Effect of water saturation and loading rate on the mechanical properties of Red and Buff Sandstones

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\textbf{1. Introduction}

A number of different parameters influence the mechanical behavior of geomaterials, and understanding the mechanical behavior of geomaterials is important for not only academic research but also various industrial applications.\textsuperscript{1} As typical geomaterials are heterogeneous in pore size and are hydrated to various degrees in nature, understanding the fracture behavior of geomaterials of different porosities and water contents under different loading conditions is crucial to understanding the role that geomaterial characteristics play in fracturing processes.\textsuperscript{2–4} For example, it is important to know how the porosities and water contents of geomaterials influence how much energy is needed to disrupt them. In addition, as the rate of loading has a significant effect on rock fragmentation processes, including drilling, blasting, hydraulic fracturing, crushing, and grinding, and on failure modes, including rock bursting, impact failure, and others,\textsuperscript{5} information about the mechanical properties and behaviors of geomaterials at different loading rates can significantly affect the safety of underground construction, the optimum energy cost, the productivity of excavation and energy extraction, and the design of impact-resistant engineered infrastructures and constructions.\textsuperscript{6–9} In the oil and gas industry, the main task of reservoir engineers is to increase the productivity of wells. Induced hydraulic fracturing is a technique that is typically used to generate fractures in rock reservoirs. At the beginning of this process, a device known as a perforating gun is lowered into a well to a designated location in the reservoir rock, and a charge is fired to perforate the steel casing, cement, and rock formation. This perforation stage creates small cracks or fractures in the rock. A mixture of water, sand, and chemicals is then injected into the wellbore under high pressure to keep the fractures open. In all steps of this process, knowledge of the effects of porosity and water content on the dynamic behavior of the reservoir rock may be useful in predicting the geomaterial properties and behaviors.

For many years, many researchers have studied the mechanical behavior of various types of geomaterials under different conditions. While a considerable amount of work has been done on the effect of porosity on the dynamic fracture mechanics of metals, composites, and ceramics,\textsuperscript{10} only a very limited amount of work has been done on geomaterials with different porosities under dynamic loading conditions.\textsuperscript{11,12} As many engineers and scientists studying rock mechanics thought that the force applied on a rock breaks a rock sample with the similar mechanism in static and dynamic loading conditions, many tests have been performed under static loading conditions. However, some researchers reported that there were significantly different rock failure mechanisms between static and dynamic loading tests.\textsuperscript{13–16} Additionally, sometimes it is not easy to obtain relevant rock samples having similar mineral compositions with remarkably different...
porosities essential to get accurate rock porosity effect on mechanical properties and behaviors.

In this study, to fill in some of the gaps that exist in knowledge of the effects of porosity and water content on the mechanical strength of geomaterials, we examined and compared the compressive strength, tensile strength, and Young’s modulus of dry and saturated Red and Buff sandstones under static, fast, and dynamic loading conditions. Our results provide insights into how the mechanical behaviors and properties of geomaterials are affected by the water content and loading rate.

2. Materials and methods

2.1. Sample preparation

Red (smaller grain size, 4.7–5.5% porosity) and Buff (larger grain size, 18.0–22.7% porosity) sandstone samples with L (length)/D (diameter) ratio of ~0.4 were prepared for tensile tests and with L/D ratio of ~2 for compressive tests using coring, cutting and grinding machines. The Red and Buff sandstone samples were soaked in water for 48 h in a vacuum chamber (25 cm Hg). Half of the fully saturated samples were placed in a dry oven at 105 °C for 48 h to prepare dry sandstone samples.

2.2. Porosity measurements

To estimate porosity, thin section analyses of Red and Buff sandstone samples were performed by TerraTek (Fig. 1). The sandstone samples were impregnated with a low-viscosity fluorescent red-dye epoxy resin under a vacuum to highlight the porosity, mounted on standard (24 mm × 46 mm) thin section slides, and ground to a 30-μm thickness. The thin-sectioned samples were stained with a mixture of potassium ferricyanide and Alizarin Red and digitally imaged under plane- and cross-polarized light using a Nikon polarizing binocular microscope equipped with a Spot Insight digital camera. Void areas stained with pink color were regarded as pore spaces and used to evaluate the porosity of the Red and Buff sandstone samples.

In addition, the porosities of Red and Buff sandstones were estimated with the weight difference between the dry and saturated samples (Table 1). The porosity of rock is the ratio of the porous volume of the rock occupied by air and water divided by the total volume, expressed as follows:

\[ P = \frac{(V_w + V_a)}{(V_w + V_a + V_s)} \]

Table 1: Porosities of Red and Buff sandstones estimated from weight differences between dry and fully saturated samples and the 300-point count method using magenta epoxy-stained samples.

<table>
<thead>
<tr>
<th>Type</th>
<th>Porosity estimated from weight difference (n=40)</th>
<th>Porosity estimated from 300-point count method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red sandstone</td>
<td>5.5% (± 0.03)</td>
<td>4.7%</td>
</tr>
<tr>
<td>Buff sandstone</td>
<td>22.7% (± 0.04)</td>
<td>18.0%</td>
</tr>
</tbody>
</table>

\[ \rho = \frac{nV_p^2(3V_s^2 - 4V_p^2)}{2V_s^3} \]  

\[ K = \frac{nV_p^2 - 4V_p^3}{3} \]

2.3. P and S wave velocity measurements

To estimate Young’s modulus, the longitudinal (P wave) and transverse (S wave) wave velocities of Red and Buff sandstone samples were measured. P and S wave velocities are intrinsic properties of solid materials. The ultrasonic pulse velocity technique was used to measure the P and S wave velocities of the rock samples. A frequency of 1.0 MHz was used to measure the P and S wave velocities of cylindrical rock samples with 3.175-cm and 5.46-cm diameters and L/D ratio of 2.0. All samples used in this study were prepared in accordance with ASTM D2845. The distance between the two transducers, the sample’s length divided by the delay or arrival time, measured by an ultrasonic machine, gave the corresponding wave velocity in the geomaterial specimens. The P and S wave values and calculated dynamic Young’s modulus obtained were shown in Table 2. The dynamic elastic properties of these types of sandstones (the dynamic Young’s modulus (E), bulk modulus (K), and shear modulus (G)) were calculated as a function of P wave velocity (\( V_p \)), the S wave velocity (\( V_s \)), and the rock density (\( \rho \)) using the following equations:

\[ E = \frac{nV_p^2(3V_s^2 - 4V_p^2)}{V_s^3} \]

\[ K = \frac{nV_p^2 - 4V_p^3}{3} \]

Fig. 1. The magenta epoxy was seen between framework grains: (A) cross-laminated Red sandstone and (B) cross-laminated Buff sandstone. Scale bars indicate 250 μm.
Table 2
P- and S-wave measurements of Red and Buff sandstones. The values in parentheses are the Standard Errors of the Means (SEM).

<table>
<thead>
<tr>
<th>Type</th>
<th>Sample size (Diameter, cm)</th>
<th>Number of samples</th>
<th>P-wave velocity (m/s)</th>
<th>S-wave velocity (m/s)</th>
<th>Calculated Young's modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red sandstone</td>
<td>3.175 (AX)</td>
<td>40</td>
<td>3977.0 (± 6.9)</td>
<td>2773.1 (± 7.2)</td>
<td>38.5 (± 1.1)</td>
</tr>
<tr>
<td></td>
<td>5.45 (NX)</td>
<td>20</td>
<td>3943.5 (± 9.7)</td>
<td>2757.3 (± 6.5)</td>
<td>37.9 (± 0.2)</td>
</tr>
<tr>
<td>Buff sandstone</td>
<td>3.175 (AX)</td>
<td>40</td>
<td>2100.3 (± 22.2)</td>
<td>1436.8 (± 12.4)</td>
<td>8.9 (± 0.2)</td>
</tr>
<tr>
<td></td>
<td>5.45 (NX)</td>
<td>20</td>
<td>2052.4 (± 27.7)</td>
<td>1468.8 (± 18.4)</td>
<td>8.6 (± 2.3)</td>
</tr>
</tbody>
</table>

Fig. 2. Schematic illustration of Split Hopkinson Pressure Bar system.

\[ G = \rho V_i^2 \]  

(4)

2.4. Static and fast loading compressive tests

Static compressive strength was measured by applying a uniaxial load to a cylindrical specimen under standard conditions. Sandstone specimens with two different diameters, AX and NX, were prepared with length-to-diameter ratios of 2:1, in accordance with ASTM standards. The sample diameter, as suggested in the standard, was selected to be more than ten times the maximum grain size. Small-diameter specimens were used to compare the corresponding static compressive strength with dynamic strength of a similar L/D ratio. After coring samples from rock blocks, each core was cut perpendicular to its axis at approximately a 2:1 L/D ratio, and the sample ends were then ground until they were parallel, in accordance with ASTM D7012. All static unconfined strength measurements were performed using a load frame equipped with an MTS Teststar IIM control system and Multipurpose Testware. For unconfined compressive strength (UCS) samples, the assigned loading rate fell within acceptable limits (0.5–1 MPa s⁻¹ or slightly less). With regard to the specific process employed for UCS testing of rock samples, this control system updated all transducer values at the system rate of 4096 Hz, and the axial force and displacement were added to the data file at 2-s intervals. A failure detector was programmed for use in the testing process. The maximum force transducer value was updated with a new maximum value for every increment of 113.4 kg (250 lb), and then the maximum force was recorded to an output file along with the 2-s data stream. Fast loading compressive tests were performed under the same experimental conditions as the static compressive tests, except for the loading rate. The loading rate for the fast compressive tests was ~200–250 kN s⁻¹ whereas the rate for the static compressive tests was 1.3 kN s⁻¹.

2.5. Static loading indirect tensile tests

The indirect tensile strength of the rock samples was determined by the Brazilian method. In this method, the compressive load was applied to a disk-shaped sample. As tensile strength values can be affected by the geometry of rock specimen, to reduce the effects of these factors, disk specimens were prepared with thickness-to-diameter ratio of 0.3–1. The tensile strength of rock was calculated using the following equation:

\[ \sigma_i = \frac{2P}{\pi D t} \]  

(5)

where \( P \) is the maximum load at failure, \( D \) is the diameter of the specimen, and \( t \) is the height or thickness of the specimen. The loading rate used in the static tensile tests was ~0.06–0.08 kN s⁻¹.

2.6. Dynamic loading compression and indirect tensile tests using Split Hopkinson Pressure Bar (SHPB)

Dynamic compressive tests and indirect tensile tests of dry and water-saturated Red and Buff sandstone samples were performed with a Split Hopkinson Pressure Bar (SHPB) (Fig. 2) as described. The dimensions of the samples tested under dynamic loading were prepared with the same way used in the static compressive and tensile tests. Also, the stress calculation equations for dynamic loading tests were the same as the equations for static loading. To measure the dynamic compressive and tensile strengths of the samples, the wave transformations were recorded in a data acquisition system at a 10-MHz sampling rate. The striker velocity was measured with an oscilloscope and a laser module.

Young’s modulus has been used in evaluating rock deformation under various loading conditions, of which value can be determined with stress–strain ratios under uniaxial load. In the typical stress-strain curve for any sample, the modulus at the beginning of the loading cycle is low (due to crack closure and seating of the platens), and then, in the linear stress–strain part of the curve, the modulus becomes constant. Based on the stress–strain curves of rock samples, the Young’s modulus values of dry and saturated Red and Buff sandstone samples were calculated by linear interpolation along the linear portion of the curve.

3. Results and discussion

In this study, we examined the effects of porosity and hydration on the mechanical strength and behavior of Red and Buff sandstones, as these two sandstones exhibit relatively homogenous grain and pore sizes, which are relevant to their behavior in mechanical strength tests. To measure the porosities of the Red and Buff sandstones, we used two methods: measuring the weight difference between dry and hydrated samples and 300-point counting of thin-section samples stained with magenta epoxy. The porosity values of the Red and Buff sandstones estimated using the two methods were quite similar. The porosity of the Red sandstone was 5.5% as estimated from the weight difference measurement and 4.7% as estimated from the 300-point count measurement. The corresponding porosity estimates of the Buff sandstone were 22.7% and 18.0%, respectively (Table 1). These results indicate that the porosity of the Buff sandstone is much higher than that of the Red sandstone. The results also indicate that both the weight difference method and the 300-point count measurement method are reliable ways to estimate the porosity of sandstones.
sandstone, whereas under dynamic loading, the strength of the sandstone was approximately 2.6 greater than that of the Buff sandstone. Under static and fast compressive loading, the strength of the Red and Buff sandstones decreased with increasing loading rate. More interestingly, the differences in the compressive strengths of the Red sandstone were approximately 1.6 times greater than the Buff sandstone. This conclusion was based on the results of the compressive strength tests, the tensile strengths of both dry and saturated Red sandstone samples were approximately 3.5 fold higher than the Buff sandstone, and the tensile strengths of both dry and saturated Red sandstone samples were approximately 3.5 fold higher than the Buff sandstone. These results suggest that tensile strength is more sensitive to the porosity of geomaterials; the porosity of the Buff sandstone is higher than that of the Red sandstone (Fig. 3, Table 3). The underlying mechanism of the higher dynamic increase factor (DIF) with higher rock porosities is not fully understood to date, but the mechanism can be explained as follows. Not only the force applied to the rock is used to break the rock but also the force is absorbed by the rock. The absorbed energy is significantly higher in a dynamic loading than a static loading condition. In a static loading condition, the force predominantly goes through the weak points of the rock resulting in slow crack propagations whereas in a dynamic loading condition, the most force can go through the grains or solid parts of the sample along the shortest route as the applied force is typically greater than the grain strength, and less force passes through the weaker points of the sample. For this reason, more force is used to break solid grains instead of breaking the weak points of a sample in dynamic loading tests when compared with static loading tests. Thus, as more weak points exist in higher porosity samples than lower porosity rocks, more drastic increase of DIF (the ratio of dynamic strength to static strength) can be observed in higher porosity rocks. Our data are consistent with evidence from other studies that geomaterials with higher porosities display higher dynamic increase factors (DIFs). In addition, the DIFs calculated in this study were within the range of values reported by other researchers.9,13,21–23 This might be caused by various rock types having different mineral compositions, degrees of cementation, and grain sizes, among other mechanical and structural characteristics of geomaterials.

3.2. Tensile strength of Red and Buff sandstones

We also examined the static and dynamic tensile strengths of the Red and Buff sandstones under dry and saturated conditions to assess the effects of porosity and water content. Consistent with the results of the compressive strength tests, the tensile strengths of the Red and Buff sandstones were greater when dry, under both static and dynamic loading, than when saturated. Intriguingly, the tensile strengths of both dry and saturated Red sandstone samples were approximately 3.5 fold higher than the Buff sandstone samples (Fig. 4). These results suggest that tensile strength is more sensitive to the porosity of geomaterials, as the compressive strength of the Red sandstone was only 1.6–2.6 times higher than that of the Buff sandstone. More interestingly, a more dramatic effect of the loading rate was observed in the tensile tests of the Red and Buff sandstones than in the compressive tests. When the percentage differences between the compressive and tensile strengths measured under static and dynamic loading conditions...
were compared, the increase in tensile strength with increasing loading rate was found to be much greater for both the Red and Buff sandstones than the increase in compressive strength, regardless of the water contents (Fig. 5, Table 3). Our data suggest that more drastic DIFs can be obtained in tensile tests with increasing loading rate than in compressive tests, which provides some insight into how loading rates and different testing methods affect the mechanical behavior of geomaterials.

3.3. Young’s modulus estimated with ultrasonic wave measurements and compressive loading tests

The ultrasonic velocity test method is a nondestructive way to characterize geological core samples. This method involves propagating ultrasonic compression and shear waves along the longitudinal axis of a sample, measuring the velocity of the waves as they travel through the specimen, and calculating the dynamic elastic properties of the specimen including Young’s modulus (the elastic stiffness) (ASTM 2845). P- and S-wave velocity measurements were used to estimate the dynamic Young’s modulus of oven-dried specimens. We also calculated the dynamic Young’s modulus from the results of the SHPB tests (dynamic compressive tests) conducted on the same samples. As shown in Tables 2 and 4, the Young’s modulus values calculated from the SHPB results were 10–20 times higher than those estimated from the ultrasonic velocity test results. The Young’s modulus estimated from ultrasonic velocity tests was very close to the value of the Young’s modulus obtained from static and fast loading tests.24 In this study, especially for dry samples, the ratio for the high-porosity material (the Buff sandstone) was less than one, but that for the low-porosity material (the Red sandstone) was greater than one.

Also interestingly, Young’s modulus of the Red and Buff sandstones were higher for dry samples under static and fast compressive loading than for saturated samples. However, the Young’s modulus values under dynamic loading were not significantly different for the Red sandstone, regardless of the hydration conditions, whereas the Young’s modulus values of the Buff sandstone samples under dynamic loading were much higher (by approximately 71%) for dry conditions than for saturated conditions (Fig. 6). These results indicate that the hydration effect on Young’s modulus is enhanced by higher porosity under dynamic loading conditions. The underlying mechanism seems to be similar to that of more DIF increase in higher porosity rocks. In dynamic loading tests, it seems that most force passes through the shortest route of the sample, whereas in static loading tests most energy goes into breaking the weak points in the sample. When developing crack front meets the water, the water can slow down crack propagation. Thus, as more water exists in higher porosity rocks than in lower porosity rocks, water saturation effect on Young’s modulus is greater with higher porosity under dynamic loading conditions. In addition, these results suggest that Young’s modulus can be used as a parameter in assessing the effects of porosity and hydration on the dynamic mechanical behavior of geomaterials.

4. Conclusions

Various parameters can be used to characterize geomaterial fracture and strength, and measured mechanical properties of rocks can differ depending on how stresses are applied. The compressive and tensile strengths of Red and Buff sandstones under static, fast, and dynamic loading conditions were measured,
and the effects of porosity and hydration on these parameters were examined. The main findings of this study are as follows: (1) The Red sandstone exhibited compressive and tensile strengths two to four times higher than the Buff sandstone under static, fast, and dynamic loading conditions; (2) the compressive and tensile strengths of both sandstones increased with increasing loading rate, and the effect of the loading rate on the tensile strength was more pronounced than the effect on the compressive strength; (3) the static, fast, and dynamic strengths of dry samples were higher than those of saturated samples—on average, water saturation reduced the rock strength by approximately 20%; and (4) the Young's modulus determined from compressive loading test results was significantly greater for the Buff sandstone when dry than when saturated but the Young's modulus values of the Red sandstone when dry and when saturated were not significantly different. The results of this study provide insights into how the porosities and hydration states of geomaterials affect their mechanical properties and behavior at various loading rates. These insights can contribute significantly to improving safety and cost-effectiveness in geotechnical applications.

References