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The influence of thermal breakage on physio-mechanical behavior of Ghulmet marble north Pakistan

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ABSTRACT

Geotechnical engineering applications comprises high temperature such as deep geological disposal of nuclear waste, exploitation of geothermal process, etc. High temperature and thermal environments can affect the mechanical properties of building materials used in civil engineering (concrete, building rock, steel, etc.). The constant action of regular thermal changes in situations of excess temperature is the main source of the alteration of marble in monumental and artistic buildings. In this study, the effect of both the specimen size and temperature on the physio-mechanical characteristics of dolomitic marble has been investigated. The temperature range selected was 20-600°C. It was observed that the color of samples changes with temperature rise. The Uniaxial compression strength (UCS), P-wave velocity (Vp), and Young's modulus decreased with temperature rise. While the peak strain increases with temperature. The UCS and the peak strain showed a decreasing trend at the high diameter specimens. In the case of 43mm diameter specimens the peak stress reduced from 60MPa-26MPa with a rise in temperature from 20-600°C. While at the same temperature range the peak strain was observed as 1.7-3.3 and Young's modulus was 34-8GPa. For 75mm diameter, the peak stress is reduced to 17MPa when the temperature rises to 600°C and Young's modulus decreased to 4GPa while the peak strain increased from 2.3 to 3.9. The pulse velocity decreased from 2.75 km/s to 0.8km/ and the porosity value increased from 0.9 to 1.5%.

Keywords: *Temperature, Specimen size, Uniaxial compressive strength, P-wave velocity, Stress*

1. Introduction

The translucence of marble overturns the concept of the solidity of marble. The main issue to address is the lack of thermal-energy performance of such a thin stone layer as the only facade component. The uniaxial compressive strength is a salient feature of the rocks that are mostly used in tunneling, underground mining, and other geotechnical projects. Many parameters affect the physio-mechanical properties of rocks, one of them is temperature. In addition to that several engineering projects are related to temperature i.e underground mining remaining from radioactive activates. It was also reported that temperature affects the mineral composition and microstructures of the building material [1]. In the existing literature, the effect of temperature on coal gasification, and subsurface storage of waste was also reported [2, 3]. Therefore, investigation of temperature effect on rock behavior is important.

Earlier studies have been carried out to quantify the thermal damages of the marble. The temperature increases developed two types of cracking i.e. thermal gradient micro-cracking and thermal cycling micro-cracking [4]. The inhomogeneous strain due to temperature developed the first case. The second case is due to the strain developed at mineral boundaries. The behavior of rock can be altered by micro-cracks in grains[5]. For example, Zhang, Mao, & Lu, assessed the temperature effect on the stress and strain curve [2]. The result of the study revealed that with a rise in temperature the peak strength value decreased. The effect of temperature on the microstructure, porosity, density, and P-wave velocity was also reported [6].The temperature effect on physio-mechanical behavior of claystone at 1000°C was investigated by, Tian et al, [7]. On the other hand, Hettema et al [8] determined the compaction manners of claystone rock at high temperatures. The literature also revealed that the high temperature significantly changes the color and decreased the wave velocity as well as the uniaxial compression of coarse grain marble [9]. The alteration change of marble in the mountainous range was also observed at extreme temperatures in a marble Quarry (Granada, Spain) [10]. Luque et al [11] studied that the environmental temperature variations bring about important physical changes in marbles that affect an increase in porosity, due to the entrance of new micro-cracks and the extension of existing ones. These cracks offer new paths into the marble which make it easier for solutions containing impurities to penetrate the material. It was also reported that the thermally weathered marble is more prone to decay [11]. According to optical microscopy studied by Plevova et al, the calcite grains show morphological anisotropy in one direction, it is obvious, that the effect of temperature on the final marble properties depends not only on mineralogical composition but also on structure, texture, and morphological alignment of grains [12]. The damage mechanical characteristics of marble have been studied by Liu [13] their results reflect the brittleness behavior of marble, the overall damage of rock changes along two evolutionary paths of high temperature and strain, reflecting the combined influences of high temperature and strain on the material damage. Moreover, Yavuz et al [6] in their study assessed the temperature influence of carbonates rock and revealed that thermal

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damages in the rock mostly occurred after twenty-four (24) hours of heating. It was also reported that the rate of expansion of rocks increased with temperature [14]. Further, Fredrich et al, [15] in their study observed that the failure modes are different for intra-granular cracks and grain boundary. Recently Yilmaz [16] investigated the thermal effect of strain rate and saturation on micro-cracks of marble. It was observed that the porosity increased 2.4% when marble specimens were heated for 24 hours. The effect of temperature on the physical behavior of the Italian Alps marble quarry was investigated by Vagnon et al [17] and found that the density, ultrasonic pulse velocity, electrical resistivity, and uniaxial compressive strength decreased with a temperature rise. They have also developed a correlation of temperature with the physical characteristics of marble. In the past, the effect of thermal damage on coarse grain marble has also been investigated and concluded that in thermal treatment the porosity increased slowly while the p-wave velocity decreased dramatically [18]. Peng et al also studied the effect of temperature on coarse grain size marble, when the specimens are exposed to high temperatures, their color changes significantly and many micro-cracks are generated in the specimens. As the applied temperature increases, the longitudinal wave velocity, uniaxial compressive strength, and Young's modulus decrease gradually and the peak strain that corresponds to the peak strength increases [9]. Rong et al [19] investigated the thermal effect on the physical and mechanical behavior of fine-grain marble and pointed that Young's modulus gradually decreases while the peak strain corresponding to peak strength gradually increased with an increased temperature. The thermal treatment has a great effect on marble sludge. It was observed that compression set, abrasion loss, cross-link density, and shear modulus increased, while rebound resilience and swelling ratio values decreased with increasing marble sludge loading in the thermal environment [20]. Yavuz [21] investigated six commercial marbles of different textures and found that marbles having small grain sizes, are more resistant against the aging tests than the ones with large grain sizes. Guo et al [22] studied the fracture behavior of marble and their results showed that the fracture toughness and elasticity modulus as well as the longitudinal wave velocity of marble decrease gradually as the temperature increases from 20 to 800 °C, while the fracture toughness and the elasticity modulus have a significant linear correlation with the longitudinal wave velocity. Under high-temperature mineral thermal expansion and reaction occurs in the rock leading to deviation in physical and mineral features [23]. The effects of both high temperature and its duration on physical properties and mechanical behaviors are studied by Zhi et al [24], in general, the thermal treatment weakens the performance of rock and improves the ductility in the deformation. When the treatment temperature is high enough (i.e., 300 °C), the effect of high-temperature duration on the rock performance is less prominent. However, when a lower treatment temperature is related, the effect of high temperature duration on the rock behaviors is non-negligible. The thermal effect on marble and limestone was investigated in the past and the measurements indicated that compaction of rock structure up to 150 °C occurred and induced calcite dilation had no significant damage effect on the rock material [6]. Recently it was also studied that the thermal stability of marble could be possible by adding plasma [25] and polymers like polyvinyl chloride [26].

The research work determined the thermal effect physio-mechanical behavior, the effect of core specimen size on Young's modulus, peak stress, and strain, UCS, and pulse velocity. Due to the unique mineral composition of Ghulmet Marble (Table 1), there is very little literature available. The findings of this research work including material and methodology, results and discussion, and conclusion are discussed below.

2. Material and Methodology

2.1. Sample preparation

The fine grain marble from the Ghulmet region of, district Nagar North Pakistan has been selected in this study. Rock blocks from different locations of Ghulmet marble quarry were collected and shifted to the rock mechanics laboratory, Department of Mining Engineering, Karakoram International University (KIU) Gilgit Pakistan. Fig. 1 shows the location map of the study area. Further, the marble looks white having some natural cracks. The XRF results of four locations (M1, M2, M3, and M4) are shown in table 1. The results of XRF revealed that the marble considered 64.02% dolomite and 30.94% calcite. The density and porosity of Ghulmet marble were recorded as 2.9g/cm^3 and 0.96% respectively.

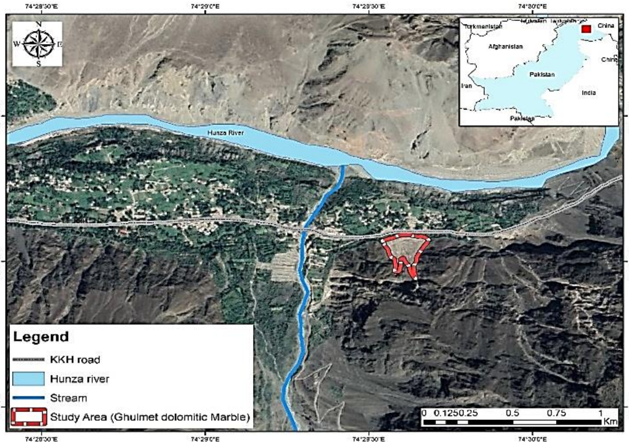

Fig. 1. Location map of Ghulmet marble deposit ((36°14′14.53″N, 74°29′28.47″E)

Table 1. XRF results of Ghulmet marble

Composition	M1 Wt%	M2 Wt%	M3Wt%	M4Wt%
MgO	64.02	75.71	80.77	77.85
CaO	30.94	15.7	14.46	17.49
Al2O3	4.45	5.48	4.36	4.13
Fe2O3	0.29	0.14	0.07	0.14
P	0.079	0.065	0.037	0.046
Zr	0.04	0.024	0.024	0.068
As	0.038	0.024	0.024	0.068
Pd	0.038	0.024	0.024	0.068
Nb	0.038	0.024	0.024	0.068
Yt	0.038	-	0.024	0.068
Ag	0.038	0.024	0.024	0.068
SiO2	-	2.95	-	-
S	-	0.18	0.14	-
Co	-	0.024	-	0.068

2.2. Experimental setup

To evaluate the effect of core sizes, cores of diameters 43mm and 75mm were prepared by a core drilling machine. The ISRM suggested method was followed for core preparation [27]. The ratio between the length and the diameter of the specimen was 2.5. The ends of the cores are polished to 0.02mm by a core lapping machine. The marble cores were heated in a furnace for a prearranged temperature with a 10 °C/min heating rate. After attaining the required temperature the specimens are heated for 4 hours. Following this, the samples are cooled down to room temperature. The 20 °C, 200 °C, 400 °C, and 600 °C temperatures were studied respectively.

Before the UCS test, the Vp of the cores after different temperatures were recorded. The ultrasonic pulse velocity transmitter was used to detect Vp. The Vp values were measured along the lengthwise of all the specimens. The centers of the two ends of the core sample were fixed by the transducers. To eliminate the air between the specimens white Vaseline was applied. The time taken by the waves through the specimens was recorded. Fig.2 (a, b) shows the P-wave velocity test setup and the universal testing machine respectively. The UCS on specimens with different sizes (diameters of 43 and 75mm) and different treatment temperatures (20, 200, 400, and 600 °C) are recorded.

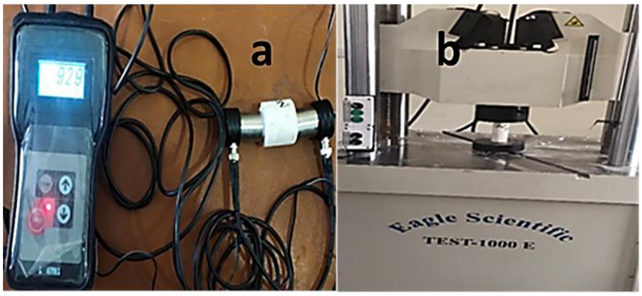

Fig. 2. (a) P-wave velocity test (b) UCS test

2.3. Geological setting:

The Ghulmat region is situated in Karakorum block, which consists of low to medium grade metamorphism, from west to east. The metamorphic grade is gradually increased due to regular movement of Indian plate drifted Kohistan Island Arc (KIA) to northward, which may create plate boundary between a Eurasian plate with Kohistan island arc, known as main Shyok Suture zone or Karakorum Thrust [28]. There are six off-shoots of Shyok suture zone crossing parallel to each other along Karakoram Highway (KKH) from Chalt Nagar to Ahmadabad, Hunza. The Chalt fault is crossing near the Ghulmat and adjacent valleys of district Nagar and Hunza which may affect the entire valley. The region falls in Southern Karakoram Metamorphic Complex (SKM) which generally comprises slate, phyletic rocks, marble, and schist with lenses of underlying ultramafic rocks. The rocks at places are intensely folded and faulted at the region [29].

2.4. Heating time and failure criteria

The heating effect on Vp is determined by increasing the heating time. The heating time is increased from four hours (4) to Hundred (100) hours at 100 ˚C to 600 ˚C. The Vp is determined after each heating time. After treatment, in uniaxial compression strength, four modes of failure could appear i.e. tensile, tensile-shear, shear and smash failure. The failure criterion is defined as:

Tensile failure occurs in hard or brittle rocks. In this case, on the core sample, there are one or more fracture planes occur in the same direction.

For Tensile-shear failure, the shear and tensile both occur. The fractures of shear and tensile may or may not intersect with each other.

There are one or more planes of shear that occur in axial loading direction in shear failure.

In smash failure, the core sample becomes crashes almost. The fractures almost appear as powder.

3. Results and discussion

3.1. Effect of temperature and specimen size on Stress-strain relationship

The effect of temperature and specimen size on the relationship of the stress-strain curve is shown in fig. 2. It was observed that the peak stress was reduced with an increased temperature. For example, at the same specimen size (43mm) the peak stress was 60MPa and it reduced to 26MPa when temperature increased to 600 ˚C. It was also observed that after 400˚C the effect of temperature is significant. In the case of 75mm diameter specimens, the peak stress was 41MPa and it reduced to 19MPa at 600 ˚C. It was also observed (fig.2) that the non-linearity of the stress-strain curve was also increased with an increased temperature. The non-linearity of the stress-strain curve is recently studied by Peng et al [30] and their study revealed that the non-linearity of the stress-strain curve increased with increasing temperature. This shows the increase of micro-cracks generated by the thermal effect. It was also reported in the literature that, the thermal treatment and specimen size have a great effect on peak stress and the relation of stress-strain [31].

3.2. Effect of treatment temperature and specimen size on UCS

The density and geometry of pores in rock were affected by increasing temperature. The effect of temperature and specimen size on the compression strength of Ghulmet marble is shown in Fig.4a. It was observed that the compression strength gradually decreased with an increased temperature. The temperature shows an inverse linear relation with UCS. Similarly, the UCS also decreases as the sample diameter increases. It was observed from fig.4a that, when temperature increased from 20 ˚C to 200 ˚C compressive strength decreased slowly but it decreases sharply from 400 ˚C to 600 ˚C. It was reported that the heating effect may generate shear cracks inside the rock specimen [32]. In Ghulmet marble such a type of failure trend was observed (fig.5), as the shear failure occurred at high temperature. In this study when temperature increased from 20 ˚C to 200 ˚C the UCS decreased from 59.9MPa to 48 MPa. Similarly, the specimen size also affected the compression strength with a rise in temperature i.e. at the same temperature (600 ˚C) for 43mm diameter the UCS value was 26MPa while for 75mm diameter it was 16MPa.

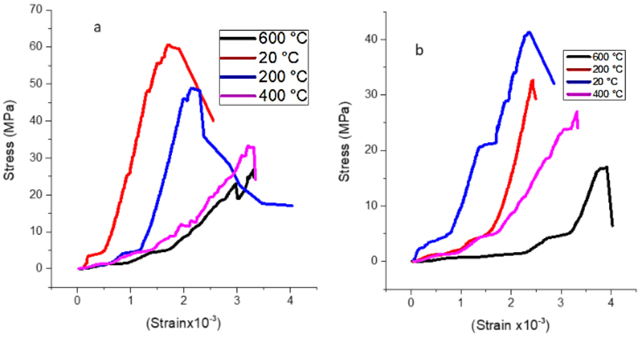

Fig. 3. Effect of temperature on stress-strain curve of (a) 43 mm diameter and (b) 75mm diameter

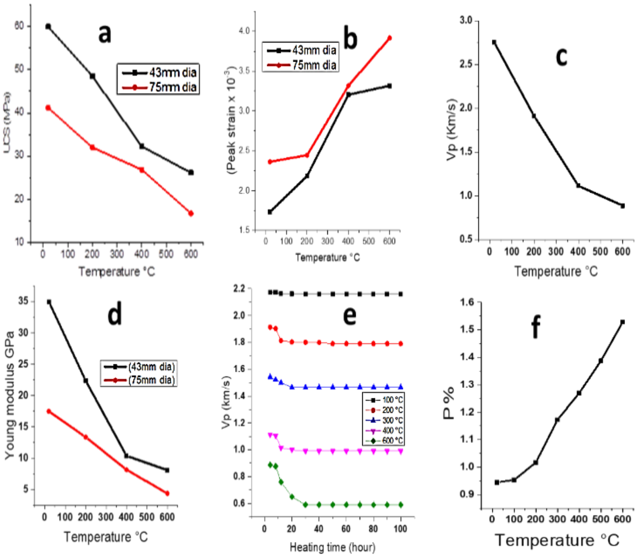

Fig. 4. Correlation of Temperature with (a) UCS (b) peak strain (c) P-wave velocity and (d) Young modulus (e) heating time (f) porosity

3.3. The effect of temperature on peak strain of Ghulmet marble

Across the maximum strength, the axial strain is called peak strain. The effect of temperature on peak strain is shown in Fig. 4b. It was observed that strain shows linear relation with temperature i.e with an increase in temperature the maximum strain linearly increased. From the figure, it was also observed that the maximum strain of the higher diameter specimen (75mm) is relatively higher than the less diameter (43mm) specimen. The sharpness of the strain line is relatively higher after 200 ˚C. There is a little increment of strain from 20 ˚C to 200 ˚C for a 43mm diameter specimen size. The strain in the same temperature for the 75mm diameter specimen is significantly increased. In the case of 43mm, diameter specimens the sharpness of the strain line increased from 400 ˚C - 600 ˚C.

3.4. Effect of temperature and heating time on P-wave velocity (Vp)

The effect of temperature and heating time on pulse velocity is shown in Fig. 4. The pulse velocity shows an inverse linear trend with an increase in temperature and heating time. Yavuz et al studied that, in marble, most of the pulse velocity decreased with increasing temperature, due to the breakage of internal fissures and void [6]. The same trend has also been observed with Ghulmet marble. The thermal breakage of the internal fissures and voids commonly occurs with the grain borders. The decrease of Vp is remarkable after 300˚C. The high temperature generates micro-cracks easily. Marble is generally more prone to micro cracks. The Vp of Ghulmet marble at room temperature was 2.549km/s, whereas at 100 ˚C it was 2.17km/s. When the temperature was increased to 200 ˚C the Vp reduced to 1.9km/s. The Vp value was sharply decreased to 0.887km/s at 600 ˚C. At a particular temperature, the Vp value is also decreased with heating time. Fig.4 also revealed that pulse velocity was decreased with an increased heating time but the Vp remain constant after a certain heating time. At 100 ˚C, when heating time is up to 12 hours the Vp value reduced from 2.17km/s to 2.16 km/s. Similarly, at 600 ˚C the Vp value decreased from 0.887km/s to 0.65km/s at 20 hours heating time. After 20 hours of heating time, the Vp of Ghulmet marble almost remained constant.

3.5. Effect of temperature and specimen size on Young modulus

The Young's modulus of the Ghulmet marble at different temperatures is shown in fig.4d. It was observed that Young's modulus gradually decreased with an increase in temperature. The value of Young's modulus was also decreased when core size is increased from 43mm to 75mm. At 200 ˚C Young's modulus value decreased from 34 GPa to 22 GPa, while it reduced to 8GPa at 600 ˚C. While at higher diameter specimens it is less than 5GPa. The Young's modulus value of 75 mm diameter specimen is lower than 43mm diameter at any temperature. The rate of decrease of Young's modulus at higher diameter cores was greater than the lower one.

3.6. Effect of temperature on porosity of Ghulmet marble

The effect of temperature with porosity is shown in (Fig. 4f). The treatment temperature also affects the porosity of Ghulmet marble. The porosity value initially increased slowly and then it was increased sharply at high temperatures (400 ˚C to 600 ˚C). The color change was also observed with an increase in temperature. This is due to the melted materials presented (Table 1) in the specimens.

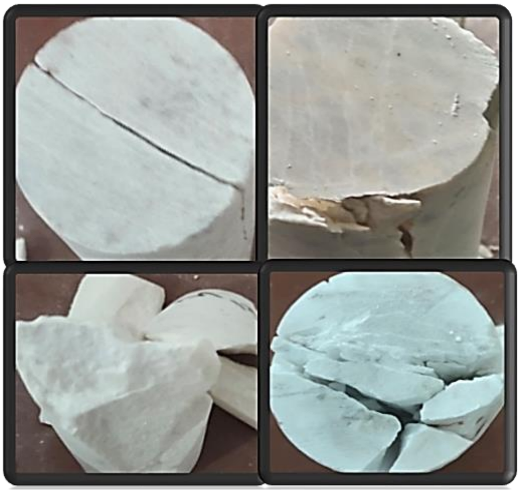

Fig.5. Thermal breakage of Ghulmet marble specimens

3.7. The failure criterion of Ghulmet marble

The failure of the cores at temperature ranges and sizes is presented in Fig. 5. It shows that the temperature and core size influence the failure style of the samples. All the samples showed a brittle failure mode. At 20 ˚C all of the samples show tensile failure. By increasing temperature tensile failure changes to tensile-shear failure, tensile-shear to shear failure, and finally ends in shear to smash failure. At 200 ˚C majority of samples showed tensile failure, but with increasing temperature at 400 ˚C tensile-shear failure occurs. Similarly at 600 ˚C few samples showed shear failure and a few showed minute smash failure. This type of thermal effect on failure criterion has also been reported by Haijian et al [33].

4. Conclusion

The research work is to study the effect of both thermal treatment temperature and core size on the strength and behavior of Ghulmet marble. After a detailed discussion, it was concluded that the strength and stress-strain rate of said marble are affected by both temperature and specimen size, as increasing temperature and Specimen size decreased the UCS, pulse velocity, Peak Stress, and Young's modulus only leaving Peak strain value which increased as temperature increases. The non-linearity of the stress-strain curve increased with an increase in temperature and specimen size. After the failure, the integrity of the cores is worse at the high temperature as compared to the low temperature. The porosity value increased with increased in temperature and it was significantly increased after 400 ˚C. The failure mode on compressive strength is generally a tensile failure. With the rise in the temperature the tensile failure change to tensile-shear, shear, and finally the sample was smashed. The temperature has a dominant effect on the physio-mechanical behavior of Ghulmet marble from 400 ˚C to 600 ˚C.

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