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Rock Crushing using Microwave Pre-treatment

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ABSTRACT: Crushing and grinding are primary contributors to a high energy demand in the mining industry, yet, both are surprisingly inefficient processes, often with efficiencies as low as 1%. We analyze size reductions during crushing and grinding operations and explore the potential of multiplying internal weaknesses in rock materials by non-mechanical means. In particular, when rock blocks (wet or even dry if polycrystalline) are exposed to microwaves, internal cracks can develop along grain boundaries via differential thermal expansion between grains and volumetric thermal expansion of water in pores. Brazilian tests conducted on granite and cement mortar specimens show that the tensile strength decreases proportional to the duration of microwave treatment. Thermal changes, excessive fluid pressure buildup and induced stresses are analyzed in the context of hydro-thermo-mechanically coupled processes. Results confirm that both differential thermal expansion of mineral grains and volumetric thermal expansion of water can generate cracks upon microwave exposure. Optimal conditions are suggested to lower the combined consumption of electric and mechanical energy.

INTRODUCTION

The U.S. has the largest mining industry in the world, which accounted for 13.4% of the total U.S. GDP in 2007 (Economics, 2009). The Industrial Technologies Program under the U.S. Department of Energy (U.S. DOE) listed the mining industry as one of the most energy-intensive industries (BCS, 2002). In fact, the mining industry consumes about 5% of total U.S. energy (BCS, 2007). Crushing and grinding are attributable to such a high energy demand, in part due to an energy efficiency as low as 1% (Fuerstenau, et al., 2002). One of most promising solutions to improve such a low energy utilization is to take advantage of natural weaknesses in a rock (Fuerstenau, 1992). Multiplying internal flaws can help enhance energy efficiency by reducing the energy consumption in non-energy released areas inside of a particle (Tromans, 2008).

Dielectric materials undergo four types of polarization when exposed to microwaves: electronic, dipolar, ionic, and space charge polarization. These polarizations result in temperature increases, because stored internal energy is lost to friction (Gueguen, et al., 1994). A rock usually consists of several minerals with different dielectric properties. Therefore, differential thermal expansion may generate internal defects along grain boundaries when a rock is exposed to microwaves

(Santamarina, 1989). Moreover, no energy is wasted because only the responsive minerals are affected by microwaves (Jones, et al., 2005).

Industry, such as coarse aggregate, cement manufacture, mineral and kaolin extraction, involves crushing and grinding processes. Figure 1 summarizes size range, prevalent mechanisms, equipment, size reduction ratios, and industrial applications of comminution. Size data in Figure 1 reveals that final products of comminution are larger than the smallest grain size of feed materials. This implies that multiplying internal cracks along grain boundaries prior to a mechanical load is a feasible idea for most materials in this industry.

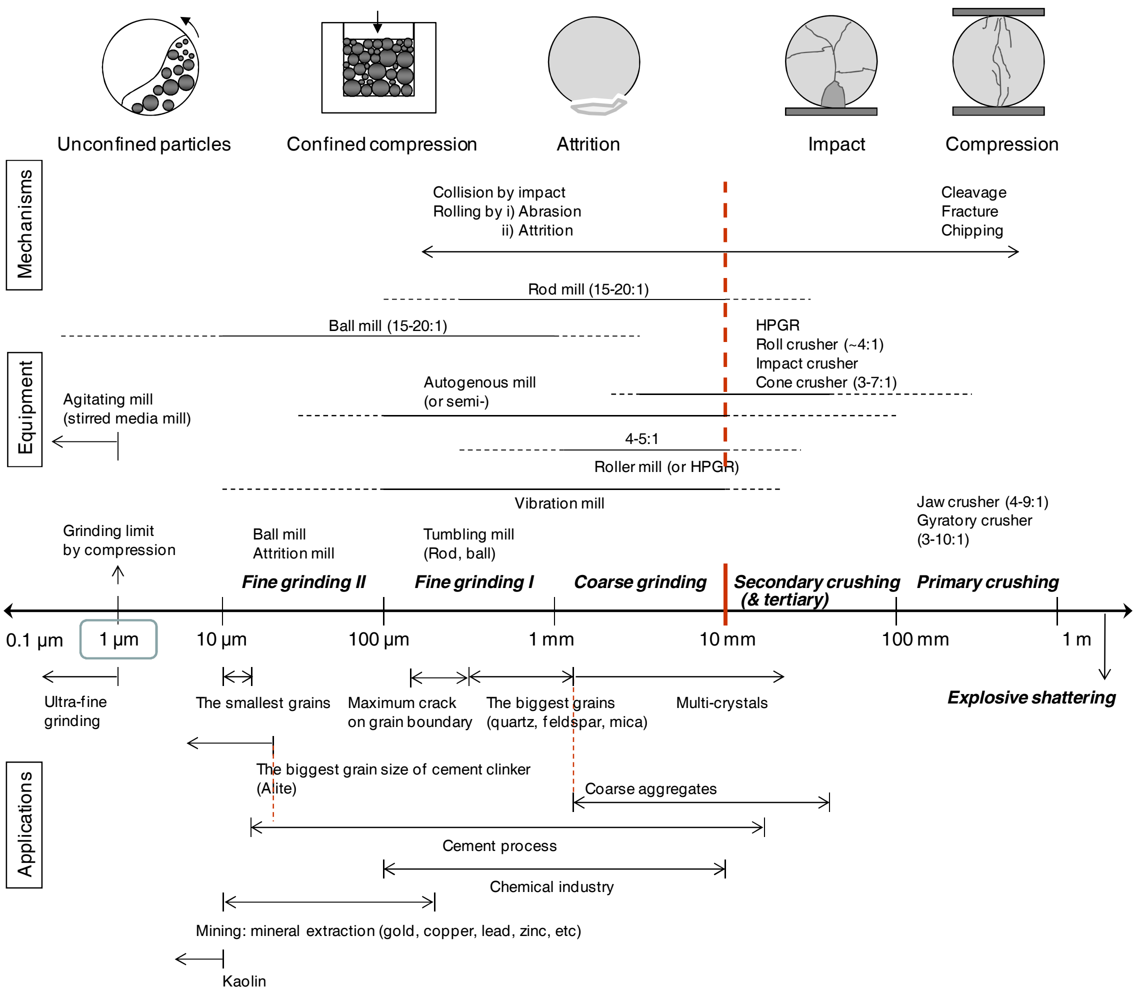

FIG. 1. Industries, equipment, and size range in comminution (continuous line: optimal operation range; dashed line: possible range). Sources are from: Fuerstenau, et al., 2002, Guimaraes, et al., 2007, Hukki, 1961, Rumpf, 1973, Tavares, et al., 2006, Wills, et al., 2006.

These factors give rise to an idea about combining a microwave treatment with a mechanical action for the purpose of energy saving. In fact, many researchers have been exploring this idea in the last decade to ease the process of rock breakage (Jones, et al., 2007, Jones, et al., 2005, Kingman, et al., 2004, Kumar, et al., 2006, Satish, et al., 2006, Scott, et al., 2008, Wang, et al., 2005). Although their studies showed promising results via the microwave treatment, they only focused on the aspect of differential thermal expansion between rock minerals. If a rock contains only "transparent" minerals as the granite does, differential thermal expansion may not be sufficient to induce any meaningful crack propagation. On the other hand, water molecules are dipole, and microwaves heat up water far more efficiently than it does on rock minerals (Gueguen, et al., 1994). In this background, we explore the following idea both experimentally and analytically: if a material is exposed to microwaves after being saturated, considerable number of cracks can be generated, thus the energy efficiency of the crushing and grinding processes can be enhanced.

EXPERIMENTAL SETUP

Tensile strength

We conducted Brazilian tests to investigate the effect of combining the microwave pre-treatment with a mechanical compression. The specimen for the Brazilian test is a circular-thin disk, thus it is in a plain stress condition. Since materials such as rock, concrete and cement clinker are much weaker in tension than in compression, the main interest is the tensile stress exerted by the platen. The minor principal stresses, which are tensile stresses, show their maximum values in the central area of the disk. We prepared two types of material for the Brazilian test, granite and cement mortar, of which explanation follows next.

Granite

We obtained two granite blocks from a quarry near Atlanta (GA, USA) and prepared about 70 granite disks through drilling, cutting and polishing processes. The granite disks' diameter is approximately 1.5 inches, and thickness is approximately 0.5 inches; the ratio of diameter to thickness is three. The disks were placed in a 100% humidity chamber in order to attain a full saturation by diffusion. The theoretically calculated hydraulic diffusivity and corresponding characteristic time are 2.9×10^{-8} m^2/s and 14 hours, respectively, based on the fluid-diffusion formula (Gueguen, et al., 1994). Nonetheless, the specimens stayed for one month to ensure their complete saturation. Porosity was determined by comparing the dry weight to the saturated one, and the average value was found to be about 0.01 (1%).

Each granite disk was then placed inside the microwave oven (GE JES738WJ) with a flask of water for 15, 30, 45, 60, 90, 120 and 180 seconds. There are two reasons to put a specimen together with a flask of water: 1) to prevent possible shattering of a rock disk during the microwave application, and 2) to measure the thermal increase of water, as well as a rock disk, to determine whether heat absorption is proportional to the microwave duration. The disks were then moved into a calorimeter to measure the increase in temperature. The temperature in the flask of water was also measured using a thermocouple. Since the granite is very heterogeneous, at least five granite disks were tested for each microwave time. Once the temperature increase is measured, energy absorption is estimated by multiplying the specific heat C_v, mass density ρ and thermal change of the material ΔT. Figure 2 shows that the energy absorption of both the granite disk and the flask of water increase linearly with respect to the microwave application time. Therefore, the material response to microwaves can be regarded stable. As a final step, the granite disks were moved from the calorimeter onto the Brazilian test frame. Test results were recorded separately according to the source of rock, as block *A* and *B*. More than 5 rock disks from each granite block were also tested without any microwave pre-treatment for the assessment of original tensile strength.

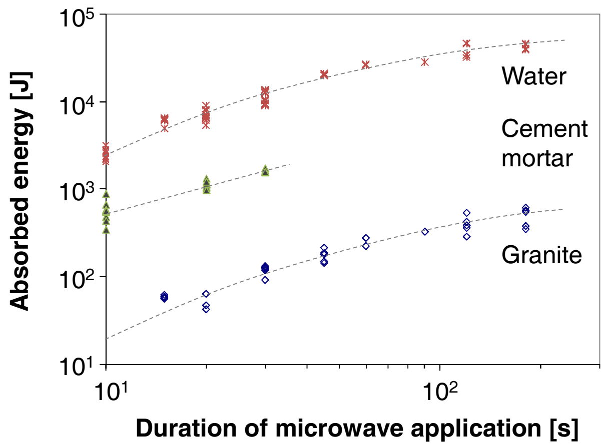

FIG. 2. Energy absorption by granite (70 specimens), cement mortar (60 specimens), and water (130 tests) during the microwave pre-treatment.

Cement mortar

Because a rock is a naturally formed heterogeneous material consisting of several minerals, additional tests with a more homogeneous material are needed to confirm the effect of strength reduction upon the exposure to microwaves. Thus, we prepared about 60 cement mortar disks by mixing water, cement and fine aggregates together. Each process of molding and preparation conformed to the international standard (ASTM, 2002). The dimensions of the mortar disks were identical with the granite disks: the diameter of 1.5 inches, and the thickness of 0.5 inches. After being removed from the mold, the mortars were cured in a 100% humidity chamber, half of them for 28 days and the other half for 35 days. The porosity was measured by comparing the saturated weight to the dry one, and the average value was found to be 0.32 (32%).

After the curing, the same procedures as in the case of granite were implemented: we removed the disks from the 100% humidity chamber and placed them in the microwave oven with a flask of water. The mortar disks were exposed to microwaves for 10, 20 and 30 seconds. Then the Brazilian tests were conducted. Test results were recorded separately according to the curing period (28 or 35 days) because tensile strength may vary depending on the curing time. We also conducted the Brazilian tests for intact 5-to-6 mortar disks from each curing time.

EXPERIMENTAL RESULTS

Granite

Figure 3-a and b suggests that the tensile strength decreases linearly with respect to the energy absorption upon the microwave pre-treatment. In particular, the linear

reduction trend in the results from rock block *B* is more evident. The results from rock block *A* also show reduced tensile strength with energy absorption, but the results are more scattered than those from rock block *B*. Since rock materials are heterogeneous, there is a possibility of having tested relatively weaker (or stronger) rock disks at specific microwave durations. Deviation from the linear trend would have been minimized if more rock disks had been tested. Nevertheless, the linear pattern found in Figure 3-a and b provides an evidence to support the effect of internal crack production achieved by the microwave exposure. These results can serve as a preliminary evidence for improving overall energy efficiency during crushing and grinding processes.

Cement mortar

Heat absorption by cement mortar disks is much more efficient than that by granite disks; indeed, it is comparable to that by water. Note that granite disks showed two orders of magnitude lower than water (Figure 2). This supports the observation that cement mortar heats up more efficiently than granite does upon the exposure to microwaves.

Figure 3-c and d summarizes the Brazilian test results. The linear reduction trend of the tensile strength upon microwave exposure is more pronounced in the case of cement mortar, partly because the mortar is more homogeneous than the granite.

ANALYSIS AND DISCUSSION

Dielectric heating of granite

Penetration depth. Penetration depth D_p [m] is a depth at which the transferred power is reduced to 37% of its original value (Kingman, 2006). Granite is a low loss material: Its loss factor ε'' lies between 0.03 and 0.2 at a frequency f=3000MHz, or a wavelength λ=100mm (Santamarina, 1989). Porosity of the granite is typically less than 1%. Therefore, we can assume that an amount of water present in a granite specimen is too small to affect the penetration depth of microwaves. Thus, the equation for a low loss material can be used to evaluate the possible range of penetration depths as follows:

$$D_p = \frac{\lambda}{2}\frac{\varepsilon^{1/2}}{\pi\kappa''} \qquad (1)$$

Granite's complex permittivity ε is between 4 and 6 (Martinez, et al., 2001), and the corresponding penetration depth D_p is between 7 and 46 inches. Hence, we can conclude that all grains inside of the granite disks were affected by microwaves during the pre-treatment.

Rate of thermal increase. We used a GE microwave oven (GE JES738WJ). The electric field strength E_{el} [V/m] can be evaluated inversely from thermal changes in the flask of water after the microwave pre-treatment. By doing so, an average value for the electric field strength was computed to be 1.775kV/m. Once the electric field strength is identified, the rate of thermal increase $\Delta T/t$ [K/s] can be evaluated as a function of the wave frequency f [Hz], density ρ [kg/m^3], and the specific heat of a material C_v [J/kg/K] (Santamarina, 1989):

$$\Delta T/_{t} = \frac{5}{9}\frac{10^{-10}\kappa'' f E_{el}^{2}}{\rho C_{v}} \tag{2}$$

We evaluated rates of thermal increase for four basic components: quartz, K-feldspar, plagioclase, and water; these are major constituents of a saturated granite. Dielectric properties and the consequent rate of thermal increase are summarized in Table 1. The rate of thermal increase for water is much higher than that of any other components. This supports the idea that water inside of a rock will help to generate cracks when exposed to microwaves, even if a feed material is primarily comprised of transparent mineral grains.

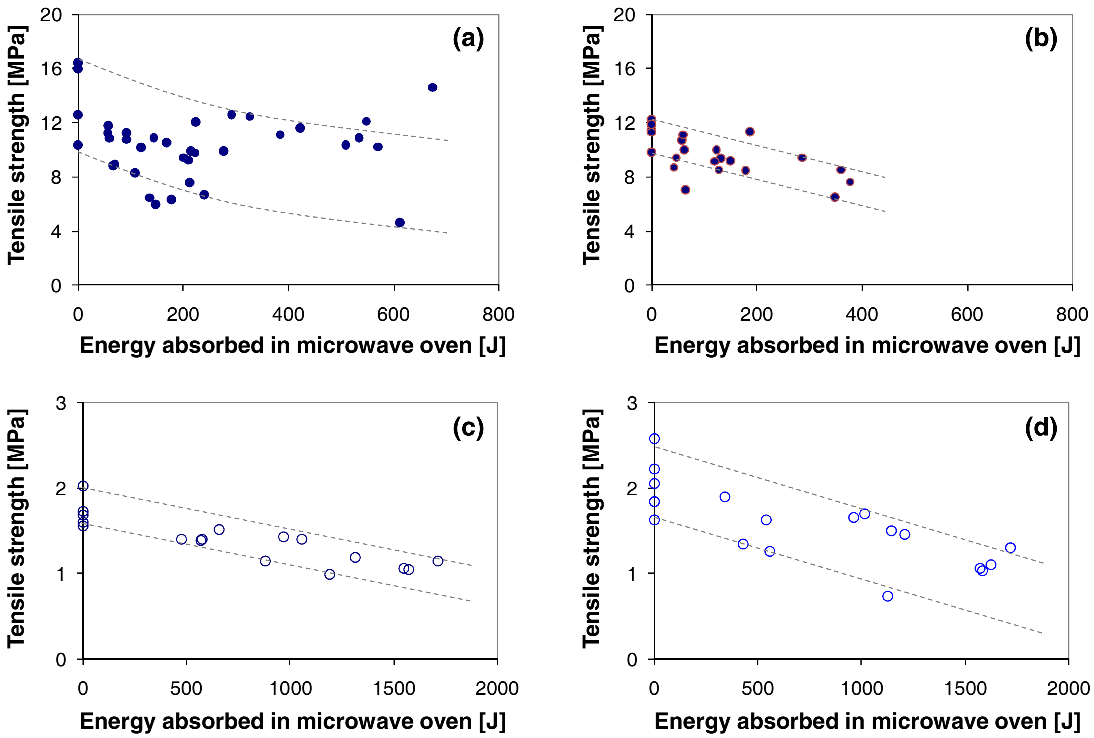

FIG. 3. Brazilian test results: Reduction in the tensile strength with respect to the energy absorption during microwave pre-treatment. Granite disks from (a) block *A* and (b) block *B*, cement mortar disks after (c) 28 days and (d) 35 days of curing.

Hydro-thermo-mechanical (HTM) coupling

Shear stress. Microwave pre-treatment in this study pertains to the hydro-thermo-mechanical coupling in the saturated porous media. Differential thermal expansion between two minerals invokes the development of shear and/or tensile stress at the grain boundary: thermo-mechanical (TM) coupling. On the other hand, the volumetric expansion of water can also induce cracks: hydro-thermo-mechanical (HTM) coupling.

Let us consider that two different minerals *A* and *B* are exposed to microwaves

(Figure 4-a). The two minerals have different dielectric properties, so different thermal increases ΔT_A and ΔT_B develop. They also have different coefficients of thermal expansion α_A and α_B. The thermal strain mismatch ($\sigma_A \Delta T_A - \sigma_B \Delta T_B$) results in the shear stress at mineral bonding. We made assumptions for a thickness of mineral bonding η=0.1μm and a scale of mineral grain L_g=100μm to draw a first-order estimate. The maximum shear stress τ_{max} that develops at the edge of mineral bonding increases with respect to the microwave duration, and is shown to surpass the average tensile strength of a rock material σ_y=5~10MPa after about one minute of exposure (Figure 4-a).

Table 1. Dielectric properties of minerals used in dielectric heating calculation

Minerals	ε'	tanδ	$\varepsilon'' = \varepsilon' \tan\delta$	$\Delta T/t$ [K/s]	α_t [1/K]
Quartz	4.31 [1]	5.0×10^{-4} [1]	2.15×10^{-3}	4.18×10^{-4}	3.4×10^{-5} [3]
K-feldspar	4.75 [1]	9.4×10^{-3} [1]	4.40×10^{-2}	8.62×10^{-3}	1.5×10^{-5} [3]
Plagioclase	6.34 [1]	2.2×10^{-2} [1]	1.39×10^{-1}	0.03	1.3×10^{-5} [3]
Water	-	-	12.04 [2]	1.23	6.9×10^{-5}

[1] Zheng, et al., 2005, [2] Santamarina, 1989, [3] Swan, 1978 (Note, ε': dielectric constant, tanδ: tangent of loss angle, and ε'': dielectric loss factor).

Tensile stress. One mineral may surround another in some cases. If the surrounding mineral expands more rapidly than the mineral inside, tensile stress σ_t develops at the boundary of two minerals (Figure 4-b). It is shown that developed tensile stress σ_t is smaller than the average strength range σ_y=5~10MPa even after 3 minutes of exposure (Figure 4-b). However, smaller tensile stress σ_t~3MPa<σ_y can also lead to the generation of cracks depending on the heterogeneity of a rock material. Notably, the shear stress developed at the mineral bonding τ_{max} is one-order of magnitude greater than the tensile stress invoked between the central mineral and the surrounding one σ_t (Figure 4-a and b). Therefore, the effect of shear stress may prevail over tensile stress in terms of generating micro-cracks.

Volumetric water expansion. Volumetric water expansion could be the most efficient way of invoking stresses during the microwave pre-treatment, based on the thermal increase rate. This expansion results in excess pore-water pressure: since some pores might be connected to each other via thread-like channels, excess pore-water pressure forces water to drain out from inside a porous medium. While some portion of excess pore-water pressure dissipates in the form of drainage, the remaining portion may contribute to propagating micro-cracks at the boundary of minerals. If a characteristic time for the dissipation of excess pore-water pressure is much longer than the duration of microwave treatment, a majority of excess pore-water pressure buildup can be used for propagating micro-cracks at mineral boundaries. We estimated the characteristic time for the permeability range of granites and cement mortars. Figure 4-c implies that the characteristic time would suffice to lead minor dissipation of excess pore-water pressure via drainage, except for the upper bound of permeability range (~10^{-17} m^2).

Industrial application

This study used a general home microwave oven, which has a multi-mode cavity in it. A microwave oven with a multi-mode cavity yields a heating rate slower than one with a single-mode cavity. Furthermore, the rate of thermal increase $\Delta T/t$ is proportional to the square of the electric field strength E_{el}^2 (Equation 2). Therefore, if we can utilize an industrial microwave system with a stronger electric field and a single-mode cavity, the effect of tensile strength reduction would be much more pronounced.

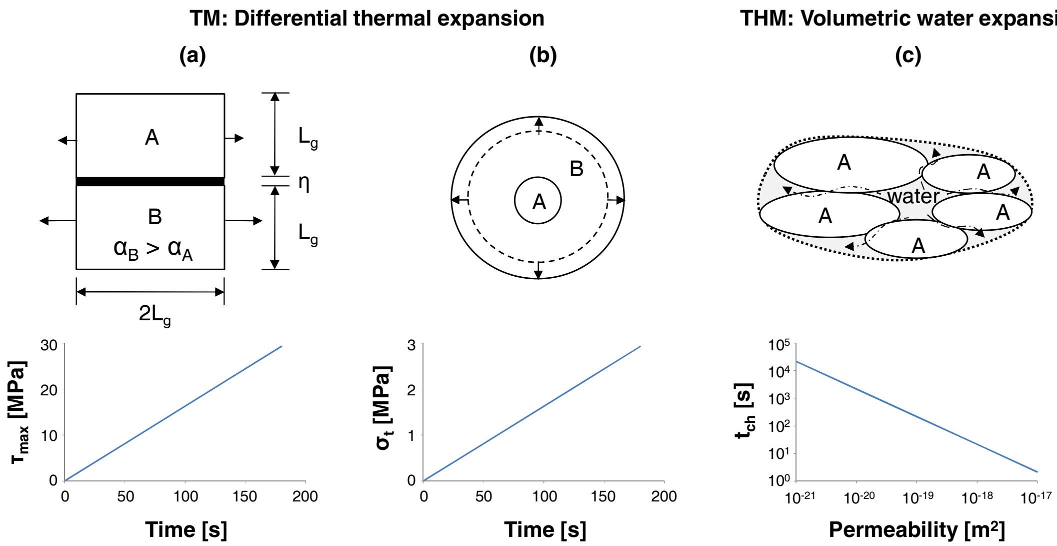

FIG. 4. Thermo-hydro-mechanical (THM) coupling invoked during the microwave pre-treatment. Differential thermally-induced stresses due to differences in their thermo-mechanical parameters (absorption, expansion, stiffness): (a) induced shear stress: $\boldsymbol{\tau_{max}} = \frac{(\alpha_B \Delta T_B - \alpha_A \Delta T_A) G \tanh \beta L_g}{\beta \eta}$; $\boldsymbol{\beta^2} = \frac{G}{\eta}\left(\frac{2}{E L_g}\right)$ (Chen, et al., 1979), (b) tensile stress at the boundary of grain A and B: $\boldsymbol{\sigma_t} = \frac{E \alpha_B \Delta T_B}{(1+\nu)(1-2\nu)}$. (c) Characteristic time for the dissipation of excess pore-water pressure due to volumetric water expansion: $\mathbf{t_{ch}} = \frac{L_{ch}^2 \mu_w}{k_{perm} K_b}$. Grain A: Quartz, grain B: Plagioclase, grain scale L_g=100μm, bond thickness η=0.1μm, Young's modulus E=30GPa, Poisson's ratio ν=0.2, shear modulus $G=E/[2(1+\nu)]$, water viscosity μ_w= 10^{-3}Pa·s, characteristic length L_{ch}=specimen radius, permeability: k_{perm}, and bulk modulus $K_b=E/[3(1-2\nu)]$.

CONCLUSIONS

We reviewed the range of size reduction and explored the idea of microwave pre-treatment, which showed potential to lower the energy consumption and thus improve the energy efficiency. Salient observations follow:

•Tensile strength of tested materials, granites and cement mortars, decreased in proportion to the duration of microwave pre-treatment. The linear reduction trend is more pronounced for the cement mortars, and it can be attributed to the heterogeneity of granites (consistency, mineralogy, and fabric). Penetration depth is sufficient for microwaves to infiltrate to the center of materials in the operational size range (D_p=7″-to-46″).

•Analysis of hydro-thermo-mechanical coupling supports that both mechanisms, differential thermal expansion of grains and volumetric thermal expansion of water, can contribute to generating cracks upon the microwave exposure. Notably, the theoretical thermal increase rate of water is much greater than that of any other grains in granite. Therefore, volumetric thermal expansion of water can play a key role in inducing internal cracks given the characteristic time for the dissipation of excess pore-water pressure is longer than the duration of microwave exposure.

•Applying the microwave system with a stronger generator and a single-mode cavity could lead to a much more appreciable impact on the reduction of tensile strength.

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