absorbed specimen and water quenched after microwave treatment

2.2 Microwave treatment

A variable power with a maximum output of 1000W and 2.45 GHz kitchen type microwave oven was used for heating. McGill *et al.* (1988) suggested that an increase in the power led to an increase in the heating rate of mineral especially for the one which had previously demonstrated an affinity for microwave radiation. Low loss materials such as quartz and orthoclase did not heat effectively, regardless of the applied power. Therefore, the power levels of 600 and 850W were applied to sample specimens with various exposure times. The specimens were placed in a transparent porcelain crucible always located in the center of the oven in order to minimize the variations of the field pattern.

2.3 Analytical methods

The mineral composition of untreated and microwave treated samples were determined by X-ray diffraction (XRD) technique. From the XRD patterns, the following mineral phases were found; feldspar (albite, calcian and microcline), quartz, biotite and hornblende. Biotite and hornblende disseminated in the rock matrix as shown in Figure 1.

2.4 Compressive strength testing

A universal testing machine was used to determine the strength of the rock samples. At least three specimens were

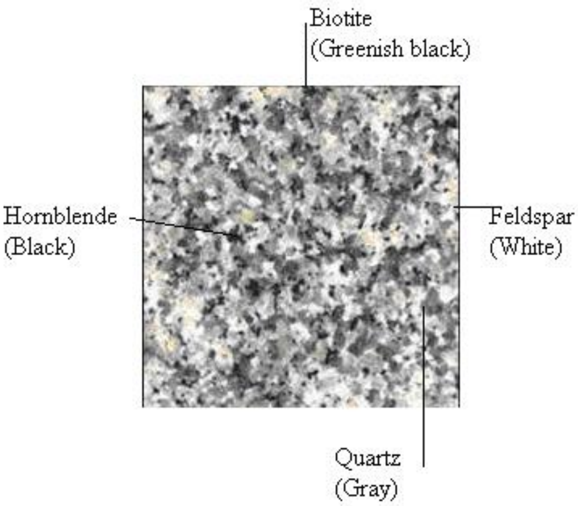


Figure 1. Rock forming minerals of Kao Tone granite used.

used per test condition and the mean value for each sample was reported. Relative compressive strength was then determined in terms of the ratio of the compressive strength of microwave-treated sample to that of the untreated one.

2.5 Cutting rate testing

A modified diamond cutting saw with constant load was used to determine the cutting rate of the rock samples. The thickness and length of the specimen was fixed at 15 mm. and 50 mm respectively. Two samples were cut per test condition and the average value for each sample was reported. Relative cutting rate was then determined in terms of the ratio of the cutting rate of microwave-treated sample to that of the untreated.

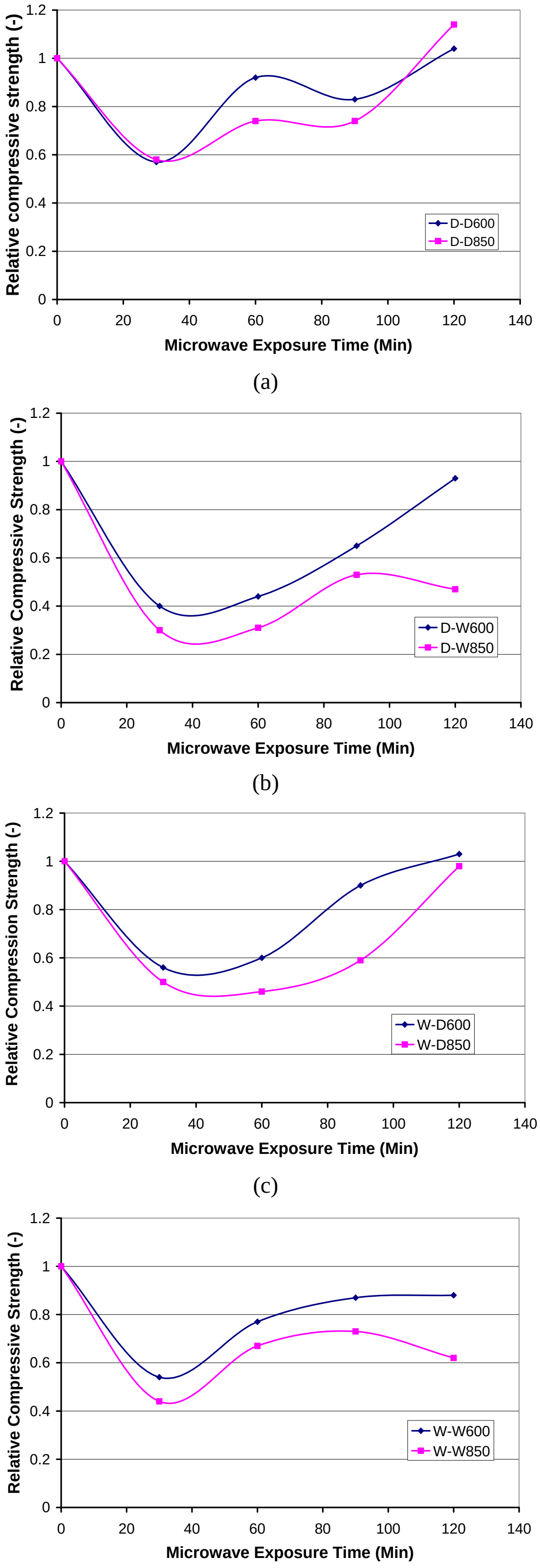
2.6 Hardness testing

A portable hardness tester was used to determine the hardness (in HRC unit) of untreated and microwave-treated samples.

3. Results and Discussion

3.1 Compressive Strength

Figure 2 shows plots of relative compressive strengths versus microwave exposure times for samples treated in the multimodal microwave cavity. It can be seen that microwave treatment has a significant effect on the strength of rock sample particularly at the highest power. However, there is not much difference for the D-D samples treated at 600 and 850W. Less than 60% of the original strength remains after 30 minutes of exposure (Figure 2a). For the D-W samples treated at 850W, there is a significant decrease in the strength of more than 70% while that of the sample treated at 600W is approx.60% after 30 minutes of exposure (Figure 2b).



(a)

(b)

(c)

(d)

Figure 2. Compression test results for various treated conditions using multimodal microwave cavity; a) D-D samples, b) D-W samples, c) W-D samples and d) W-W samples.

Similar results can be observed for the W-D and W-W samples as shown in Figure 2c and 2d respectively. One of the reasons for the decrease in compressive strength of the granite rock is differential dielectric properties of the individual mineral phases such as albite, quartz, microcline, hornblende and biotite within the rock matrix. As the individual mineral phases are heated within the applied microwave field they undergo differential thermal expansion (the thermal expansion coefficients of feldspar, quartz, hornblende are 6.6x10^{-6}~12x10^{-6}, 7.6x10^{-6}. 23.8x10^{-6} K^{-1} respectively). Biotite has a higher thermal expansion of 280% at 700^{o}C due to gas or vapor inclusions in biotite that escape through open pores after heat treatment. This expansion creates stress within the lattice, especially at grain boundaries. When rock is air-cooled or water-quenched, the thermal shock causes the mineral phases to contract, then generates stresses within the matrix, and eventually leads to fracture in rock specimen (Kingman *et al.*, 2000).

It was also apparent for all samples treated at 600 and 850W that the strength of a rock after reaching its minimum points has increased for prolonged treatment time more than 30 minutes. This is due to relief of the induced stresses in the rock specimen caused by long time heating. This phenomenon causes less fracture at the grain boundaries; therefore the strength tends to increase. There is some evidence from the data that it is possible to induce only a certain amount of thermal damage for a certain applied power level and exposure time.

Actually, strains generated by mechanical stress appear to be a more significant effect in producing failure than those by thermal stress, mainly because of the comparative slowness with which the latter stress increases. It is conceivable, however, that thermal stress may become the major contributing factor to failure if rock is submitted to thermal shock (heating and quenching). Since the combination of large strain amplitude and rapidly increasing heating rate would lead to considerably higher strain associated with thermal stress (Leach and Rubin, 1988). This condition would be enhanced by the presence of inhomogenieties and discontinuities in the rock. The results for the D-W samples (heated and water quenched samples) agree well with the reasons expressed above. For the D-W samples treated at 600 and 850W, compressive strengths decreased by up to 60% and 70% respectively, after 30 minutes of exposure (Figure 2b) compared to those for the D-D samples (heated and air-cooled samples) which decreased only 43% and 42% when treated at 600 and 850W respectively (Figure 2a). The images of rock matrix shown in Figure 3 seem to agree well with the experimental results. Figure 3b shows more micro cracks induced in treated granite rock matrix of the D-W whilst Figure 3a and Figure 3c illustrate less cracks in untreated sample and the treated D-D sample respectively.

The effect of absorbed water molecules in the rock specimen on the compressive strength of the microwave-treated samples was also investigated. Results for the W-D and W-W samples which refer to the treated water absorbed samples were illustrated in Figure 4a and 4b. The moisture content of water absorbed specimens was about 0.24% so that gaseous evolutions (water) as well as gangue mineral expansion may cause the reduction in strength (Marland *et al.*, 2000). Because a water molecule has a dipole which is easy to exhibit a dipole movement when heated with a microwave radiation, this causes friction and then gives rise to heat. This effect can be observed in Figure 4b for the W-D and for the W-W samples treated at 850W. However, there is no effect when the low power of 600W was applied (Figure 4a). An increase in the heating rate causes the water absorbed in the pores of granite rock to expand until it is sufficient to

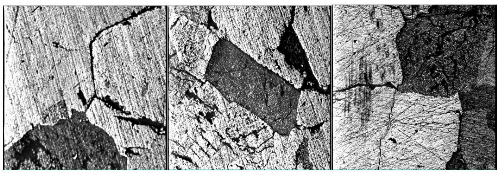

(a) (b) (c)

Figure 3. The images of granite rock matrix of D-W and D-D samples (50 x magnifications) as microwave treated at 850W for 90 minutes; a) Dry specimen before treatment, b) water quenched specimen of after treatment and c) air cooled specimen after treatment.

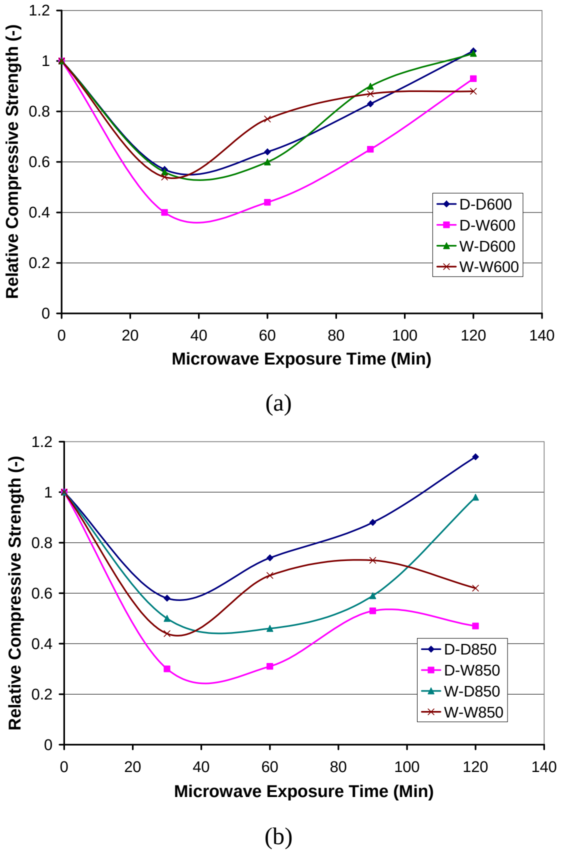


Figure 4. Compression test results for various treated conditions using multimodal microwave cavity at a different power level; a) 600W and b) 850W.

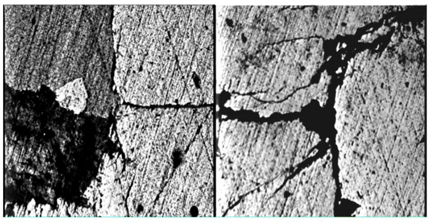

(a) (b)

Figure 5. The images of granite rock matrix of W-W sample (50 x magnifications) as microwave treated at 850W for 30 minutes; a) water absorbed specimen before treatment and b) water quenched specimen after treatment.

cause micro cracks. The images of granite rock matrix illustrated in Figure 5 support well to this finding. Figure 5b clearly exhibits crack induced in rock specimen after treatment.

It can be concluded that the D-W samples, which refer to the treated dry specimens of granite rock and water quenched after microwave treatment at 850W for 30 minutes of exposure, exhibits the most significant reduction in compressive strength up to about 70% (Figure 4b).

3.2 Cutting rate

As illustrated in Figure 6, it can be seen that the microwave treatment of the D-D and D-W samples at 600W has a significant effect on the cutting rates of granite rock. The cutting rates can be enhanced up to 33% for the D-D samples and 38% for the D-W samples after 10 minute treatment. From reasons mentioned above, micro cracks were induced in granite rock matrix by microwave treatment for a certain time due to thermal stresses generated by differential dielectric property of rock forming minerals together with thermal shock generated by water quenching after heating. Another reason is that microwave treatment also causes a decrease in hardness of the D-D and D-W samples as shown in Figure 7. This leads to improvement of the cutting rate of treated rock. However, the cutting rates drop slightly (33% and 38% for the D-D and D-W samples respectively) with an increase in microwave exposure time because the relief of induced stresses at the prolonged heating duration leads to a slight increase in strength. It was also found that microwave treatment has no effect on the cutting rates of the W-D and W-W samples which refer to the water absorbed specimens treated at 600W. This could be because absorbed water in the rock specimen of the W-D and W-W samples had negligible effect on the hardness of treated granite rock (Figure 7).

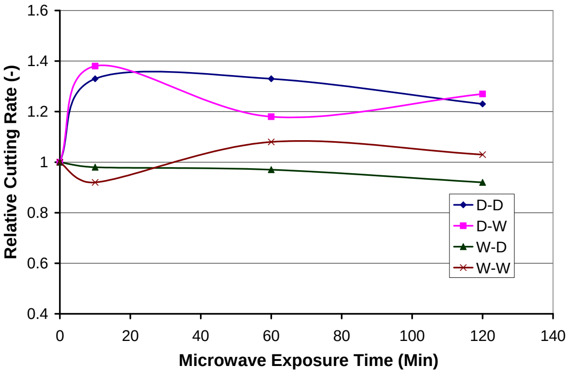


Figure 6. Cutting rate test results for various treated conditions using multimodal microwave cavity at 600W.

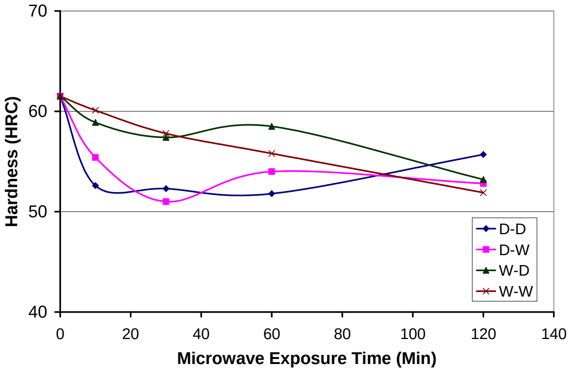


Figure 7. Hardness test results for various treated conditions using multimodal microwave cavity at 600 W

3.3 Hardness

The original hardness of the granite rock sample was 61.5 HRC. Figure 7 shows the hardness of the D-D, D-W, W-D and W-W samples treated at 600W for various exposure times. It can be seen that the microwave treatment has imposed a significant effect on the hardness of the D-D and D-W samples. These samples exhibit reductions in hardness down to about 52.6 and 55.4 HRC after 10 minutes of treatment. For the W-D and W-W samples, a significant decrease in hardness occurs only after prolonged heating times. Therefore, it is possible to induce certain amount of thermal damage for a certain exposure time. However, the microwave treatment at the power of 600W has imposed only a modest effect on the hardness of granite rock. In addition, the hardness of wet samples (W-D and W-W samples) seems to be higher than that of dry samples (D-D and D-W samples). This could be because of absorbed water in the pores of treated rock.

4. Conclusions

The change in compressive strengths and cutting rates of granite samples exposed to microwaves in multimodal cavities has shown to be associated with applied microwave powers, and cooling rates of treated samples. Differential dielectric property of individual rock forming minerals has to some degrees involves in the induced micro cracks generated by the heating with a microwave. Absorbed waters in the pores of rock specimens have an effect on the compressive strengths and cutting rates. This is most probably caused by the heat generated water vapor that escaped through open pores and induced stresses after heat treatments. Consequently, decreases in strength of granite rock had been observed.

Compressive strengths of all treated samples were found to be less than 60% of the original strength after 30 minutes of exposure. The D-W samples, referring to the water quenched samples after microwave heat treatment, were the most affected samples that exhibited a significant decrease in compressive strength up to 70% with an increase in cutting rate of up to 38%. Prolonged treatments caused relaxation of thermal induced stresses in the rock specimen, leading to a little further increase in compressive strengths and a slight further decrease in the cutting rates.

It can also be concluded that microwave treatment has a significant effect on the hardness of treated samples. The D-W and the D-D samples exhibited reductions in hardness down to about 52.6 and 55.4 HRC after only 10 minutes of treatment, but showed little further decrease in hardness with increased exposure time. The W-D and W-W samples, however, exhibited reductions in hardness with increased exposure time. This could be due to the absorbed water in the pores of treated rock that caused induced stresses with prolonged treatment.

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