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Correlations between the physical and mechanical properties of sandstones with changes of water content and loading rates

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1. Introduction

Understanding the mechanical properties of rocks is crucial not only for academic research but also for various industrial applications.[1–7] Many physical properties (e.g., density, porosity, water content, mineral composition, inhomogeneities) of rocks can affect their mechanical properties.[8–12] Thus, understanding the correlations between the physical and mechanical properties of rocks is important for comprehending the rock mechanics, especially for industrial purposes.[13–15] However, most studies have been conducted under quasi-static conditions even though many rock mechanical applications and phenomena such as blasting, fracturing, drilling, mining, rock burst, and strong earthquakes are also related to dynamic loading conditions.[6,16] Thus, understanding the loading rate effect on rock mechanical properties will substantially impact the engineering processes of rocks for those applications and phenomena.[17] In addition, it is important to know how the water content of rocks affects their mechanical properties because the input energy used for rock disruption and fragmentation changes with its water content.

For many decades, the mechanical properties of rocks have been studied with various techniques. While many studies have been conducted on the effects of physical properties of metals, composites, and ceramics on their dynamic mechanical properties, not as many investigations have been reported on rocks and geomaterials that employed dynamic tests.[18,19] Thus, a comprehensive study is necessary to fill in some knowledge gaps concerning how changes in the physical properties of rocks affect their mechanical properties under different loading rates and water contents. This information would undoubtedly contribute to improving the safety of underground structures and the cost-effectiveness of excavation and energy extraction.[20–23]

In this study, three different dry and saturated sandstones (Red, Berea, and Buff) were tested under static and dynamic loading conditions. Red, Berea, and Buff sandstones containing small amounts of clay minerals (5.7–7.6%) primarily consist of quartz with ~ 5.6%, 16.0%, and 22.7% porosity, respectively (Tables 1, 2). Additionally, the bulk density values of these sandstones vary from 2.17 g cm^{-3} to 2.46 g cm^{-3} (Table 1). Thus, Red, Berea, and Buff sandstones are very useful rock materials to answer the question of how changes in the bulk density and porosity of rocks affect their mechanical properties under varying loading rates and water contents.

In this investigation, the static compressive, static tensile, dynamic compressive, and dynamic tensile strengths of the rock samples were measured with uniaxial compressive strength (UCS), splitting tensile strength (STS), and split Hopkinson pressure bar (SHPB) machines. The results demonstrated that the mechanical properties of sandstones were significantly correlated with their physical properties and that the equations obtained from these static and dynamic measurements can be used to predict how changes of density, porosity, and water content affect the mechanical properties of sandstones, contributing significantly to the improvement of the cost-effectiveness of mining processes and safety of geostructures.

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Table 1
Bulk density and porosity of Red, Berea, and Buff sandstones. The value in parentheses is the standard deviation ($26 \le n \le 70$).

Physical properties	Red	Berea	Buff
Bulk density (g cm^{-3})	2.46 (± 0.03)	2.18 (± 0.01)	2.17 (± 0.11)
Porosity (%)	5.55 (± 0.2)	16.03 (± 0.97)	22.66 (± 0.26)

2. Materials and methods

2.1. Sandstone sample preparation

Red, Berea, and Buff sandstone blocks were collected in Utah and Ohio (USA) and were kept in a relaxed condition at least one year prior to coring and testing. The sandstones were prepared with ~2 L/D ratio (length: ~ 115 mm, diameter: ~ 55 mm) for UCS tests, and ~ 0.4 L/D ratio (length: ~ 20 mm, diameter: ~ 55 mm) for compressive and tensile tests under static and dynamic loading rates. Each sandstone sample was soaked into water for 48 h inside a vacuum chamber (25 cm Hg, 1/3 standard atmospheric pressure) to quickly and fully remove air inside the rock samples, allowing water to fill the air removed pores of the samples as previously described.[20] Half of the fully hydrated samples were dehydrated in an oven at 105 °C for 48 h to prepare the dry samples.

2.2. Porosity assessment

The porosities of the Red, Berea and Buff sandstones were determined from the weight difference of the samples before and after water saturation (Table 1). The rock porosity can be expressed by the ratio of the porous volume of the rock filled with air and water divided by the total volume as follows:

$$P = \frac{(V_w + V_a)}{(V_w + V_a + V_s)} \quad (1)$$

where V_a is the volume of air, V_w is the volume of water, and V_s is the volume filled with solid material. The rock porosities were estimated by the water saturation method as described.[24] In brief, the rock samples were dried in an oven at 105 °C for 24 h. After cooling, each oven-dried sample was weighed, and then, the samples were soaked in distilled water under a vacuum of 25 cm Hg for 48 h. After blotting with a moist cloth, the water-saturated samples were weighed again. Based on the difference of the dry and water-saturated weights of each sample and the density of distilled water at room temperature (997 kg m^{-3}), the porosity values of sandstones were calculated.

2.3. Bulk density measurements

The bulk density values of Red, Berea, and Buff sandstones were determined according to ASTM D4543.[21,25] Diameter and length of the test samples were measured with a caliper. Cross sectional area perpendicular to the core axis was calculated with the diameter, and the volume was obtained by multiplying the cross-sectional area by the length. The bulk density (g cm^{-3}) was calculated by dividing the sample weight (g) by the sample volume (cm^{-3}).

2.4. Mineral and clay composition analysis with X-ray diffraction (XRD)

The mineral and clay compositions of Red, Berea, and Buff sandstones were analyzed with a Rigaku Ultima III Advance X-ray diffractometer from 2 to 36 degrees two-theta (2θ) using Cu K-alpha radiation. Micas greater than 4 µm in size were excluded from the clay separate, and micromicas less than 4 µm were listed as illite in the clay analysis. In addition, mixed layers of illite-smectite was listed as illite/smectite.

2.5. Static compressive and indirect tensile strength tests using a hydraulic loading frame

For the static compression tests, a uniaxial load was applied to a cylindrical sandstone sample under standard conditions. In this experiment, sandstone samples having a 2:1 ratio of a length-to-diameter (L/D) were prepared according to the standard ASTM protocol. To ensure that the surfaces of the cut ends of the samples were ends flat and parallel to each other, the surfaces were ground according to ASTM D7012.[26] Additionally, the diameters of sandstone samples were at least 10 times larger than the maximum grain size as recommended in ASTM D7012. All of the unconfined static strength measurements were conducted with a 1.3 kN s^{-1} loading rate using a load frame equipped with an MTS Teststar IIM control system and Multipurpose Testware. Young's modulus of the sandstone samples was determined with average modulus of linear portion of axial stress-strain curve as described in the Fig. 2(b) of ASTM D7012.

For the indirect tensile strength measurements, the sandstone samples were tested with a splitting tensile strength (STS) device with a ~0.06–0.08 kN s^{-1} loading rate. The disk-shaped specimens for this test were produced with a thickness-to-diameter ratio of 0.3–0.4. The splitting tensile tests were conducted according to ASTM D3967,[27] and the tensile strength values of the sandstones were calculated using:

$$\sigma_t = \frac{2P}{\pi D t} \quad (2)$$

where D is the sample diameter, P is the maximum load at failure, and t is the sample thickness sample as previously described.[6]

2.6. Dynamic loading compression and indirect tensile tests using the Split Hopkinson Pressure Bar

Dynamic compression and indirect tensile measurements for the Red, Berea, and Buff sandstones were conducted using a split Hopkinson pressure bar (SHPB). In brief, the SHPB apparatus primarily consists of two long steel rods (bars) with strain gages, a gas gun, a projectile (striker) and a data acquisition system (Fig. 1).[28,29] Following the impact, the rest of the energy was transmitted to the second rod (transmitted bar). The obtained data were recorded with a 10 MHz sampling rate using the data acquisition system as described.[28] Consistent with the static tests, the sandstone samples were prepared according to ASTM D7012. The dynamic compression and tensile strength

Table 2
Mineral and clay compositions of Red, Berea, and Buff sandstones by XRD (unit: %).

Sample	Non-clay									Clay					
	Quartz	K-feldspar	Plagioclase	Calcite	Ankerite/ Fe-dolomite	Dolomite	Pyrite	Fluorapatite	**Total non-clay**	Smectite	Illite/ Smectite (IS)	Illite + Mica	Kaolnite	Chlorite	**Total clay**
Red	83.3	8.3	0.0	0.2	0.0	0.0	0.7	0.0	**92.5**	0.0	4.6	2.8	0.0	0.0	**7.4**
Berea	86.7	2.5	4.1	0.2	0.7	0.0	0.0	0.0	**94.5**	0.0	2.3	0.9	0.9	1.6	**5.7**
Buff	57.7	6.5	20.8	2.2	1.3	2.1	0.0	1.4	**92.3**	0.0	1.4	4.7	0.7	0.8	**7.6**