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The impact of high temperature on compressive strength and density of two types of granites from India

Physical properties of rocks have significant engineering value. Compressive strength and density of rocks are used in many rock mechanics related studies pertaining to civil and mining activities, stability of the excavations and estimation of the support required. In addition, rocks like granite are used as a building material and are encountered in many civil and infrastructure projects. However, these properties vary with increase or decrease in their temperature. A host of data exists on heat treatment of different rocks. In order to augment such studies and to further the know-how in this discipline, a comprehensive analysis of 56 samples of two types of granites from India was taken up in this study. The tests for compressive strength and density with increase in temperature from 35°C to 600°C were devised and conducted. The results revealed that the behaviour of two groups of the granite varied in a noticeable range on a linear scale. A reduction of 45% to 49% in strength from room temperature to 600°C in the two types of granites points to the loss of strength with increasing temperature. A reduction of 4.3% to 6.3% in density of the samples on heating can be considered to be mild. The rearrangement of grains, loss of water content initially and increase in volume on further heating are considered to be the major reasons for reduction of such physical properties in a linear manner. Colour changes have also observed in the heating process which needs to be explained in future.

Keywords: Granite, heat treatment, compressive strength, density.

1.0 Introduction

Granite is widely encountered in civil works and power projects where tunnels and caverns are excavated and is used as a construction material (Chaki et al., 2008; Dwivedi et al., 2008). Due to excavations at deeper depths the stress gets redistributed. Such stress distribution under varying loads is critical for conducting failure and fracture analysis of rocks in different types of underground workings and other constructions. The physical properties like compressive strength and density are very important variables considered in structural stability and modelling the behaviour of rockmass in such cases. However, the temperature changes such properties of the rocks and results in variation in prediction of stability and support estimations. The thermal behaviour of granite under static and dynamic conditions (Yang et al., 2017) are considered important for determination of rock behaviour under loading conditions. In underground engineering, the rock stability assessment and safety measure is an important factor in support methods and since temperature is a sole factor for changing the mechanical properties of rocks it assumes importance in rock mechanics (Liu and Xu, 2014). The temperature also affects the load bearing capacity of the rocks. The slow and rapid cooling after heat treatment effects the energy distribution and mechanical properties of granite have been dealt with by various authors (Kumari et al., 2017, 2018; Shao et al., 2014; Q. Wu et al., 2019).

Gautam et al.(2018) noted that when subjected to heat rocks show changes in their physical properties like density, compressive strength and pore of water content along with the change in their crystalline structure. Such changes are of concern in geological engineering particularly mining, energy extraction process, coal gasification and different hydrothermal processes as temperature changes impact the crystalline structure and also influence the mechanical as well as the physical properties of the rocks (Allison and Bristow, 1999). Different thermal treatments such as slow heating and slow cooling or quenching, rapidly affect the mechanical and physical properties of granite (Jin et al., 2019). Rapid cooling and quenching method after heat treatment has also been found to affect the strength as well as the elastic properties of granite (Kumari et al., 2017) with a marked differentiation in crack propagation in rapid and slow-cooling methods. The duration of time of heating of rocks is an influencing parameter of changing microstructure and thermal treatment that weaken the rock and its behaviour while influencing the ductility (Tang et al., 2019).

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Mambouet al. (2015) analyzed the effect of temperature in granite specimens with abrupt changes of mechanical properties from middle point to surface of the specimen and observed that such changes are directly related to internal stress and strain. In order to define a relation between fatigue life and peak stress, Chen et.al. (2012) conducted experiments on granite and measuring the uniaxial compressive while heating and cooling the rock. Yang et.al. (2017) observed that the static Poisson's ratio decreases up to 600˚C and then increase rapidly in granite. They also carried out the microscopic observation of uncompressed granite specimen in different elevated temperature range. Yin et.al. (2016) experimented with thermal treatment of granite and observed the rock failure mode along with changes in mechanical properties of granite at high temperatures. They observed that the peak stress-strain and failure mode of granite have an exceptional difference at high temperature treatment.

Wu et.al. (2019) researched fine grain and medium grain granite specimen with cyclic heating, and cooling in dry nitrogen environment to measure their mechanical and physical properties. They observed that the grain size significantly changed the mechanical properties of granite during heating and cooling. Hu et al. (2019) compared the damage in granite samples where one of the samples was heated to supercritical water condition and other was heated by air. They observed that the micro-damages are more remarkable in water treatment than in the air heated samples.

Li et al. (2019) investigated the energy storage at high temperature of granite with uniaxial compressive stress and analyzed the stress development, failure mode and micro crack behaviour. They concluded that the microstructure changes also affect the failure mode of granite and mechanical behaviour of rocks. Zhao et al. (2019) analyzed the shear stress on heat treated granite and crack propagation in rocks and found that the peak strength and the shear stiffness decrease with increase in temperature. Alm et al. (1985) analyzed the micro crack density of the Stripa granite while heating the samples between the temperature ranges of 100˚C to 600˚C for 3h. They found that the tensile strength is higher of the heat-treated specimen than the non-heat-treated specimen.

There are several other important works on the micro crack generation, physical, thermal and mechanical properties changes of granite due to changing of environmental temperature (Chaki et al., 2008; Dwivedi et al., 2008; Guo et al., 2018; YIN et al., 2016). Some of the findings of papers on heat treatment of granite have been summarized in Table 1.

It is evident from Table 1 that the temperature changes the impact on the physical, mechanical or structural properties of the rocks. The rate of change of such properties varies in

Table 1: Categorization of works of different authors on heat treatment of granite

Year	Citation	Factors treated	Rocks investigated	Temperature ranges	Findings	Objectives
1999	Allison and Bristow (1999)	High temperature and rock weathering	Dolerite Chalk Wehrlite Serpentinite	1000°C	Natural fires affect rock material properties	Weathering of Rock on high temperature fire.
2012	Chen et al. (2012)	Thermal treatment	Granite	1200°C	Effect of temperature on mechanical properties.	Mechanical properties changes under uniaxial compression and fatigue loading.
2014	Liu and Xu (2014)	High temperature treatment	Qinling biotite granite	1000°C	Static and dynamic mechanical properties	To measure the wave-velocity, compressive strength and tensile strength.
2015	Mambou (2015)	Loading and firing	Granite	500°C	Finding the internal stress-strain behavior.	Effect on mechanical properties for loading and firing.
2016	Yin et al. (2016)	Thermal treatment	Granite	800°C	Failure mode of granite under high temperature.	Change of Stress, strain and elastic modulus.
2017	Kumari et al. (2017)	Mechanical behavior	Australian Strathbogie granite	800°C	Mechanical behavior under different temperature limit.	Heat treatment of granite followed by slow cooling and rapid cooling.
2017	Yang et al. (2017)	High temperature treatment	Granite	800°C	Thermal damage and failure mechanical behavior.	Change of strength and static electrical modulus under high temperature.
2019	Jin et al. (2019)	Thermal treatment	Granite	500°C	Thermal treatment of Granite	To observe physical, mechanical and transport properties changes.

different rocks. In order to further the know-how on the subject with Indian example, this study was conceived. The main aim of this paper is to observe the compressive strength changes and density changes of granite due to change in temperature and to compare the rate of change of such properties.

2.0 Material and experimental procedure

Granite is a common type of igneous rock available in India. There are many varieties of granites available throughout the country. Granite basically consists of 20% to 60% of quartz and at least 35% of feldspar and micaceous minerals. The granite samples analyzed in this study were collected from Jaipur in Rajasthan. Two types of granites were used for testing purpose i.e., 1. Multi-coloured granite with deep brown colour and 2. black granite. From the collected samples, specimens were prepared in the following dimensions:

1. 150 mm × 120 mm × 25 mm, and
2. 60 mm × 60 mm × 25 mm.

In this manner, a total of 56 numbers of samples of granite were prepared for testing. The flowchart of the testing procedure is given in Fig.1.

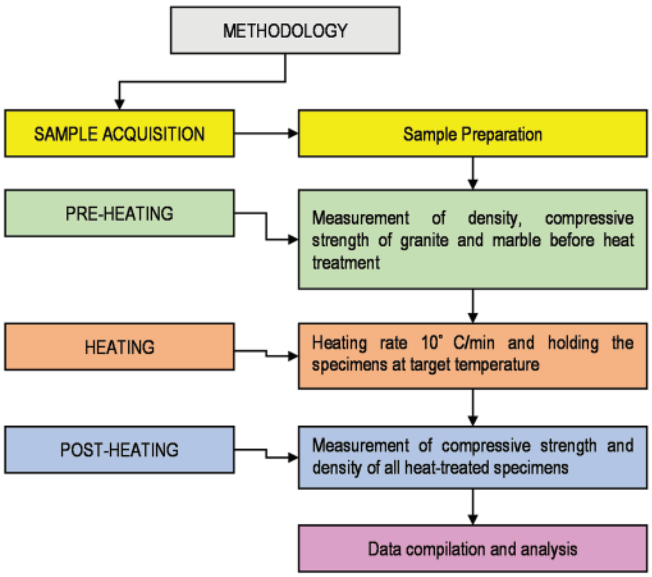

Fig.1: Flowchart of the methodology adopted to determine the impact of heat treatment

2.2 Heating and testing procedure

A box type muffle furnace is used for conducting the heating process as is shown in Fig.2. The furnace has a high precision control and the maximum operating temperature of 1200°C.

The specimens were divided into six categories and each categories contain two types of rocks. The specimens were heated at the rate of 10°C/min and the temperature varied from room temperature i.e., 35°C to 600°C. The slotting of temperature was 100°C, 200°C, 300°C, 400°C, 500°C, 600°C.

Fig.2: A view of the samples arranged in the heating furnace

Another set of specimens were tested at room temperature. After reaching the particular temperature the specimens were kept inside the furnace, constantly for 30 minutes and after that these were cooled down in air to achieve the room temperature. The samples tested were divided in 7 groups for each class of granite with 4 samples in each group for better appraisal of results.

2.3 Physical and structural properties test

Two basic physical properties i.e., the mass and density were measured of the above-mentioned specimens before and after heat treatment process. The mass was measured with help of a digital weight machine and the density is measured with help of water displacement method. To measure the changes of density of the specimen in different temperature, the mass and volume were also measured with respect of room temperature. The rate of change of volume (σ_v), the rate of change of mass (σ_m) and the rate of change of density (σ_ρ), were calculated using the following equations:

$$\sigma_v = \frac{v_1 - v_0}{v_0} \times 100\%$$
$$\sigma_m = \frac{m_1 - m_0}{m_0} \times 100\%$$
$$\sigma_\rho = \frac{\rho_1 - \rho_0}{\rho_0} \times 100\% \qquad \text{... (1)}$$

Where, v_0, m_0, ρ_0 are the volume, mass and density before heat treatment and v_1, m_1, ρ_1 are the volume, mass and density after heat treatment.

2.4 Compressive test

The uniaxial compressive tests were performed of the 150mm × 120mm × 25mm dimension heat treated specimens. An electro-hydraulic servo compressive tester was used for testing the specimens (Fig.3). Both types of the specimens i.e., specimens at room temperature and the heat-treated ones were tested for determination of the uniaxial compressive strength of such samples.

Fig.3: View of the machine used for compressive strength testing of the samples

The complete data of the tests is presented in Tables 2 to 7.

2.5 Regression analysis

Regression is the statistical analysis of two or more variable basically one variable is the cause of the other variable. If X (independent) and Y (dependent) are variable the equation can be expressed as follows

$$\hat{Y} = a + bX \quad \text{... (2)}$$

where, $\hat{Y}$ is the estimated values of Y for a particular value of X. Thus, the regression analysis can be used for the purpose of the prediction of the values of dependent variable, given the values of independent variables.

Karl pearson's coefficient of correlation can be expressed by the following equation.

Table 2: Compressive Strength of specimens at temperature 35°C

Materials	Temperature (°C)	Compressive Strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	35° C	100.1	98.82	2.66	2.65
		98.2		2.65	
		98.3		2.69	
		98.7		2.61	
Black granite	35° C	99.7	99.85	2.76	2.74
		101.6		2.73	
		99.3		2.78	
		98.8		2.72	

Table 3: Compressive strength of specimens at temperature 100°C

Materials	Temperature (°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	100°C	101.2	99.9	2.67	2.64
		99.3		2.58	
		98.8		2.61	
		100.3		2.72	
Black granite	100°C	102.2	100.72	2.59	2.6
		101.7		2.63	
		99.3		2.61	
		99.7		2.57	

Table 4: Compressive strength of specimens at temperature 200°C

Materials	Temperature (°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	200°C	97.2	96.32	2.61	2.6
		96.3		2.59	
		95.4		2.6	
		96.4		2.62	
Black granite	200°C	95.6	95.45	2.65	2.61
		96.1		2.62	
		94.9		2.59	
		95.2		2.61	

Table 5: Compressive strength of specimens at temperature 300°C

Materials	Temperature (°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	300° C	90.1	88.72	2.58	2.54
		88.8		2.52	
		89.7		2.61	
		86.3		2.48	
Black granite	300° C	87.7	87.35	2.68	2.58
		88.1		2.51	
		84.8		2.62	
		88.8		2.54	

Table 6: Compressive strength of specimens at temperature 400°C

Materials	Temperature (°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	400°C	76.4	78.3	2.67	2.55
		77.8		2.53	
		80.3		2.51	
		78.7		2.49	
Black granite	400°C	75.8	76.35	2.62	2.54
		77.1		2.53	
		76.6		2.48	
		75.9		2.55	

Table 7: Compressive Strength of specimens at temperature 500°C

Materials	Temperature (°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm^3)	Average (g/cm^3)
Multi granite	500°C	63.3	64.22	2.66	2.54
		64.1		2.51	
		64.3		2.49	
		65.2		2.53	
Black granite	500°C	60.2	61.37	2.67	2.55
		63.4		2.48	
		60.8		2.49	
		61.1		2.57	

$$r = \frac{\Sigma(X_i - \bar{X})(Y_i - \bar{Y})}{n.\sigma_x.\sigma_y} \quad \text{... (3)}$$

where, X_i and Y_i is the i^{th} value of X variable and Y variable. $\bar{X}$ and $\bar{Y}$ is the mean value of X and Y. n is the no. of pair of observation of X and Y. σ_x and σ_y are the standard deviation of X and Y.

3.0 Results and discussion

3.1 Change in compressive strength with increasing temperature

The relation between the mechanical and physical behaviour of rocks under high temperature treatment is an interesting topic of scientific research. Many publications exist on high temperature treatment of rocks are highlighted in the literature survey, above. The compressive strength distribution with temperature for multi granite and black granite are provided in Fig.4.

From Fig.4, it can be observed that the compressive

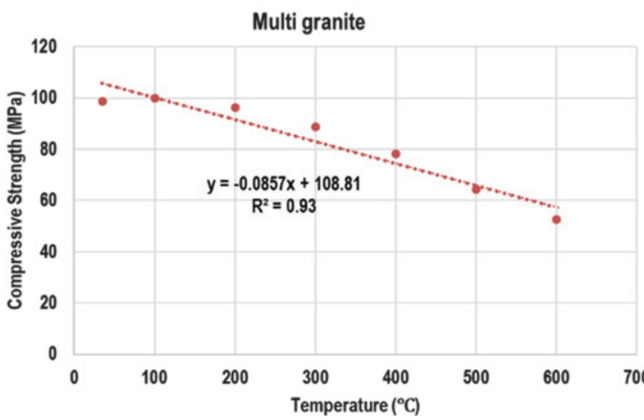

Fig.4: The relationship between temperature and compressive strength of the multi-granite

strength (σ_c) of multi-granite up to a temperature of 200°C is practically same and then shows a decrease in σ_c up to a temperature of 600°C. The trend of decrease is of linear nature

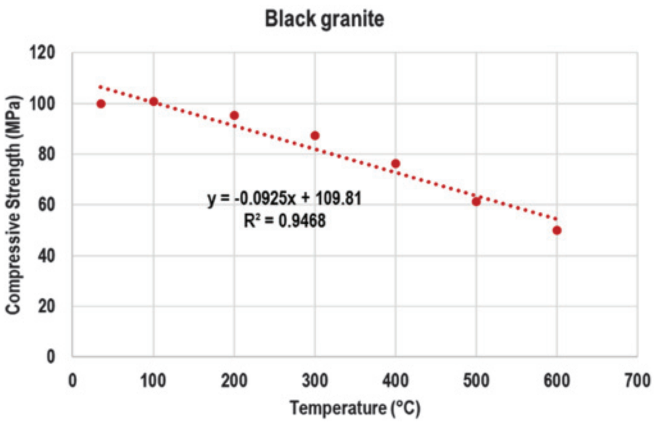

Fig.5: The relationship between temperature and compressive strength of the black granite

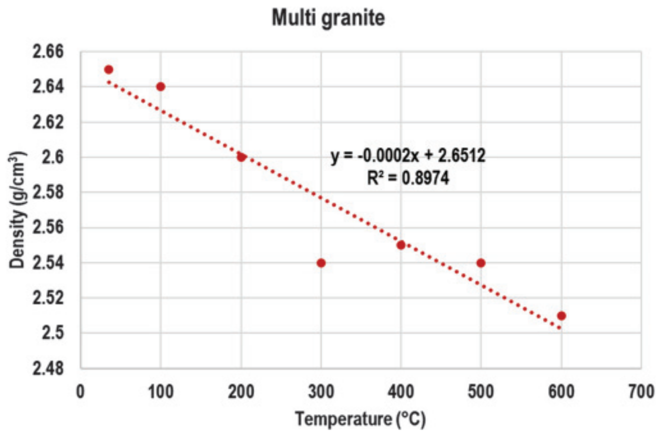

Fig.6: Change of density with increase in temperature in multi-granite

with increase in temperature. The variation of σ_c with temperature for the black granite is shown in Fig.5.

As can be seen from Fig.5, the results of decrease in s_c in case of black granite are similar to that of the multi-granite. In both the cases of granite, the trends are similar with high level of correlation of compressive strength with temperature i.e., R^2 of 0.93 in case of multi-granite and R^2 of 0.94 in case of black granite. However, at a subtle level, it is observed that the rate of decreasing nature of compressive strength is higher in case of black granite and the rate is lower in case of multi-granite (Table 8). The reasons for the variation may be due to the grain size distributions and subsequent crack generation along such boundaries with differential stress generation.

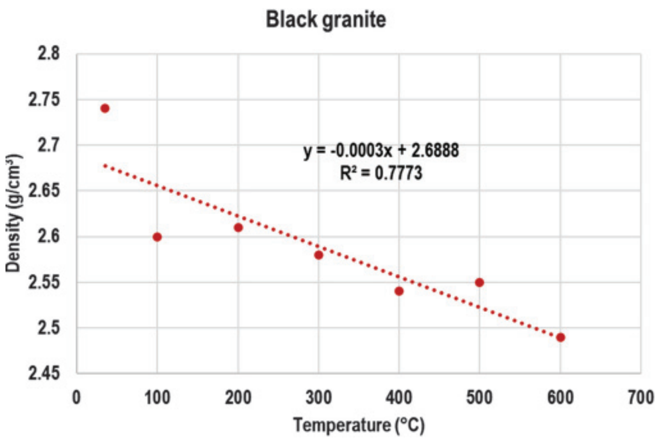

Fig.7: Change of density with increase in temperature in black granite

3.2 Change in density with increasing temperature

Density of test rocks (ρ_r) at different temperatures was measured with water displacement method. The measure is the mass and volume of test samples and were taken before and after heat treatment at different temperature. Figs.6 and Fig.7 show the changes in density with temperature of specimens of two types of the granites analyzed in this study.

Table 9 shows comparison of change in density with increasing temperature. The change in density also shows decreasing linear trends in both the cases of the granite. The trend in case of multi-granite is more prominent over the entire range of the temperature varied (Fig.6), but the black granite trend is somewhat moderate due to scatter in the data over the test temperature range (Fig.7). Also, it is observed that the rate of change of density is higher in case of black granite and less in case of multi-granite. The rate of decrease of the density with temperature over the test range is provided in Table 9.

The volume changes of rocks are more than zero means the volume increases after high temperature treatment from room temperature to 600°C temperature range. It is seen that the volume increases after high temperature treatment. In case

Table 8: Compressive Strength of specimens at temperature 600°C

Materials	Temperature(°C)	Compressive strength (MPa)	Average (MPa)	Density (g/cm³)	Average (g/cm³)
Multi granite	600° C	52.1	52.45	2.61	2.51
		52.8		2.51	
		51.1		2.42	
		53.8		2.51	
Black granite	600°C	49.5	50.17	2.61	2.49
		50.1		2.45	
		49.9		2.41	
		51.2		2.52	

Table 9: Comparison of change in compressive strength with increasing temperature

Rock	Eq. Constants		σ_c at 35°C	σ_c at 600°C	% Change (MPa) Full temp. range	Gradient/100°C (MPa)
	m	c				
Multi-Granite	– 0.0857	108.8	105.8105	57.39	45.8	8.57
Black Granite	– 0.0925	109.8	106.5725	54.31	49.0	9.25

Table 10

Rock	Eq. constants		r_r at 35°C	r_r at 600°C	% Change (g/cm^3) Full temp. range	Gradient/100°C (g/cm^3))
	m	c				
Density	-0.0002	2.7	2.644	2.531	4.3	0.020
Density	-0.0003	2.7	2.678	2.509	6.3	0.030

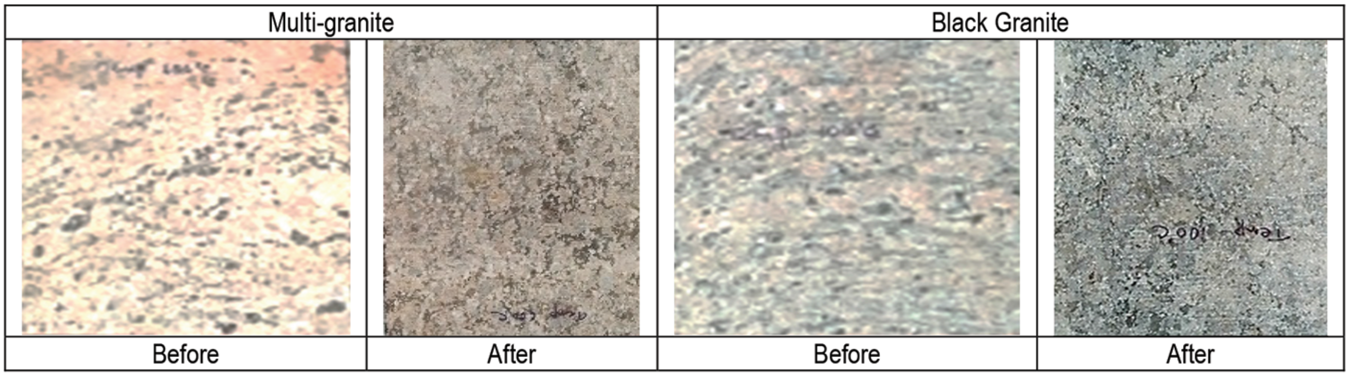

Fig.8: Color variation during heating process in multi-granite and black granite (100°C to 600°C)

Table 11: Regression equations for the two types of granites for density and compressive strength

Types of rocks	Properties	Regression equation
Multi granite	Density	ρ_r = –0.0002T+2.6512
		R^2 = 0.8974
	Compressive strength	σ_c = –0.0857T+108.81
		R^2 = 0.93
Black granite	Density	ρ_r = –0.0003T+2.6888
		R^2 = 0.7773
	Compressive strength	s_c = –0.0925T+109.81
		R^2 = 0.9468

ρ_r is density in g/cm^3, σ_c is compressive strength in MPa, T is temperature in °C

of granite the volume in initial stages decreases and then increases. The possible reasons for the mechanism is that the initial rearrangement of mineral grains and water loss results in decrease in volume followed by the expansion of mineral grain particle due to thermal effect resulting in the increase of volume at higher temperatures. After reaching the temperature 500°C the volume increase is significant. After 600°C temperature the volume increases at about 2.25% of initial volume.

It is observed that the mass of granite specimens decreases with increase of temperature. The mass decreases up to 400°C temperature due to diffusion of water particle in high temperature from the rock specimen. After 400°C temperature the rate decrease of mass is near constant up to 600°C temperature.

The colour variation of the specimens was also observed in this experiment. A change of colour occurs in the granite specimen after heat treatment process. It is observed that up to temperature 300°C the colour change is not remarkable. When temperature reaches up to 600°C the colour change takes place of the specimen shown in Fig. 8. The multi granite specimen becomes reddish and the black granite specimen becomes gray type after high temperature treatment.

4.0 Summary and conclusions

Keeping in view the importance of temperature effects on the physical properties of granites, a comprehensive analysis of significant samples of two types of granites from India was taken up in this study. The objective of the study was to log and augment the existing know-how on the impact of high temperatures on granite that can be of use to the construction industry. The tests for compressive strength and density with increase in temperature from 35°C to 600°C were devised and conducted. The results were compiled and analyzed statistically.

The regression analysis of the data conducted resulted in four equations for the four groups of the rocks as provided in Table 10.

It is evident from the analysis that there is a significant change in compressive strength while heating the samples up to 600°C, while as the change in density is mild. The conclusions can be summarized as below:

- In case of multi granite and black granite specimens, the compressive strength shows a decreasing and significant linear trend but the rate of decrease is greater in case of black granite above 300°C temperature in comparison with multi-granite. A reduction of 45% to 49% in strength from room temperature to 600°C in the two types of granites points to the loss of strength with increasing temperature and is of great engineering significance.
- The density also shows a decreasing trend in both the types of granites but the trend is more prominent in case of multi-granite. A change of 4.3% to 6.3% in density of the samples on heating, although considered to be mild, can have significant engineering implications.
- The overall volume decreases initially but increases after 300°C. The mass of the granites also shows decreasing trend with increasing temperature.
- The rearrangement of grains, loss of water content initially and increase in volume is considered to be one of the major reasons for reduction of the physical properties.
- A variation of colour in both the types of samples is also registered and needs to be further investigated.

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List of symbols

v_0	Volum of rock before heat treatment
v_1	Volume of rock after heat treatment
m_0	Mass of rock before heat treatment
m_1	Mass of rock after heat treatment
ρ_0	Density of rock before heat treatment
ρ_1	Density of rock after heat treatment
X	Independent variable
X_i	*i*th value of *X* variable
Y	Dependent variable
Y_i	*i*th value of Y variable
$\hat{Y}$	Estimated values
$\bar{X}$	Mean value of X
$\bar{Y}$	Mean value of Y
σ_x	Standard deviation of X variable
σ_y	Standard deviation of Y variable

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