Impact of High-Temperature Treatment on Granite

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Temperature changes have significant effects on rock properties. The changes in properties vary for different rocks with different temperature ranges. Granite is an igneous type of rock that is common in India and is frequently used for construction and domestic purposes. Granite is mainly composed of quartz and feldspar and shows a considerable response to temperature changes. The heating effects of granite on its physical and mechanical properties become increasingly pronounced with increasing pick temperatures.

granite temperature changes thermal damages

1. Introduction

The role of temperature change of rocks in the mechanical weathering of rocks over time is a well-established concept in geology [1][2][3]. The temperature changes have a profound effect on the physical, mechanical, dynamic, and thermal properties of the rocks [4][5][6][7]. The thermal change may happen in various ways. It may be heating and followed by slow cooling or fast cooling/quenching method or cyclic freeze–thaw method. A host of the literature is available on the thermal effects of rocks at different low- to high-temperature limits [8][9][10]. At high temperatures, rocks increase the resistance several times with a reduction of plasticity [11][12][13]. In recent decades, the temperature effects on rocks have become popular due to the development of technologies and underground mining activities [14][15][16]. At high temperatures, the structural changes lead to the effects on mechanical properties and physical properties, which are the basic phenomenon of the materials. The critical assessment of the thermal profile while drilling granite material is of utmost importance. The elevated temperature will deform the drilling tool to a great extent [17][18][19]. The elevated temperature generated through drilling activities challenges the hot hardness and hot toughness of the drilling tool material. In order to make a realistic and pragmatic strategy [20][21]. The understanding of heat generation during drilling is very much crucial.

2. Influence of Temperature on Physical Properties

2.1. Stress–Strain

An increase in temperature results in the sudden fracturing of the rock surfaces. Su et al. [4], while studying strain burst of rocks, concluded that the kinetic energy increases with an increase in temperature up to 300 °C but decreases sharply at temperatures between 300 °C to 700 °C [22][23][24]. Sheng-Qi et al. [5] observed that Poisson’s ratio first decreases up to 600 °C then increases rapidly up to a temperature of 800 °C with ductile failure due to axial stress and the development of tensile crack [25][26][27]. In the study on fine-grained granite [6], the authors observed that the stress threshold decreases with increased temperature and the cracks propagate in stable conditions as evidenced by acoustic emission signatures. Similar observations were recorded in the Australian Strathbogie Granite [7] with thermal shock. Effects of tensile stress and thermal crack/microstructure distribution on heat-treated five sets of samples of the Westerly Granite were reported [8][28][29]. Chaki et al. [9] presented a study on the temperature effects of granite up to 600 °C, observed the rock behavior in different stages, and presented a consistency between mechanical, transport, and physical properties [30][31][32].

The temperature changes in granite affect the peak stress and decrease due to an increase in temperature. In the temperature range between 25 °C to 100 °C, the peak stress behaves almost linearly, and this non-linearity depends on the geometry and initial density of cracks [33][34][35]. The free water evaporates with an increase in temperature, and the density of the rock decreases with a decrease in peak stress [36][37][38]. This introduces the cracks; pores with an increase in the axial pressure further enhance the crack propagation. The relationship between peak stress and temperature is represented by a quadratic function [2][39][40].

$$\sigma = 221.92 - 0.82T + 1.75 \times 10^{-3} T^2$$

where σ denotes the peak stress, and T represents the temperature.

Due to changes in temperature from room temperature to 300 °C, the peak stress increases slightly, but after 300 °C, it decreases [4][41][42] with an overall 80% decrease from room temperature to 1000 °C [6][43][44]. The rate of change of peak stress reduces after 400 °C [10][45][46]. The increase in temperature affects the kinetic energy of the particles, and thus, the energy release rate is related to the stress of the material [47][48].

Strain is the measure of deformation or displacement of body particles of a material. Rock is a heterogeneous material, and the nature of deformation is distinct from metals. The stability of rocks is measured with the help of the post-peak strain. Peak strain deformation is an important strategy to evaluate in the geo-mechanical field [11]. Due to temperature effects, the internal structure of rocks is in stretchable condition with the development of new cracks. The internal strain developed within rocks varies with temperature. The peak strain increases with an increase in temperature initially, and after 300 °C, the rate slows down. A quadratic equation represents the change in peak strain under rising temperature as:

$$\epsilon = 4.1 \times 10^{-3} + 4.96 \times 10^{-6} T - 9.46 \times 10^{-9} T^2$$

where ϵ denotes the strain, and T is the temperature of the material.

From the experiments, it was found that the peak strain varies slightly from the temperature range between 30 °C to 300 °C. From the temperature range between 300 °C to 700 °C, the peak stain increases linearly [4]. The peak strain between the temperature range of 700 °C to 1000 °C increases three times more than the initial condition [6]. The peak strain of granite initially increases around 7% from room temperature to 100 °C, nearly 4% up to 200 °C and remains near constant after 300 °C. At the initial stage the strain is non-linear due to the opening of micro cracks, and their density is non-linear due to an increase in temperature.

The range of elastic deformation is obtained by the ratio of radial strain to axial strain. The peak axial strain is near constant up to 300 °C temperature, then increase by 18% up to 400 °C. It was further observed that the peak strain increases up to three times from room temperature to 1000 °C [5].

2.2. Density

Density is the intrinsic property of rocks. The average density of granite lies between 2650 to 2750 kg/m^3. The density of rocks depends on three basic factors, i.e., temperature, pressure, and composition. During heating, the dry, tough outer part expands and leads to a decrease in density. It was observed that the density of heat-treated rocks decreased gradually [1]. The impact on the dense bonding of molecules after high-temperature heating may also decrease the density. The density also depends on the basis of thermal damage and the quality of the materials. The rate of losing mass shows an increasing trend with an increase in temperature. So, the mass of granite decreases after high-temperature treatment. Such a rate is lesser in the case of a rapid quenching process [1] than in slow cooling. The volume of granite also increases with an increase in temperature. The thermal expansion of axial and lateral strain causes the micro-cracking of granite minerals. The computed tomography (CT) number is generally a function of the density and chemical composition of the material [5]. Dehydration of molecules and tight bonding may cause a decrease in the density of granite [12].

2.3. Porosity

Granite is generally non-porous, but some in situ spaces may result in porosity. Porosity is defined as the ratio of a volume of void space with in a rock to the total bulk volume of the rock.

Yang et al. [5] investigated the physical behavior of granite from room temperature to 800 °C. It was observed that from 25 °C to 300 °C, the porosity decreases 0.828% to 0.685%. Then, porosity increases from 0.685% to 3.460% up to a temperature of 800 °C due to the rapid formation of micro-cracks. During the opening of micro-cracks and reproduction of new cracks between temperatures from 100 °C to 500 °C, some structural changes are induced, and as a result, the porosity increases. The increasing rate is noticeable after 500 °C with a large increase in cracks [9]. Moreover, a high temperature results in the evaporation of water molecules from the minerals [12]. Generally, the porosity of granite ranges from 0.2% to 0.8% at normal temperatures. However, it increases up to 2.85% at 600 °C [13]. Vagnon et al. [14] established an exponential relationship between porosity and temperature from experimental data and pointed out that the porosity increases up to 3% at 600 °C. The crack propagation and the rate of increase in porosity are effective at 500 °C to 600 °C [15][16]. The heterogeneity of minerals generates new cracks due to thermal expansion at high temperatures and hence an increase in porosity [17]. Guangsheng Du et al. have analyzed the temperature generation and the effect of the temperature on rock microstructure changes which are basically granite rocks, as indicated by an analysis of the micro-inhomogeneity. Denature of crystal takes place when the temperature rises above 400 °C [49].

2.4. Permeability

The permeability of rocks depends on void space, grain size, and the cementation of mineral constituents. However, if the rock pores are isolated from one another, then the rock would be impermeable. A triaxial compression experiment was conducted on Beishan granite [18] to measure the permeability changes in crack effected region. A permeability changes model was established and was presented with the help of a numerical simulation technique. The heat treatment process on the Beishan Granite up to 800 °C [19] concluded that the cracks developed due to the phase transformation of quartz and hence changed in permeability under unconfined conditions. Moore et al. [20] examined the rate of decrease of permeability from 300 °C to 500 °C and observed that after 400 °C decreasing rate of permeability is high due to greater reactivity of the material. The permeability of the rapidly cooled sample shows increases in porosity than the slowly cooled samples [21] and is directly dependent on crack formation.

Thermal effects on Jalore granite to examine the mechanical and physical properties were performed up to 600 °C [12], and the results were compared to granites of other countries. The authors [12] also observed the changes in the water content and mineral in the granite specimen with the temperature. Isaka et al. [13] analyzed the micro-structure distribution and the basic difference of crack propagation of slow cooling and rapid cooling of the Harcourt Granite up to 1000 °C. The pore connectivity model and shock induced during cooling were also observed. An experiment on the Stripa Granite up to a temperature range of 600 °C [50], with the help of an optical microscope, pointed to the distribution of elastic and fractural properties of rocks. Homend and R. Houpert [15] predicted the thermal crack propagation and estimation of crack porosity under tensile as well as compressive loading of a granite sample at a heating range between 20 °C to 600 °C. Hewze [51] presented a review article on the high-temperature treatment of granite and an analysis of the different thermo-mechanical properties of rocks. Liu and Xu [52] conducted a study on the Qinling Biotite granite under high-temperature treatment to assess the rock stability and protection for constructional progress at underground technology. Nasseri et al. [16] presented a study on the Westerly Granite for analysis of crack density and porosity with an increase in temperature, and they predicted a relation between the fractural length and crack density of the sample. Xu et al. [17] conducted an experiment on granite up to 1200 °C to predict the tensile fractural stress and microstructure analysis to determine the chemical characteristic of rocks. Yin et al. [22] analyzed the failure made of granite under different temperature limits, especially the splitting failure and shear failure. Chen et al. [23] presented a study on heat treatment of granite up to 800 °C to observe the microstructural mineral changes in granite with the help of scanning electron microscopy while analyzing such rocks for different mechanical properties changes under the temperature. Wu et al. [24] analyzed the effect of nitrogen cooling on heat-treated granite specimens and observed the mechanical and physical properties changes in medium- and fine-grained granite. Yang et al. [25] conducted a simulation method of failure of granite material containing preexisting holes under different temperatures to observe the meso-mechanics of granite material and distribution of crack propagation. Zhao et al. [26] presented a study on the thermally treated Beishan Granite up to 400 °C for rough fracture and micro-crack generation. Zuo et al. [27] carried out an experiment on Beishan Granite under high-temperature treatment with the help of a Scanning Electron Microscope. They observed that the direction of micro-crack generation depends on the distribution of the mineral grains. They also determine the elastic modulus and stress intensity factors. Dong Zhu et al. [53] conducted a

Brazilian splitting test on granite material to investigate the effect of heating and cooling on the mechanical properties of granite. They also observed the plasticity increases with an increase in temperature. Xiangxi Meng et al. [54] have discussed the thermal cracking and permeability changes under the uniaxial compressive test of granite at a temperature of 100 °C to 650 °C. They have observed that the permeability of granite increases above the critical temperature.

3. Influence of Temperature on Mechanical Properties

Mechanical properties like Young's modulus, Poison's ratio, tensile strength, compressive strength, and p-wave velocity record changes with an increase in temperature. A few publications addressing such changes by various authors up to 1000 °C are reviewed here.

3.1. Young's Modulus of Elasticity

Young's modulus is a measure of the stiffness of a material under tension and compression. Basically, it is a relation between stress and strain of a material. Young's modulus is a measure of the characteristic of a material and is used in geo-mechanical engineering design [28]. Young's modulus generally decreases due to an increase in temperature. The decreasing rate is more enhanced in the rapid cooling method than in the slow cooling method [1]. The dynamic damages basically depend on the elastic modulus and wave velocity of the material. The elastic modulus is classified into three basic categories, i.e., initial elastic modulus, tangent elastic modulus, and secant elastic modulus [2]. The slope of the linear elastic stage is represented by this equation:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1}$$

where E is elastic modulus, σ_1 and σ_2 are initial and terminated stress, respectively, ε1 and ε2 are initial and terminated strains of the material tested.
The relationship between elastic modulus and wave velocity can be represented by the following equation [2]:

$$E = \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \rho \nu^2$$

where E and μ represent the elastic modulus and Poisson's ratio, respectively. The ρ and ν are the density and longitudinal wave velocity of the material.

The dynamic and static elastic modulus decrease with an increase in temperature. Young's modulus of granite after high-temperature treatment shows a decreasing trend. The rate of decrease of static modulus is higher than the dynamic modulus for the same temperature variation rate [5]. The elastic modulus decreases rapidly after 400 °C to 800 °C, and the rate of decrease is around 10% than the room temperature [6]. It was observed that the decreasing rate is more extreme in the case of rapid quenching than in slow cooling. The decreasing rate of '*E*' during rapid quenching and slow cooling is about 60% and 50% up to 600 °C temperature, respectively [1]. The rate of decrease in Young's modulus creates thermal cracks, which decrease the strength of the materials [29][30]. The change of elastic modulus usually effects on elastic stages of the stress–strain curve, and it causes dynamic damage to the material [2].

In case of strain burst in the granite sample, Young's modulus reduces with an increase in temperature. The strain distribution is due to changes in Young's modulus and the yield point [4]. With an increase of temperature up to 800 °C, the stress–strain curve of the granite becomes non-linear, and the material reaches a yielding point. If the temperature limit is high, the materials deform slowly and with thermally deformation cracks that affect the fracture propagation [5]. If the temperature increases up to 1000 °C, the elastic modulus decreases by 20% of the normal value [6]. In the case of the Strath Bogie Granite, the rate of decrease of Young's modulus is about 15% between temperatures 600 °C to 800 °C [7]. The constant slow-temperature heating and varying temperature rapid-heating effects on the mechanical behavior of granite, and slow cooling prevents the thermal shock after heating along with decreasing Young's modulus [9]. The elastic modulus tends to steady state up to a temperature of 200 °C due to less dependency on the elastic property of granite. Then, between 300 °C to 800 °C decreases gradually with an increase in temperature [10]. After 400 °C, it was found that the elastic modulus is greater in the case of fine-grain granite than the medium-grain and coarse-grain granite. The crack density increases, and the thermal crack development is the main reason for such diverse nature of elastic modulus during heating [20].

3.2. Poisson's Ratio

Poisson's ratio is one of the most important deformation mechanical properties indicating the brittle–ductile transition characteristic of a rock. Poisson's ratio is the ratio of the transverse contraction strain to the longitudinal extension strain. It was observed that up to 500 °C, the Poisson's ratio decreases by 25% for the slow cooling process but in the case of the rapid cooling process, the reduction rate of Poisson's ratio is 20% up to 300 °C [10]. However, up to 800 °C, the Poisson's ratio increases by 38% for slow cooling and 50% for the rapid cooling process. The reduction of Poisson's ratio is due to micro-crack generation and an increase in transverse strain.

The Poisson's ratio is related to the ratio of p-wave velocity and s-wave velocity. The ratio decreases as the temperature increases [14]. Aim et al. [50] observed the Poisson's ratio changes in Stripa Granite up to 600 °C in two unconfined stress conditions. Homond-Etienne and Houpert [15] observed a negative Poisson's ratio of granite in compression as well as in tensile stress conditions up to 600 °C. The abnormality sign of lateral strain leads negative Poisson's ratio, which is theoretically considered for isotropic material. Yang et al. [5] tested the ratio in granite up to 800 °C. They observed that the static Poisson's ratio decreases from 0.127 to 0.038 up to 600 °C and then increases rapidly from 0.038 to 0.367 up to 800 °C. However, the dynamic Poisson's ratio does not depend on the temperature. Wu et al. [24] showed that the Poisson's ratio does not show a noticeable effect on cyclic heating and cooling due to rock heterogeneity.

3.3. Compressive Strength

The compressive strength of a material is the capacity to withstand the load under compression. The compressive strength is basically performed for stress–strain analysis of a material under different loading conditions. Compressive strength [31] determined at different temperatures revealed that it decreases with an increase in temperature [1][31]. The tests were performed under different heat treatment conditions, i.e., under slow cooling–heating or rapid heating–cooling and also quenching in a different medium. In the case of slow cooling, it was observed that the compressive strength reduces by about 5%, but strength reduces when heating the sample beyond 600 °C.

From the experimental results, it was found that the compressive strength first increases slightly up to 300 °C and then decreases gradually up to 800 °C [5]. As the rocks are heterogeneous materials, the strength distribution is unequal in different positions, and the stress concentration affects the formation of cracks. The expansion of the thermally affected rock matrix reduces the distance of minerals, resulting in the enhancement of the bonding strength. So, firstly, the overall strength increases [32][33]. Further, the increase in temperature results in the weakening of grain boundaries, permanent damage to the rock due to the formation of cracks, and a decrease in compressive strength. The rapid cooling method significantly reduces the compressive strength than the slow cooling method due to the thermal shock [10]. Jinhui Xu et al. describe the typical dynamic mechanical characteristic of granite material under strain and temperature. They have discussed that the dynamic compressive strength manifests and increments when the rise of temperature is from 50 °C to about 100 °C. Dynamic compressive strength after that point becomes reduced with higher temperature. However, the elastic modulus becomes more sensitive toward the change in temperature in comparison to the strength rate. The damages related to thermal behavior appreciably decrease at a lower temperature. They recommended that 110 °C is a critical temperature that inflicts alteration in thermomechanical properties and has a relationship with the dynamic strength of granite samples [55]. Sheng-Qi Yang et al. [56] experimented on granite up to 800 °C temperature. The axial compressive test was conducted, and thermal damages, strength, and deformation were measured. Kai Chen et al. [57] have conducted the uniaxial compressive test of heat-treated granite, and the Weibull distribution damage law demonstrates the analysis of the damage behavior of granite.

3.4. Tensile Strength

Tensile strength of granite after thermal treatment for both slow cooling and rapid quenching show decreasing trends. In the slow cooling process, the reduction rate of tensile strength is 73% up to 600 °C and about 78% for the rapid cooling process. After 400 °C, the rate of decrease of tensile strength changes sharply [1]. Gautam et al. [12] observed that the tensile strength of Jalore Granite increased gradually up to 300 °C due to the expansion of rock molecules and compact specimen, but beyond this temperature, the tensile strength decreased sharply up to 600 °C. The sharp decrease beyond 300 °C is ascribed to the loss of water molecules and minerals from the material, the expansion coefficient of minerals, and the distribution of thermal stress. In the case of the Stripa Granite, tensile strength first increased slightly up to 100 °C then decreased up to 600 °C due to the increase in the microstructure of the material [50]. The tensile strength of the Senones Granite decreased more rapidly than the Remiremont Granite up to 600 °C due to an increase in the density of micro-crack [15]. The tensile strength of Biotite Granite decreased up to 1000 °C from 25 °C with decreasing rate of 35% [52]. The tensile strength of granite decreased by about 20% when it was in cyclic heating to 600 °C and subsequent quenching in liquid nitrogen [24]. R. Tomas et al. [58] conducted an experiment on 46 cubic granite samples, heating the temperature from 105 °C to 700 °C and cooling the specimen in different conditions. They have observed that the tensile stress is different between the two adjacent particles and improved the hardening effect of granite. The elastic modulus improved due to the hardening effect when the temperature was below 500 °C. Timo Saksala [59] approaches a 3D numerical prediction model to predict the effect of the tensile strength of granite. The sample is heated up to Curie point (near 527 °C), and then the sample is cooled down with air. The simulation results are validated to predict the tensile strength analysis and induced thermal crack propagation.

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