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Dynamic Brazilian Split Tests on Gypsum as a Model Material for Soft Rocks

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Abstract. Understanding the deformation behaviour of rocks under dynamic loads is crucial in rock mechanics. This study investigates the rate-dependent tensile strength and fracture response of gypsum, a model material for soft rocks, across two different sample porosities. Quasi-static Brazilian disc tests were conducted using a servo-controlled universal testing machine, revealing that tensile strength decreases with increasing porosity. However, in the quasi-static regime, strength remains relatively constant across different strain rates. Dynamic tests were performed using a Split Hopkinson Pressure Bar (SHPB) setup, showing that dynamic tensile strength is consistently higher than quasi-static strength, regardless of porosity. Furthermore, as the dynamic strain rate increases, strength values further rise, indicating a strong rate dependency. Also, due to gypsum's brittle nature and low tensile strength, fracture resulted in significant powder formation. To capture real-time fracture evolution, high-speed imaging was employed. Full-field strain distribution and fracture evolution has been studied using Digital Image Correlation (DIC). The findings demonstrate a strong correlation between porosity, tensile strength, and fracture behaviour, offering valuable insights into the dynamic response of soft rocks.

1 Introduction

The expanding construction activities in mountainous regions have necessitated a deeper understanding of rock behaviour during various operations such as tunnelling, blasting, and drilling. These activities subject rocks to a broad spectrum of dynamic strain rates. The strain rate sensitivity of brittle materials, including rocks, significantly influences their compressive and tensile strength characteristics [1]. The dynamic tensile properties of rocks often differ significantly from their compressive behaviour under varying strain rate conditions [2]. Therefore, understanding and evaluating these tensile properties are crucial for characterizing the dynamic response of rocks. Various techniques are employed to study the dynamic behaviour of rocks, with the Split Hopkinson Pressure Bar (SHPB) being one of the most widely used methods. The dynamic strength of rocks is commonly expressed through the Dynamic Increase Factor (DIF), which quantifies the increase in strength under dynamic conditions compared to quasi-static conditions [3].

Previous studies have investigated the effect of strain rate on dynamic tensile strength of rocks. Gong and Zhao [4] conducted indirect tensile experiments on sandstone and found that its tensile strength increased with rising strain rates. Padmanabha et al. [2] conducted dynamic split tensile tests on various rock types, including basalt, granite, marble, and sandstone, and confirmed the strain rate dependency of these materials. In 1993, Dutta and Kim [5] performed tensile tests on limestone using the Brazilian method at strain rates of 80 to 100 /s with a specialized low-temperature Split Hopkinson Pressure Bar. They reported that tensile strength was more influenced by loading rate than by temperature. More recently, Tripathi et al. [6] investigated the tensile behaviour of thermally treated Barakar sandstone. Their study identified a critical temperature below which the tensile strength (both quasi-static and dynamic) increased due to water evaporation but decreased beyond this temperature.

While numerous studies have focused on the effect of strain rate on the dynamic behaviour of rocks, other influencing factors such as temperature, confining stress, and porosity also play a crucial role in determining their mechanical response and failure mechanisms. In this study, we systematically investigate the combined effects of strain rate and porosity on the tensile strength and failure behaviour of gypsum samples. Gypsum is a widely used model material for soft rocks known for its homogeneity, isotropy, and ease of fabrication properties [7]. Samples with two distinct porosities (50.1% and 56.7%) are tested over a wide range of strain rates, from quasi-static to dynamic regimes. Additionally, we analyse the Tensile Dynamic Increase Factor (TDIF) to quantify the rate-dependent strengthening effect. Digital Image Correlation (DIC) is employed to capture full-field strain evolution and crack propagation, providing further insights into the deformation mechanisms.

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2 Methodology

The gypsum samples used in this study were prepared by mixing calcium sulphate hemihydrate (commonly known as Plaster of Paris or POP) with distilled water. When water is added to POP ($CaSO_4.\frac{1}{2}H_2O$), a hydration reaction occurs, resulting in the formation of gypsum ($CaSO_4.2H_2O$).To obtain samples with two different porosities, distilled water was added in specific proportions by weight of POP. The porosity of each sample was determined based on the relationship between the dry density and void ratio.

All the prepared samples have a length to diameter ratio of 0.5:1 for both static and dynamic tests, with corresponding diameters shown in Fig. 1. These samples are referred to as Brazilian disc samples, named after the Brazilian split test – a standard method for indirect tensile testing in rock like materials [8].

The experimental setup consists of a servo hydraulic universal testing machine (UTM) with a load capacity of 100kN for static testing, and a split Hopkinson pressure bar (SHPB) for dynamic testing. In the quasi-static region, tests have been performed over varied deformation rates to obtain strain rates of order 10^{-4}/s to 10^{0}/s. In general, three samples have been tested per strain rate, per porosity. In the dynamic case, tests are conducted at various velocities of the striker bar to achieve strain rates of order 10^{1}/s to 10^{2}/s. A high speed camera has been used to capture the failure of speckled samples under dynamic loadings at a frame rate of 160000 fps. Speckling is a technique where a random pattern of black dots is applied to the surface of the sample to enable accurate tracking of deformation using a high-speed camera during Digital Image Correlation (DIC).

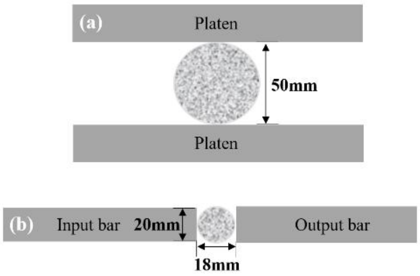

Fig. 1. Schematic diagram of Brazilian split samples in (a) UTM and (b) SHPB

In quasi-static region, the peak load at failure is used to determine the indirect tensile strength of gypsum (σ_s) using Eq. 1. In the dynamic region, the indirect tensile strength (σ_d) is determined using Eq.2 [6].

$$\sigma_s = 2P/\pi DT \quad (1)$$

$$\sigma_d = (E_b D_b^2/2L_o D_s)\mathcal{E}_t{}^{max} \quad (2)$$

where P is breaking load, D and t is the diameter and thickness of the static Brazilian disc sample, E_b is Young's modulus of bar, D_b is the diameter of bar, D_s and L_o is diameter and thickness of dynamic Brazilian disc sample, and $\mathcal{E}_t{}^{max}$ is the maximum strain measured in transmitted bar.

3 Results and Discussion

This section studies the strain-rate dependent tensile behaviour of gypsum samples with two different porosities, over a wide range of strain rates from quasi-static to dynamic region.

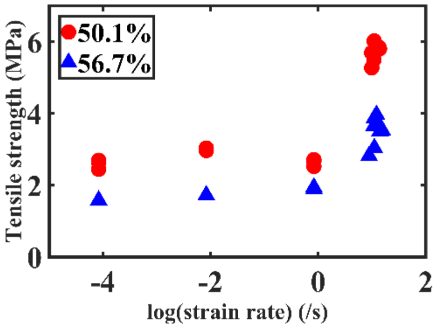

Fig. 2. Impact of porosity and strain rate on Brazilian tensile strength

Figure 2 illustrates the variation of tensile strength with strain rate (on a logarithmic scale) for gypsum samples with porosities of 50.1% and 56.7%. As expected, higher porosity samples exhibit lower tensile strength across all strain rates. In the quasi-static regime (strain rates below 10^{0} /s), the tensile strength remains nearly constant for both porosities, indicating minimal strain rate sensitivity at lower loading rates. However, in the dynamic regime, a significant increase in tensile strength is observed. For the 50.1% porosity sample, the strength increases from an average of 3 MPa to approximately 6 MPa, while for the 56.7% porosity sample, it rises from 1.5 MPa to nearly 4 MPa. This strength enhancement at high strain rates is attributed to strain rate-dependent hardening mechanisms, stress wave interactions, and delayed crack initiation under rapid loading conditions.

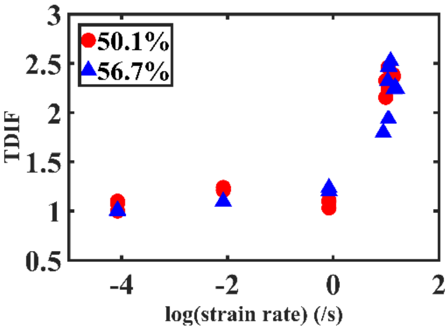

Fig. 3. Impact of porosity and strain rate on TDIF

Figure 3 shows the variation of the Tensile Dynamic Increase Factor (TDIF) with strain rate for gypsum samples with 50.1% and 56.7% porosity. TDIF is obtained by taking a ratio of the dynamic tensile strength to the quasi-static tensile strength. Below 10^{0} s^{-1}, TDIF remains close to 1, indicating negligible strain rate effects. In the dynamic regime, TDIF increases up to ~2.5, reflecting strain rate-dependent strengthening. However, the effect of porosity on TDIF is minimal.

Since TDIF measures the relative strength enhancement rather than absolute strength, the underlying strengthening mechanisms—such as inertial resistance, thermo-activated mechanisms, and viscosity effects—remain similar across different porosities [9]. Therefore, despite the absolute strength being lower for higher porosity samples, their dynamic strengthening follows a comparable trend to lower porosity samples.

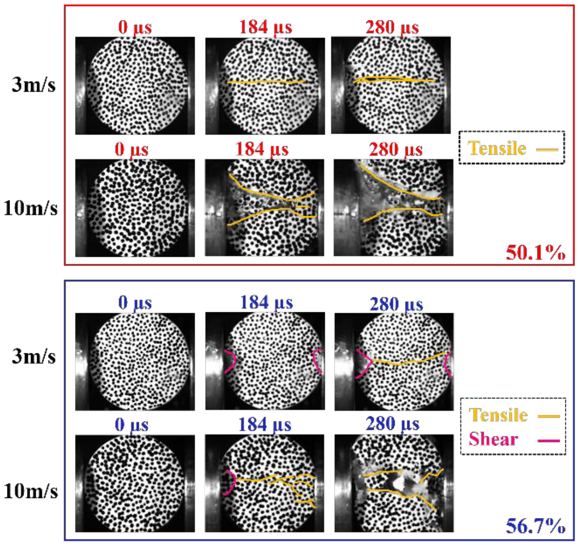

Fig. 4. Failure pattern of 50.1% and 56.7% porosity samples at 3m/s and 10m/s impact velocity

Figure 4 illustrates the influence of porosity and impact velocity on the failure behavior of gypsum samples under dynamic loading. For 50.1% porosity at lower impact velocity of 3 m/s, the failure pattern is dominated by a central tensile crack typical of brittle behavior. In contrast, the 56.7% porosity sample at the same velocity exhibits initial shear deformation near the loading points, followed by a tensile crack. Similar behaviour has been observed for both the porosities at higher impact velocity of 10m/s. However, higher fragmentation is observed, indicating a transition from controlled crack growth to dynamic fragmentation.

To further understand the failure mechanisms, the vertical displacement (**v**) values obtained from DIC analysis are examined. These values represent relative motion in the vertical direction—positive *v*-values indicate downward displacement, while negative values indicate upward displacement. The steep displacement gradients between these zones reflect the internal stress distribution within the sample, which ultimately governs the initiation and propagation of cracks.

Figure 5 presents the DIC analysis for gypsum samples with 50.1% and 56.7% porosity subjected to impact velocities of 3 m/s and 10 m/s. All four cases share a common vertical displacement scale ranging from 42 μ to -126 μ using 1 pixel = 0.14 mm conversion. The images used for analysis are taken just before the formation of a central tensile crack—at 165 μs (50.1% at 3 m/s), 116 μs (50.1% at 10 m/s), 275 μs (56.7% at 3 m/s), and 169 μs (56.7% at 10 m/s). The earlier crack initiation at higher velocities highlights the rate-sensitive nature of failure, while the delayed response in higher porosity samples can be attributed to the initial formation of shear zones at the ends before the onset of central tensile cracking as was observed in Fig. 4. At higher velocities, both samples exhibit extreme displacement values, indicating intensified vertical motion and pronounced strain localization near the central tensile crack. In contrast, lower velocity tests show smoother, more distributed displacement fields.

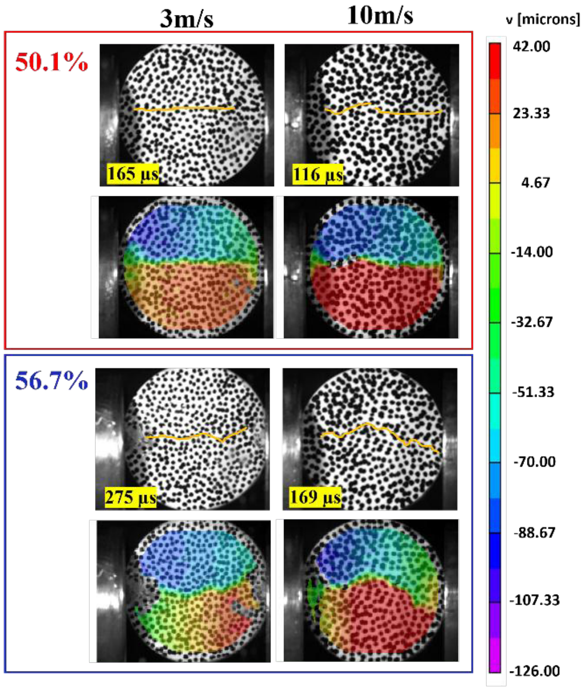

Fig. 5. DIC analysis showing vertical displacement values for 50.1% and 56.7% porosity samples at 3m/s and 10m/s impact velocity

In summary, the results demonstrate that lower porosity samples (50.1%) exhibit a stronger response in terms of higher tensile strength and more distinct central tensile failure, and higher velocities amplify these deformations, as captured by the **v**-values in DIC analysis. These observations underscore the combined influence of material porosity and loading conditions on the failure behavior of gypsum samples.

Conclusions

This study investigates the dynamic tensile behaviour of gypsum at different porosities and strain rates. The main conclusions from the study are:

- Higher porosity results in lower tensile strength at all strain rates. Despite this, dynamic strengthening behaviour is similar for both porosities. The strain rate has a more significant impact than porosity on tensile strength.
- Tensile strength increases significantly in the dynamic regime for both porosities. The TDIF rises from 1 at quasi-static rates to about 2.5 at high strain rates. This indicates clear strain rate sensitivity in gypsum.

- Considering the two samples presented, no significant impact of porosity on TDIF is observed, despite the failure pattern being primarily governed by porosity.
- Lower porosity samples primarily fail through the formation of central tensile crack, while higher porosity samples first develop shear zones, followed by tensile crack formation.
- DIC analysis shows that higher velocities result in more extreme displacement and sharper strain localization, accelerating crack initiation. In contrast, lower velocity tests show smoother, more distributed displacement fields.

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Data will be made available on reasonable request.
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