Numerical Analysis of Thermo-Mechanical Characterization of Indian Sandstone under Dynamic Compressive Loading Condition

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ABSTRACT: It is quite impractical to ascertain the in-situ mechanical behavior of rocks subjected to high temperature and high confining pressure under dynamic loading conditions. Hence, the present study aims to numerically determine the thermo-mechanical properties of Kota sandstone rock under dynamic compressive loading conditions using a split Hopkinson pressure bar (SHPB) device. Thereafter, a numerical model is developed similar to the experimental setup used for the dynamic characterization of Kota sandstone using a commercially available finite element (FE) software package, ABAQUS. The specimen size of Kota sandstone was modeled with a 54 mm diameter and 0.5 slenderness ratio as taken by Mishra et al. (2019). A thermally sensitive strain rate-dependent constitutive model is adopted to validate the numerical parameters with experimental results tested at room temperature. The effect of the temperature and loading rate on the mechanical behavior of the Kota sandstone rock is studied numerically and stated herein.

Keywords: Dynamic Loading, Finite Element, SHPB, Strain Rate Dependent, Temperature, Drucker-Prager.

1 INTRODUCTION

Molten lava under the earth's crust and its time-to-time eruption as volcanoes signify the presence of higher temperatures deep inside the earth's surface. These volcanic eruptions may also result in the movement of tectonic plates causing various natural hazards such as tsunamis and earthquakes to name a few. Therefore, it becomes highly crucial to study the effect of dynamic loads on underground structures, the result of which may be sensitive to surroundings such as nuclear repository sites emitting constant temperature.

The laboratory characterization of rocks was done to determine the in-situ behavior of rock. Uniaxial and triaxial compressive loading on rocks have been widely done by researchers under static and dynamic loading conditions. Triaxial testing was performed on six different types of rock by Brace & Martin (1968). It was found that the degree of damage increases with loading rate increases. Christensen et al. (1972) studied the effect of dynamic loading on the stress-strain and failure characteristics of nugget sandstone at strain rates from 10^2/s to 10^3/s and confining pressures to 30 ksi. It was found that all rocks tested exhibit an increase in strength with an increase in the loading rate. Grady & Kip (1980) stated that the rock can get damaged in three patterns, i.e., the tensional pattern, the shear pattern, and the mixed pattern.

However, the temperature dependent mechanical properties of rocks under dynamic loading condition is sparsely available in the literature. Nasseri et al. (2007) observed that after heat treatment of Westerly granite of up to 850 °C, the number and average opening distance of micro-cracks increases. Ming et al. (2014) observed that for coal-serial sandstone, there is a gradual increase in both elastic modulus and peak stress values with increase in the strain rate. Whereas the strain at peak stress for coal-serial sandstone initially decreases and then increases in the form of a quadratic function. Huang & Xia (2015) investigated the effects of heat treatment of up to 600ºC on the dynamic compressive strength of Longyou sandstone. Their results showed that the uniaxial compressive strength of Longyou sandstone increases with an increase in loading rate for a given heat treated temperature. At the same time, the uniaxial compressive strength of Longyou sandstone also decreases with increase in temperature except for 450ºC. Liu & Xu (2015) studied the dynamic compressive tests of sandstone at seven different temperatures ranging from room temperature to 1000°C and at five different impact velocities ranging from 11.0–15.0 m/s. The results show enhancement effects of strain rates on dynamic compressive strength, peak strain, and energy absorption ratio of sandstone under high temperatures.

Hence, it is summarized from the literature that the strength of the rock increases with an increase in the loading rate. However, with increase in the temperature of rock specimen, the strength of the rock decreases at a particular loading rate. There prevails limited research on thermo-mechanical properties of rock under dynamic loading conditions. It is also studied from the literature that there exist no well proven constitutive relations to determine the failure behavior of rock under thermal and dynamic loading effects. The dynamic process on rocks is always associated with a rise in temperature and pressure. However, the effect of temperature on rocks in conjunction with loading rate has seldom been studied in the literature. So, the objective of the present study is to perform thermo-mechanical finite element analysis of split Hopkinson pressure bar testing on sandstone rock using thermal and strain rate sensitive Drucker Prager constitutive model available in ABAQUS. First, the loading rate is varied systematically keeping temperature constant and then the temperature is varied systematically with constant loading rate to study the effect of temperature and loading rate on the stress-strain response of sandstone rock.

2 MATERIALS AND METHODS

2.1 Constitutive Model

The strain rate-dependent constitutive relations have been effectively defined using Drucker Prager model in ABAQUS Finite Element (FE) software for brittle materials like rocks and concrete under dynamic loading conditions. This non- linear model incorporates all the three stress invariants and allows for a yield surface to grow in the deviatoric plane that may not be circular. This is necessary to account for varying yield values under triaxial tension and compression, inelastic flow in the deviatoric plane, as well as distinct dilation and friction angles. The yield criterion of linear Drucker Prager model is written as

$$F = t - p \tan \beta - d = 0 \qquad (1)$$

where, β is the slope of the linear yield surface in the *p-t* stress plane, *d* is the cohesion of the material, *p* is the equivalent pressure stress, *q* is the von Mises equivalent stress, r is the third invariant of deviatoric stress, *K* is the ratio of the yield stress in triaxial tension to the yield stress in triaxial compression. When $K = 1$, $t = q$, which implies that the yield surface is the von Mises circle in the deviatoric principal stress plane, i.e., the Π-plane, in which case the yield stresses in triaxial tension and compression are the same. To ensure that the yield surface remains convex requires, $0.778 \leq K \leq 1.0$.

$$t = \frac{1}{2}q\left[1 + \frac{1}{K} - \left(1 - \frac{1}{K}\right)\left(\frac{r}{q}\right)^3\right] \quad (2)$$

2.2 Validation Study

The experimental data for the thermo-mechanical characterization of Kota sandstone rock was taken from Mishra et al. (2019). Mishra et al. (2019) have presented the stress-strain response of Kota sandstone under dynamic compressive loading conditions using SHPB device. A three-dimensional finite element model similar to Mishra et al. (2019) was developed using ABAQUS. A strain rate dependent non-linear constitutive model was used to capture the stress-strain behavior of sandstone rock with 25ºC as room temperature and 11.76 m/s as the striker bar velocity. The numerical result was validated with the experimental data of Mishra et al. (2019) and is shown in Figure 1.

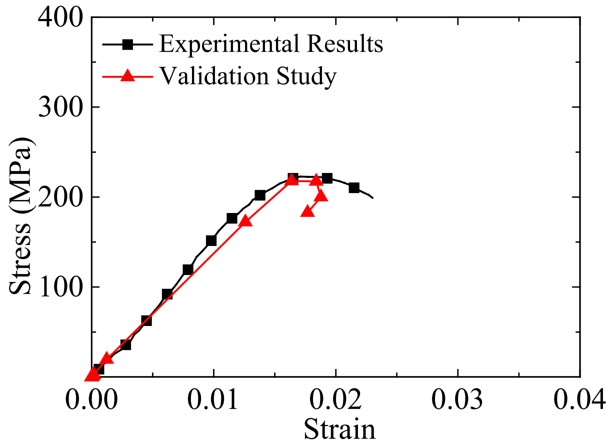

Figure 1. Validation graph of numerical model with experimental data of SHPB test (Mishra et al. 2019).

3 RESULTS AND DISCUSSION

The finite element used for validation study was used to study the effect of loading rate under constant temperature and effect of temperature at constant loading rate. The Drucker Prager model is used for assigning the properties to the specimen in the numerical model. The model parameters used for the numerical simulation are presented herein in Table 1.

Table 1. Input parameters for Drucker-Prager model.

ρ, kg/m^3	*E*, GPa	ν	ϕ, degree	*K*	ψ, degree
2339	15.12	0.12	35	0.778	4.38

Note: ρ = density; *E* = Young's modulus; ν = Poisson's ratio; ϕ = Angle of internal friction; *K* = Flow stress ratio; ψ = Dilation angle

The stress-strain responses obtained from numerical simulation with varying striking velocities at a constant room temperature of 25ºC under the dynamic compressive loading are shown in Figure 2. It is observed that the peak stress and strain values increase with increasing velocities of the striker bar and is shown in Figure 3. However, the elastic modulus remains constant as it is not varied as an input parameter with striking velocities. It is quite crucial to note that the increase in peak stresses and peak strains is not linear with the increase in the striking velocities.

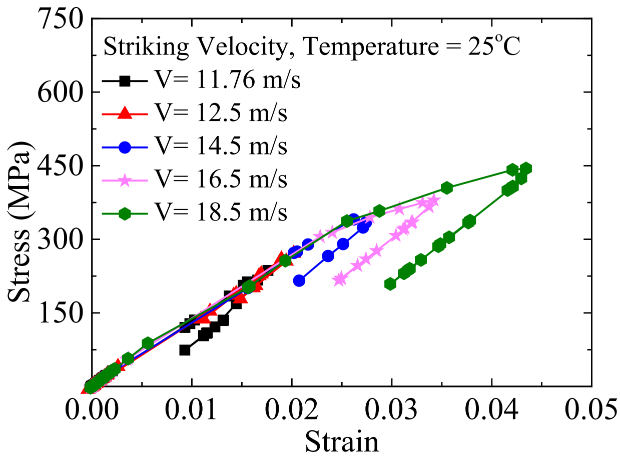

Figure 2. Stress vs strain graph at constant temperature of 25°C and varying striker velocity.

The peak stress increases by 14.72% for an increase in striking velocity from 11.76 m/s to 12.5 m/s with an increase in strain of 14.65%. Similarly, the increase in peak stress values from 12.5 m/s to 14.5 m/s, 14.5 m/s to 16.5 m/s and 16.5 m/s to 18.5 m/s striking velocities are by 25.54%, 11.52% and 16.97%, respectively and peak strain values are 22.88%, 30.67% and 26.95%, respectively.

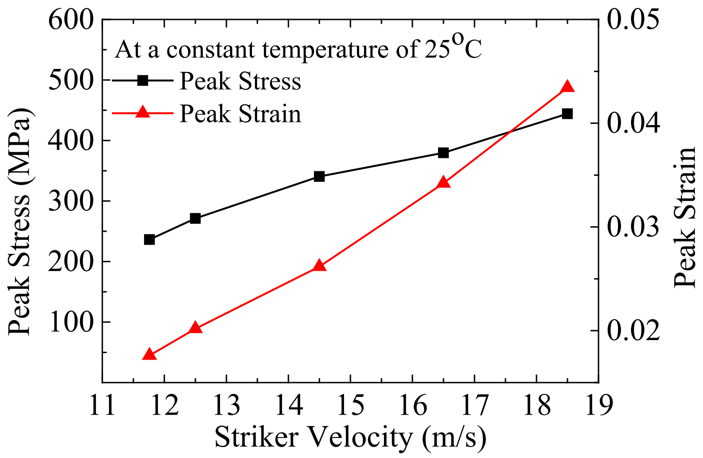

Figure 3. Effect of peak stress and peak strain values with increase in striking velocities at constant temperature of specimen at 25°C.

Now, the effect of temperature was studied on the stress-strain response of sandstone rock under varying loading rate of 11.76 m/s. The stress-strain responses obtained from numerical simulation with varying temperature and at constant loading rate is shown in Figure 4. It is seen that the peak stresses and peak strain values decrease with increasing velocities of the striker bar and is shown in Figure 5. However, similar to varying loading rate with constant temperature, the elastic modulus is constant with increase in temperature as it is not varied over the simulations.

It is worth noting that the percentage decrease in peak stress and peak strain values with varying temperature from 25 degree Celsius to 100 degrees Celsius is 1.04% and 3.47%, respectively. Similar to that, the percentage decrease in peak stress values with increase in temperature from 100-200 degree Celsius and 200-400 degree Celsius are 14.89% and 7.15%, respectively and peak strain values are 6.94% and 7.29%, respectively.

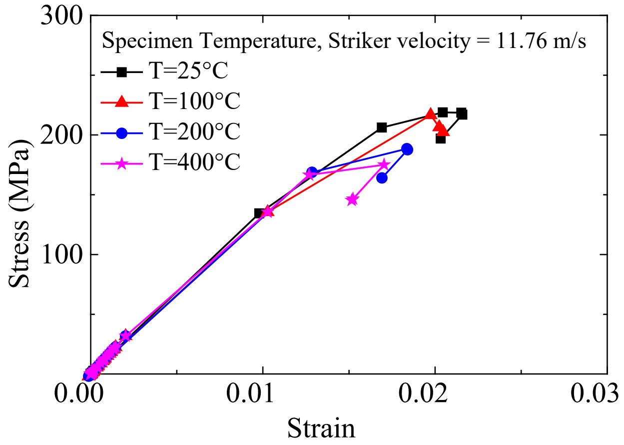

Figure 4. Stress vs strain graph at constant striker velocity of 11.76 m/s and varying specimen temperature.

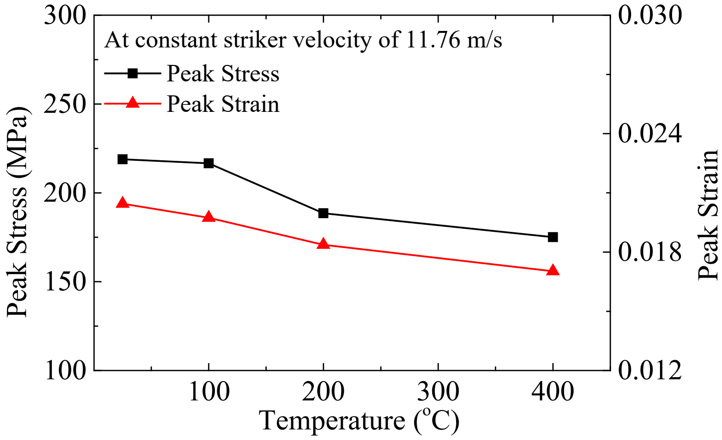

Figure 5. Effect of peak stress and strain with varying temperature and at constant striker bar velocity of 11.76 m/s.

Hence the finite element analysis shows that for constant striker velocity of 11.76 m/s, the sample at 25°C has the highest strength, while the sample at 400°C has the lowest strength as seen in Figure 5. The decrease in strength at 400°C can be explained by the formation of voids & thermal stress induced by micro-cracks (Huang & Xia 2015).

4 CONCLUSION

In this present work, the finite element model of split Hopkinson pressure bar (SHPB) system was used to investigate the thermo-mechanical properties of Indian sandstone. The SHPB test was validated at room temperature of 25ºC and striker velocity of 11.76 m/s with Mishra et al. 2019 on sandstone rock. In the first stage, the velocity of the striker bar was varied (11.76 m/s, 12.5 m/s, 14.5 m/s, 16.5 m/s, 18.5 m/s), keeping the temperature of the specimen constant at 25ºC. In the second stage, the temperature of the specimen was varied (25°C, 100°C, 200°C & 400°C), keeping the velocity of the striker bar constant at 11.76 m/s.

It is concluded from the numerical analysis that the peak stress and peak strain values were observed to increase with the increasing striker bar velocity at a given heat-treatment temperature of 25ºC and decreases with the increase in temperature at a constant striker bar velocity of 11.76 m/s. The results indicate that the heat-treatment of sandstone rock significantly affects the dynamic compressive strength of rock. The peak strength is found to be sensitive to the velocity given to the striker bar. The FE simulation for the SHPB test with Drucker-Prager model was able to capture the loading rate and temperature dependent numerical analysis data. Hence, the test results in this work will be a useful tool to comprehend the thermo-mechanical characteristics of rock.

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