Influence of water content on mechanical behavior of basalt in Baihetan Hydropower Station, China

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Abstract. Water content is a critical factor affecting rock strength in numerous geotechnical engineering applications. This study experimentally investigates the influence of water content on the mechanical behavior of basalt in the Baihetan Hydropower Station. Uniaxial compression tests were performed on basalt specimens at five moisture content levels. The strength evolution of shale and sandstone specimens with different water content levels were also analyzed through an extensive literature review. The results show that an increase in water content can exacerbate the initial damage to the basalt specimens, increasing the nonlinearity in the initial deformation stage of the stress-strain curve. As the water content increases, both uniaxial compressive strength and Young’s modulus gradually decrease, but Poisson’s ratio remains almost constant. Splitting failure is the dominant mode for all tested specimens. Because of the differences in pore structures and mineral compositions, the mechanism of water-weakening on the compressive strength of shale, sandstone, and basalt is different. The negative exponential function provides a good representation of the compressive strength versus water content of shale and sandstone, but unsuitable for describing that of basalt.

1. Introduction
The study of rock mechanical properties is an essential topic in the field of rock mechanics. So far, research has found numerous factors that significantly influence the mechanical behavior of rock, including internal factors, such as mineral composition, grain size, anisotropy, and porosity, and external factors, such as loading rate, temperature, and water content. In numerous geotechnical engineering applications, water-rock interaction permanently affects rocks, especially for rocks at dam foundation or hydropower station slopes. The presence of water can significantly weaken the rock strength [1–6]. Hence, a sufficient understanding of the effect of water-weakening on the mechanical behavior of rocks is critical for the design and stability of engineering applications.

Researchers have conducted extensive laboratory experiments investigating the effect of water-weakening on the mechanical behavior of rocks, especially for sedimentary rocks. Hawkins and McConnell [3] discussed the variations in uniaxial compressive strength (UCS) and Young’s modulus with increasing water content for 35 types of British sandstones. The results showed that the water content significantly weakened the strength of clay-rich sandstone, which was consistent with the conclusions summarized by Mann and Fatt [7]. Vánásárhelyi [8] established linear relationships between UCS and Young’s modulus (tangent and secant) for dry and saturated sandstones by
statistically interpreting the test data of Hawkins and McConnell [3]. Lin et al. [9] analyzed the mechanism of the water-weakening effect of sandstones microscopically. Intergranular fractures and the dissolution of chlorite significantly reduced the strength of sandstone specimens. Kim and Changani [10] compared the UCS, tensile strength, and Young’s modulus of two types of sandstones in dry and saturated states under static, fast, and dynamic loading conditions. They concluded that the strength of dry specimens was higher than that of saturated specimens irrespective of the loading rate. Numerous tests were also conducted on shale to study the relationship between mechanical behavior and water content [2, 11–14]. The reduction in shale strength was because of a combination of multiple factors, such as an increase in pore water pressure, a decrease in capillary tensile strength, a reduction in friction, and loss of the intergranular contact area [2, 11]. Furthermore, Jiang et al. [15] used the X-ray computerized tomographic scanning method to analyze the water-weakening mechanism of mudstone, highlighting that the volumetric swelling of clay minerals and dissolution of carbonate were the principal factors reducing the strength of rock specimens. Yilmaz [16] found that UCS and elastic modulus of gypsum were sensitive to water content, and even a 1%–2% increase in water content could cause a considerable loss in the strength of gypsum. The strength characteristics of igneous and metamorphic rocks also showed a decreasing trend with the increase in water content [17–19], but not to the same extent as sedimentary rocks [20–22]. Krokosky and Husak [23] concluded that under normal atmospheric conditions, stress corrosion caused by water evaporation decreased the strength of basalt specimens. Vánásárhelyi [24] measured various physical and mechanical parameters of three types of tuffs under dry and saturated conditions, and a linear or power relationship was found for UCS, Young’s modulus, impedance, and destructive work under both conditions. Chen et al. [25] studied the influence of water saturation on the degradation of welded tuff subjected to freeze-thaw action and observed a critical saturation of ~70%. When the saturation degree exceeded 70%, UCS, P-wave velocity, and porosity of rock specimens began to significantly decrease. Although extensive laboratory tests have been conducted to study the influence of water content on the mechanical behavior of rocks, most rocks studied were sedimentary rocks. There is a limited contribution to understanding the effect of water content on the strength properties of crystalline rock, which is the dominant rock type in numerous hydropower projects. For instance, basalt, a typical crystalline rock, is widely distributed at the dam foundation and slopes in the Baihetan Hydropower Station, which is the largest hydropower station under construction in the world. As the water level of the reservoir rises and falls, the weakening effect of water significantly influences the mechanical behavior of basalt. Consequently, knowledge of the variation of mechanical parameters of basalt possessing different water content is critical for assessing slope stability. This study experimentally investigates the effect of water content on the mechanical behavior of basalt in the Baihetan Hydropower Station. The stress-strain curves, UCS, Young’s modulus, Poisson’s ratio, and failure modes of rock specimens at different water contents are studied and analyzed. Moreover, the strength changes of shale, sandstone, and basalt with water content are compared and discussed by comparing the test data of this study with data collected from various publications.

2. Materials and methodology

2.1. Rock specimen characterization

The rock material used in this study is basalt mined from the dam foundation of the Baihetan Hydropower Station, Jinsha River, China. A massive intact basalt block with a rough dimension of 700 × 200 × 300 mm was collected on-site. The basalt block texture is uniform without visible defects and gray-green. According to the X-ray diffraction results, the rock is predominantly composed of plagioclase, pyroxene, magnetite, and basalt glass. All tested specimens were extracted from the same rock block to ensure the homogeneity of specimens. Cylindrical cores with a diameter of 50 mm were drilled out from the rock block. Following the recommendations of the International Society for Rock Mechanics (ISRM) [26], rock specimens with a height-to-diameter ratio of 2.0 were cut from the cylindrical cores, and the ends of all specimens were carefully ground and polished, ensuring a surface roughness less than 0.02 mm. Before water-treatment and mechanical tests, several rock specimens
were prepared for routine experiments. The physical and mechanical properties of rock specimens in the natural state were determined (Table 1). Another twelve rock specimens were prepared for subsequent testing.

**Table 1. Physical and strength properties of basalt block in a natural state**

| Property                  | Value  |
|---------------------------|--------|
| Density (g/cm³)            | 2.87   |
| Porosity (%)               | 2.85   |
| P-wave velocity (m/s)      | 4,243.15 |
| Young’s modulus (GPa)      | 55.42  |
| UCS (MPa)                  | 178.07 |
| Poisson ratio              | 0.20   |
| Water content (%)          | 0.12   |

2.2. Water content measurement
Following the ISRM recommended method [27], water content (w) is defined as

\[
\text{w} = \frac{M_w}{M_s} \times 100\% = \frac{M_{\text{sat}} - M_s}{M_s} \times 100\% ,
\]

where \(M_w\) is the pore water mass, \(M_s\) is the grain mass (a solid component of the specimen), and \(M_{\text{sat}}\) is the saturated surface dry mass.

This study examined five levels of water content (~0%, ~0.12% (natural state), ~0.17%, ~0.28%, and ~0.39%). Besides the natural state, the rock specimens were first subjected to an air-dry oven at 105°C for 24 h to remove moisture from the interior of the specimens (Figure 1a). The specimens were cooled naturally in the oven until they reached room temperature, after which the grain mass was obtained. One set of dry specimens was placed in the laboratory with excellent ventilation to maintain a dry state (the water content is ~0%) for subsequent tests. The other three sets of rock specimens were immersed in water under vacuum pressure of 0.1 MPa for 24 h to reach a saturated state (Figure 1b). After surface drying, the specimens were weighted to determine the saturated surface dry mass. The water content of specimens was calculated using Eq. (1). In this study, the water content of saturated specimens is only ~0.39% because of the low porosity of basalt. Two sets of rock specimens were taken from the water and weighed every 30 m. The uniaxial compression tests were performed when the water contents of two sets of specimens were ~0.17% and ~0.28%, respectively.

2.3. Uniaxial compression test
Figure 1c shows that a TAW-3000 hydraulic servo-controlled compression system was used to perform uniaxial compression tests on specimens with different water contents. The maximum axial load of the system is 3,000 kN, and the load control accuracy is 0.01%. Figure 1d illustrates that the axial and lateral strain were measured using linear variable differential transformers (LVDTs). The measurement ranges of axial and lateral LVDTs are 2.5 mm and 6.5 mm, respectively, and the accuracy of both is 0.0001 mm. Before the compression test, the two LVDTs were carefully calibrated, ensuring the fidelity of deformation data. Axial displacement-controlled loading was used with a loading rate of 0.02 mm/min. The axial stress, axial strain, and lateral strain were recorded during the loading process. Under each water content level, three rock specimens were tested. The average UCS was then calculated to minimize the test error.
3. Experimental results

3.1. Stress-strain curve
The stress-strain curve provides a fundamental explanation of the mechanical behavior of the rock during compression loading. Figure 2 presents the representative stress-strain curves of rock specimens with different water contents. Like the results from previous laboratory compression tests, the deformation of the rock specimen under uniaxial compression can be divided into four stages, namely the crack closure, elastic, crack propagation, and failure stages [28–32]. During the initial loading stage, the stress-strain curve exhibits an up-concave shape (nonlinearity), which is related to the closure of microdefects within the rock. Figure 2 shows that the nonlinear behavior of basalt specimens at this stage significantly depends on the water content. As the water content increases, a more pronounced nonlinear behavior of the rock specimen can be observed. Basalt is a silicate-based rock susceptible to stress corrosion when exposed to moist environments. Studies have indicated that the tips of preexisting cracks are preferential sites for hydrolysis reactions between water and silica [33]. Water molecules can cause breaking strained silicon-oxygen bonds at or near the crack tips, increasing the internal microdefects of the rock, especially when the water content is high [33–35]. With increasing axial load, the axial stress-axial strain curve enters a linear-elastic phase. The axial stress increases almost linearly with the axial strain. No new microcracks are generated at this stage. Subsequently, with the continuous generation, development, and coalescence of microcracks in the rock, the axial stress-axial strain curve gradually deviates from the linear behavior until reaching peak strength. In the post-peak deformation stage, a sudden stress drop following the peak stress can be found for all basalt specimens, implying that they all failed in a form of brittle failure.
Figure 2. Stress-strain curves of specimens possessing different water contents

3.2. Strength and elastic behavior

Figure 3a presents the variations in UCS with water content, and Table 2 summarizes the test data. The water content significantly affects the UCS of rock specimens. In the natural state, the UCS of basalt specimens is 176.07 MPa. However, for the oven-dried specimens (the water content is ~0.00%), the average UCS is 180.66 MPa, which is 2.5% higher than that of the natural specimens. From Figure 3a, the UCS of the rock specimens gradually decreases with an increase in water content. When the water content of the sample reaches 0.39% (saturated state), the UCS is 122.13 MPa, which is only 67.6% of the dry state. Furthermore, the reduction magnitude of the UCS of the specimens gradually increases with increasing water content.

Young’s modulus ($E$) and Poisson’s ratio ($v$) are calculated from the linear segment in the stress-strain curve. The linear stage of the stress-strain curve is identified by visual observation. Five stress intervals and corresponding strain intervals were selected in the linear part, and the intervals overlap. The Young’s modulus and Poisson’s ratio are calculated using Eq.(2) and Eq.(3), respectively. Take the average of the five calculations as the final value.

$$E = \frac{\Delta \sigma}{\Delta \varepsilon_1}, \quad \text{(2)}$$

$$v = \frac{\Delta \varepsilon_3}{\Delta \varepsilon_1}, \quad \text{(3)}$$

where $\Delta \sigma$ is the stress difference in the linear part of the stress-strain curve, and $\Delta \varepsilon_1$ and $\Delta \varepsilon_3$ are the difference in the axial and lateral strain, respectively.

Figure 3b shows the variations of Young’s modulus with water content. Like the results of the UCS, water content also significantly influences Young’s modulus. As the water content increases, Young’s modulus tends to decrease. From dry to saturated state of rock specimens, Young’s modulus decreases ~18.7% (Table 2). However, water content does not significantly influence Poisson’s ratio. Figure 3c shows that the Poisson’s ratio of rock specimens of different water contents almost remains unchanged, and the average value of the Poisson’s ratio is within the range of 0.20–0.22.
Table 2. Strength and deformation behavior of basalt specimens possessing different water contents

| No. | Water content (%) | UCS (MPa) | Young’s modulus (GPa) | Poisson’s ratio |
|-----|-------------------|-----------|-----------------------|----------------|
| 0–1 | 0.00%             | 179.85    | 58.27                 | 0.20           |
| 0–2 | 0.00%             | 183.32    | 60.12                 | 0.23           |
| 0–3 | 0.00%             | 178.81    | 57.29                 | 0.22           |
| Average |               | **180.66** | **58.56**             | **0.22**       |
| 1–1 | 0.12%             | 172.96    | 61.05                 | 0.21           |
| 1–2 | 0.12%             | 174.82    | 53.89                 | 0.20           |
| 1–3 | 0.12%             | 180.45    | 55.78                 | 0.22           |
| Average |               | **176.07** | **56.91**             | **0.21**       |
| 2–1 | 0.17%             | 173.24    | 51.52                 | 0.21           |
| 2–2 | 0.17%             | 176.46    | 55.89                 | 0.19           |
| 2–3 | 0.17%             | 168.85    | 50.39                 | 0.21           |
| Average |               | **172.85** | **52.60**             | **0.20**       |
| 3–1 | 0.28%             | 163.29    | 50.52                 | 0.21           |
| 3–2 | 0.28%             | 148.85    | 47.89                 | 0.21           |
| 3–3 | 0.28%             | 154.36    | 49.07                 | 0.22           |
| Average |               | **155.50** | **49.16**             | **0.21**       |
| 4–1 | 0.39%             | 117.96    | 43.29                 | 0.23           |
| 4–2 | 0.39%             | 123.39    | 48.81                 | 0.19           |
| 4–3 | 0.39%             | 125.04    | 50.76                 | 0.19           |
| Average |               | **122.13** | **47.62**             | **0.21**       |

3.3. Failure mode

Figure 4 presents the failure modes of basalt specimens with different water contents after uniaxial compression tests. Splitting failure is the main failure mode for all tested rock specimens. However, some differences exist between specimens with different water contents. For the oven-dried and natural specimens, the failure mode is a single fracture failure throughout the specimen (Figures 4a and 4b). When the water contents reach 0.17% and 0.28%, the failure of rock specimens is associated with the generation of the main fracture, accompanying several secondary fractures (Figures 4c and 4d). As the water content continues to increase to ~0.39%, in addition to axial splitting failure, local shear failure is also observed for the rock specimen (Figure 4d).
Figure 4. Failure modes of basalt specimens possessing different water contents after uniaxial compression tests: (a) 0.00% (b) 0.12% (c) 0.17% (d) 0.28% (e) 0.39%

4. Discussion
Rocks are typically heterogeneous materials, and the sensitivity of different types of rocks to water content varies significantly because of the differences in porosity, mineral composition, and packing density [3]. In this section, an extensive review of the weakening effect of water content on the strength behavior of three types of rocks (clay rock, clastic rock, and crystalline rock) was conducted. Shale, sandstone, and basalt were selected as representative rocks for further analysis. Based on the test data in this study and other data collected from previous publications [3, 13, 36], the relationship between normalized UCS and water content was analyzed (Figures 5–7). The effect of water content on UCS is significantly different for diverse types of rocks. Figures 5 and 6 show that the normalized UCS of shale and sandstone specimens also exhibits a decreasing trend with increasing water content, but the decline gradually moderates. Figure 5 shows that as the water content increases to 7%, the normalized UCS of shale specimens decreases by more than 90%. For sandstone specimens, before the water content reaches 1%, the normalized UCS shows a sharp decline in the trend, after which there is only a 10%–20% reduction (Figure 6). Furthermore, distinctions in the strength behavior of diverse types of sandstone exist regarding sensitivity to water content. Hawkins and McConnell [3] highlighted that the relative proportions of quartz to clay minerals predominantly control the strength reduction of sandstone. The effect of water content on the UCS of clay-rich sandstone is more significant than that of quartz-rich sandstone. For shale and sandstone specimens, clay minerals are dominant diagenetic minerals. The adsorption of water can weaken the cementation between the minerals, reduce friction between particles, and induce softening and swelling of the minerals [13], dramatically reducing the overall strength of the specimen. Such a weakening effect is most pronounced during the initial saturation phase, especially for specimens with a high proportion of clay minerals. With increasing water content, the weakening effect of water on clay minerals becomes progressively minor. Additionally, shale and sandstone have much higher porosity than basalt. As the pores of the rock are gradually saturated, the pore pressure increases considerably. If the pore fluid in the rock is stressed during compression, an outward pressure gradient is created, reducing the strength of the rock.

The relationship between the strength and water content of shale and sandstone can be well described by the negative exponential function (Figures 5 and 6). Tables 3 and 4 list the detailed fitting function and corresponding parameters of shale and sandstone, respectively. However, the negative exponential relation cannot reflect the strength behavior of basalt regarding water content. Figure 7 shows the variation of the normalized UCS of basalt with the water content. As the water content increases, the reduction rate of the UCS of basalt first increases slowly and then rapidly, contrary to the results of shale and sandstone. Basalt is a compact crystalline rock rich in silica. The weakening effect of water on the strength of basalt largely depends on stress corrosion (Section 2.3). At low water content levels,
the effect of stress corrosion is relatively insignificant, leading to only a small decrease in the strength of the basalt specimens. An increase in water content enhances the effect of stress corrosion, resulting in a more pronounced decrease in the strength of the basalt specimen. However, because of the lack of test data, it is challenging to propose a model capturing the variation of rock strength with water content for basalt. Collecting more test data of basalt to comprehensively study the water content effect is a promising topic.

Figure 5. Normalized UCS of shale versus water content

Figure 6. Normalized UCS of sandstone versus water content
Figure 7. Normalized UCS of basalt versus water content

Table 3. Fitting curve parameters of shale specimens

| Shale   | UCS = \( \exp(a + bw + cw^2) \) | \( R^2 \) |
|---------|----------------------------------|---------|
| Shale A | \( a = 0.012 \pm 0.026 \)       | 0.99    |
|         | \( b = -0.488 \pm 0.037 \)      |         |
|         | \( c = 0.007 \pm 0.010 \)       |         |
| Shale B | \( a = -0.038 \pm 0.060 \)      | 0.97    |
|         | \( b = -0.645 \pm 0.104 \)      |         |
|         | \( c = 0.025 \pm 0.033 \)       |         |
| Shale C | \( a = -0.017 \pm 0.038 \)      | 0.98    |
|         | \( b = -0.327 \pm 0.055 \)      |         |
|         | \( c = -0.013 \pm 0.016 \)      |         |
| Mud shale | \( a = -0.026 \pm 0.046 \)    | 0.98    |
|         | \( b = -0.740 \pm 0.083 \)      |         |
|         | \( c = 0.045 \pm 0.029 \)       |         |
| Clay shale | \( a = -0.044 \pm 0.062 \)  | 0.96    |
|         | \( b = -0.319 \pm 0.086 \)      |         |
|         | \( c = -0.013 \pm 0.025 \)      |         |

Table 4. Fitting curve parameters of sandstone specimens

| Sandstone | UCS = \( A \exp(-w/t) + UCS_0 \) | \( R^2 \) |
|-----------|-----------------------------------|---------|
| DQ        | \( A = 0.226 \pm 0.026 \)        | 0.94    |
|           | \( t = 0.219 \pm 0.055 \)        |         |
|           | \( UCS_0 = 0.794 \pm 0.010 \)    |         |
| LORS      | \( A = 0.302 \pm 0.024 \)        | 0.95    |
|           | \( t = 0.297 \pm 0.072 \)        |         |
|           | \( UCS_0 = 0.658 \pm 0.015 \)    |         |
| MG        | \( A = 0.236 \pm 0.011 \)        | 0.98    |
|           | \( t = 0.482 \pm 0.054 \)        |         |
|           | \( UCS_0 = 0.756 \pm 0.007 \)    |         |
| IIBG      | \( A = 0.525 \pm 0.019 \)        | 0.99    |
|           | \( t = 0.590 \pm 0.052 \)        |         |
|           | \( UCS_0 = 0.476 \pm 0.012 \)    |         |
| TR        | \( A = 0.502 \pm 0.042 \)        | 0.95    |
|           | \( t = 0.915 \pm 0.189 \)        |         |
|           | \( UCS_0 = 0.509 \pm 0.024 \)    |         |
| CF        | \( A = 0.226 \pm 0.015 \)        | 0.98    |
|           | \( t = 0.264 \pm 0.051 \)        |         |
|           | \( UCS_0 = 0.766 \pm 0.015 \)    |         |
| PnA       | \( A = 0.533 \pm 0.016 \)        | 0.99    |
|           | \( t = 0.413 \pm 0.027 \)        |         |
|           | \( UCS_0 = 0.457 \pm 0.007 \)    |         |
| PnB       | \( A = 0.542 \pm 0.027 \)        | 0.98    |
|           | \( t = 0.536 \pm 0.066 \)        |         |
|           | \( UCS_0 = 0.482 \pm 0.019 \)    |         |
| PnC       | \( A = 0.541 \pm 0.017 \)        | 0.99    |
|           | \( t = 0.396 \pm 0.036 \)        |         |
|           | \( UCS_0 = 0.462 \pm 0.009 \)    |         |
| PrB       | \( A = 0.246 \pm 0.038 \)        | 0.93    |
|           | \( t = 0.236 \pm 0.061 \)        |         |
|           | \( UCS_0 = 0.827 \pm 0.009 \)    |         |
| PrD       | \( A = 0.180 \pm 0.030 \)        | 0.96    |
|           | \( t = 1.080 \pm 0.428 \)        |         |
|           | \( UCS_0 = 0.820 \pm 0.031 \)    |         |

5. Conclusion
This study experimentally investigated the effect of water content on the mechanical behavior of basalt in the Baihetan Hydropower Station. The results show that water content significantly affects the strength and deformation of the rock. With an increase in water content, the nonlinearity in the initial deformation stage of the stress-strain curves becomes more pronounced. The UCS and Young’s modulus show a decreasing trend with water content, while the Poisson’s ratio has no significant change. Splitting failure is the predominant failure mode for all tested basalt specimens, but local shear failure is also observed under saturated conditions. The literature review results show that the variations in the strength of basalt specimens with water content are significantly different from that of
shale and sandstone specimens. The differences in the internal structure (pore structure and mineral composition) among the rocks result in different mechanisms of water-weakening.

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