Influence of grain-size on damage in thermally treated granites- A Review and Novel quantification techniques

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ABSTRACT: Response of thermally treated granites are analyzed by several authors for processes like geothermal energy extraction, underground disposal nuclear waste, energy storage and structures exposed to fires. Although the conducted research helps to increase our understanding on the granites, quantification of thermal rock damage requires further studies which consequently alter the physico- mechanical response. So far, thermal damage is determined as a function of elastic modulus. However, an accurate determination of elastic modulus requires specialized laboratory facilities. When the treated granites (600°C) are allowed to cool in ambient temperature, the density decreases by 7.7%, 2.2% and 3.67% for coarse, medium and fine-grained granite, respectively. This reduction is primarily caused by the volumetric expansion of the mineral grains as seen by internal micro-cracking. In this study, the authors have quantified damage as a function of rock properties other than elastic modulus to appreciate the influence of temperature on varying grain-size.

Keywords: Granite, Mineralogy, Morphology, Temperature, Damage.

1. INTRODUCTION

Granite, a common rock type found in the Earth's crust, is a mixture of various rock forming minerals and can contain heat-producing radioactive isotopes (K, Th, U) that can impart temperature anomalies within the crust and elevated geothermal gradients (Shao, S.S. et al 2013). Granites are relatively stronger and possess large load bearing capacity depending on their mineralogical, morphological and weathering conditions. These attributes make granites suitable for processes such as enhanced geothermal systems (EGS), underground research laboratories (URL), nuclear waste disposal in deep geological repositories (DGR), underground energy storage and to be used as constructional materials. Since these processes generally exhibit an interaction of the strata with high temperatures, a detailed understanding of the thermal response of granite is critical in addressing the technical challenges encountered in the successful application and deployment of such processes. However, differences in mineralogical composition, grain size distribution, degree of weathering, and microstructural properties result in varied physical and mechanical response of rocks under ambient and high temperature conditions (Sirdesai et al., 2018a). Depending on the nature and conditions of thermal interaction, certain combinations of mineralogical and morphological features can result in accelerated microcracking in form of inter, intra or trans-granular microcracks, and physico-chemical degradation and deterioration of minerals (Sirdesai et al., 2018b). Since granites in nature occur in various grain sizes, it is crucial to understand the impact of size distribution and the behavior of grain boundaries on the thermal response of granites found in the aforementioned process. Consequently, this study aims to explore the influence of grain size on thermal damage in granites. Further, effect of cooling rate has been analyzed to evaluate the variation in induced thermal stresses. Thermal damage (D_T) has been computed using conventional, modulus-based relation, and a comparative analysis has been performed against novel damage indices that have been developed using other physico-mechanical properties of granites.

2. DATA COLLECTION AND DAMAGE QUANTIFICATION

Data on physico-mechanical properties of granites at ambient and elevated temperatures was collected from the literature by performing a thorough review of studies conducted on granites. Studies and the data therein were categorized based on the grain size (coarse, medium and fine-grained) and heat treatment protocols namely, rate of heating, target temperatures, duration at target temperature and rate of cooling (slow, quenching). Further, it was ensured that the data was collected from studies that adhered to ASTM standards and/or ISRM suggested methods (ASTM, 2014; ISRM, 1981). Granite specimens in the studies were analyzed under controlled deformation ranging from 0.002-2 mm/min. Filtering the data suggests that most research have been performed on Australian granites (9 studies) and Chinese granites (over 16 studies) from the Shandong (9), Hubei (5), Fujian (2) and other provinces. Additionally, data on granites found in Germany (2), Canada (1), India (1), Iran (1), and Pakistan (1) have been reviewed. Several studies utilize the conventional, modulus-based model ($D_T(E)$) for analyzing damage as proposed by Hueckel et al. (1994). In this study, novel damage models have been developed that employ physico-mechanical properties such as density (ρ), porosity (η), ultrasonic wave velocity (V), compressive (σ_c) and tensile strength (σ_t), and strain-at-failure (SAF) (ε) since these properties exhibit similar alterations at high temperatures as elastic modulus. Equation form of the novel models has been maintained similar to the modulus-based model as enlisted in Table 1. Since porosity and SAF increase with temperature, respective models have been developed and evaluated as a ratio of their magnitude at room ($_0$) to target temperature ($_T$). This further aids in analyzing damage in the positive quadrant. Comparative analysis has been performed for novel and conventional models.

Table 1. Conventional and Novel Thermal Damage Models along with symbols and notations.

DAMAGE MODELS	
$D_T(\rho) = 1 - \rho_T/\rho_0$	$D_T(\sigma) = 1 - \sigma_{(c/t)T}/\sigma_{(c/t)O}$
$D_T(\eta) = 1 - \eta_0/\eta_T$	$D_T(E) = 1 - E_T/E_O$
$D_T(V) = 1 - \left(V_T/V_O\right)^x, x = 1, 2, 3$	$D_T(\varepsilon) = 1 - \varepsilon_O/\varepsilon_T$

3. RESULTS & DISCUSSION

Nature of thermal treatment and associated physico-chemical changes induce damage within the granitic specimen (Somerton, 1992; Sirdesai et al., 2018c; Sirdesai et al., 2016). While damage in fine, medium and coarse-grained granite generally increases with temperature, a closer analysis suggests that grain size has a major influence on damage since it impacts nucleation and propagation of microcracks. At relatively lower temperatures (up to 500°C), a large variation in damage can be observed using the conventional model. Magnitudes for fine, medium, and coarse-grained granites on an average are 26.86%, 19.26% and 22.54%, respectively. However, as temperature increases (at and above 600°C), similarity in damage is observed within fine (~52%), medium (~56%) and coarse (~59%) grained granites. While damage increases gradually with temperature in granites composed of smaller grains (< 1 mm), coarse grained granites (> 5 mm) report a gradual growth up to 200°C followed by accelerated growth beyond 400°C. This can be attributed to the anisotropic expansive properties and phase-change of minerals at high temperatures (Winkler, 1997; Sirdesai et al., 2017; Sirdesai et al., 2019).

Correlation damage between conventional and novel models with respect to rate of cooling has been illustrated in figures 1 and 2. Under slow cooling conditions, stronger correlation is observed between conventional and novel models based on strength (σ_c, σ_t) and strain (ε) properties for damage in Jalore, Strathbogie, Shandong, Suizhou and Bieshan granites (Gautam et al., 2018; Kumari et al., 2017; Jin et al., 2019; Sha et al., 2020; Miao et al., 2021). Similar correlation with density-based model is found for Jalore, Shandong and Suizhou granites. For Beishan granites, damage similar to conventional model can be seen using the porosity, wave velocity, strength and strain-based models. Negative damage (*healing*) reported by conventional model in fine- and coarse-grained granites cooled slowly at ambient conditions is also observed using the porosity-based model, which further confirms the efficacy of the novel models (Shang et al., 2019; Kumari et al., 2017). Healing can be attributed to the closure of inherent defect and voids on heating at low temperature (<200 °C).

Under quenching conditions, medium-grained granites illustrate a good correlation between the conventional and novel models (Z. Zhang et al., 2020; F. Zhang et al., 2018; Li et al., 2020; Sha et al., 2020; Miao et al., 2021; Zhu et al., 2021). However, a strong correlation is observed for mechanical properties as compared to physical properties, especially density. Fine-grained Buner granite illustrates a strong correlation with velocity-based models (Khan et al., 2022).

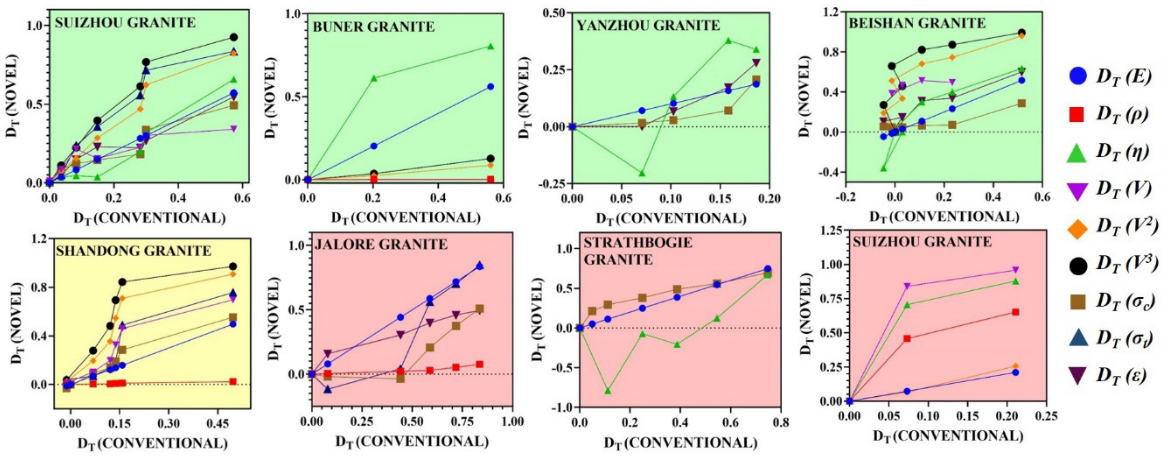

Figure 1. Correlation of conventional and novel damage models for coarse (pink), medium (yellow) and fine-grained granites (green) for slow cooling conditions.

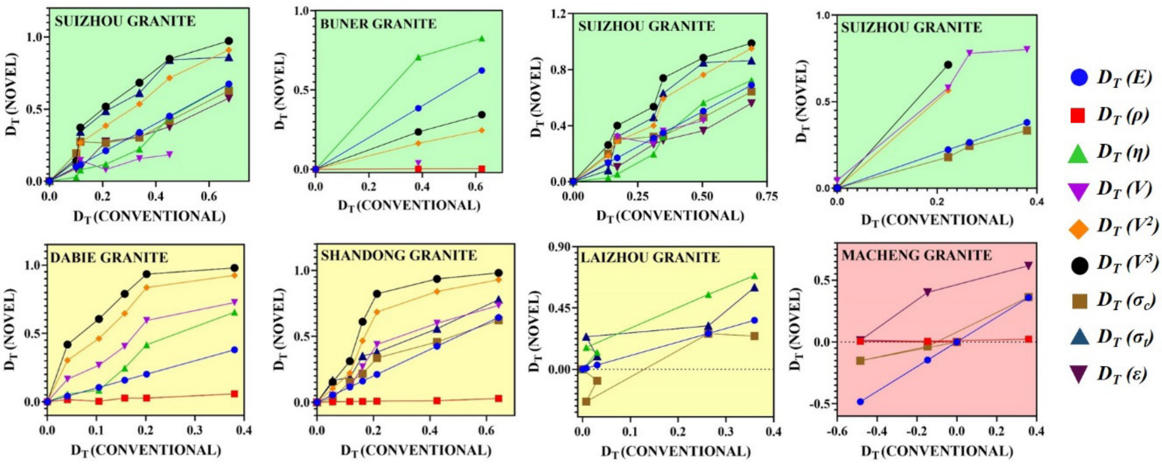

Figure 2. Correlation of conventional and novel damage models for coarse (pink), medium (yellow) and fine-grained granites (green) for rapid cooling conditions.

Excellent correlation with velocity and strain-based models is observed for fine-grained granites under slow and rapid cooling conditions. Further, rapid growth in the damage beyond 400°C is observed with strength and strain-based models when compared to physical properties. Figure 3 correlates normalised strain-at-failure (β) to the normalised elastic modulus (α) based on the data available in literature. Normalised values have been calculated by dividing the magnitude of the property at high temperature to that at room temperature for elastic modulus (E_T/E_0) and vice-a-versa for SAF ($\varepsilon_0/\varepsilon_T$). Damage can be calculated by subtracting both the normalised ratios from unity. Further, rise in treatment temperature for the rocks tested in literature has also been illustrated in the figure. A close observation of the data along with the line indicating treatment temperature suggests that as the temperature rises, the magnitude of both the ratios tend towards zero. When compared with room temperature, the magnitudes of elastic modulus and SAF are nearly half and double, respectively. While ratios less than 1 indicate damage, healing can be observed in certain granitic specimens when the normalised ratio is more than 1. Variations in elastic modulus and SAF can be attributed to the change in the compactness of the rock material due to the onset of microcracking (Shang et al., 2019; Sirdesai et al., 2019). As illustrated in the figure, a linear correlation exists between the normalised elastic modulus and failure strain with a high degree of confidence (0.97). Plot suggests that data points close to the regression line indicate similar damage as calculated by the conventional model. Data points away from the curve either under-estimate or over-estimate the damage calculated by the novel model. The relationship between α & β further addresses the competence of novel strain-based damage model in predicting thermal damage and phenomenon such as healing, thermal softening and temperature-induced-ductility (TID). Further, the correlation between SAF and elastic modulus can be improved by using strain data corresponding to yielding and crack damage. This will help in reducing the estimation error that restrain the effectiveness of novel damage model.

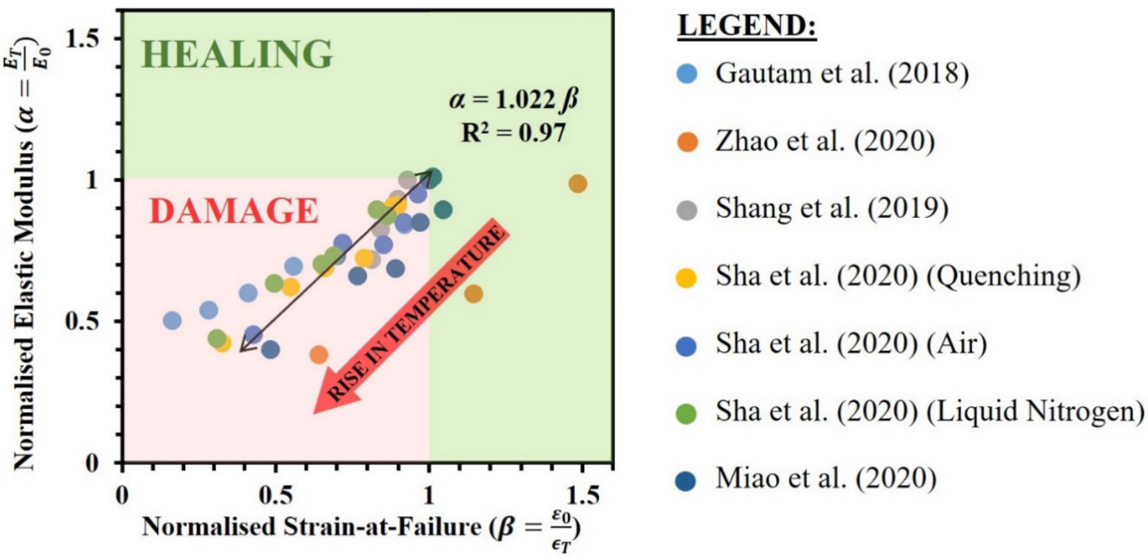

Figure 3. Normalized modulus plotted with respect to normalized strain.

4. CONCLUSION

Influence of grain size and rate of cooling on the damage in thermally treated granites have been studied by analyzing the experimental data found in literature. Novel damage models based on various physico-mechanical properties have been proposed and compared with conventional modulus-based model. Greater damage is observed in coarser grained (> 5mm) granites using conventional and novel models. When cooled rapidly, granites experience a higher magnitude of damage due to a large a thermal gradient. Novel models based on porosity, wave velocity, strength and strain quantify damage similar to conventional models. Accelerated damage is observed for all granites beyond 400°C under all cooling conditions as a result of nucleation, propagation and coalescence of microcracks. Reduction in damage at high temperatures (*healing*) as reported for few granites using the conventional model is also identified using porosity model. A linear correlation is observed between novel strain-based & conventional damage model. Efficacy of the proposed models can be further improved by testing and validating more granitic specimens. The models can also be applied to other dry rock types for further verification. The similarity of the response in other rocks is subject to lithology, mineral composition and grain-size distribution.

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