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Full Length Article

Characterization and modeling of long-term stress–strain behavior of water confined pre-saturated gypsum rock in Kurdistan Region, Iraq

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ABSTRACT

In order to understand the effects of soaking time and confined water pressure on the strength of rock due to dissolution of gypsum, rock samples with 96% of gypsum content collected from Kurdistan Region in northern Iraq were investigated. Laboratory tests were then performed on the normal gypsum rock samples under pre-saturated condition to obtain their uniaxial compressive strength (UCS) values. The pre-saturated samples were submerged in distilled water for 35 d, 70 d and 105 d, respectively, under confined water pressures of 0–0.5 MPa. The gypsum content decreased by 11% after 105 d of soaking under confined water pressure of 0.5 MPa. The UCS of the normal gypsum rock was 19.6 MPa and it decreased to 6.3 MPa and 2 MPa after 105 d of soaking under confined water pressures of 0 and 0.5 MPa, respectively. A nonlinear constitutive model was used to simulate the experimental stress–strain relationships of rock samples under various conditions. The constitutive model parameters were sensitive to the gypsum content.

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1. Introduction

Gypsum rocks cover more than 20% of the earth surface with seven million square kilometers covering by highly soluble gypsum-bearing rocks (Dreybrodt et al., 2002). Construction failures and geological problems globally resulted from the presented properties of gypsum content, for example, surface collapse in roads and bridge in Ripon, UK (Cooper and Saunders, 2002) and 400 m^3 sinkhole and 5.5 m land surface drop in northeastern Mosul in Iraq (Al-Layla and Thabet, 1990).

Gypsum is a soluble mineral that deposits from natural water as a result of evaporation. Gypsum can transform to anhydrite by losing its hydration water, or anhydrite can transform to gypsum by the addition of water (Holiday, 1978; Jaworska, 2012). The resistance of gypsum to compression is not high. The average uniaxial compressive strength (UCS) of gypsum rock has been found to be in the range of 9–16 MPa (Shafiei et al., 2008; Zheng et al., 2009). The influence of saturation on compressive properties of gypsum rock has been considered by many researchers. Usually with increasing soaking time, i.e. increasing degree of saturation, the strength of gypsum rock decreases (Vásárhelyi and Ván, 2006; Heidari et al., 2012). Water is suggested to be a significant factor that influences the stability and mechanical properties of the gypsum rock (Dusseault, 2011). The mechanical properties of gypsum rocks were reported being closely related to the moisture content (Liang et al., 2012). The failures caused by the dissolution of the gypsum content in rock have been investigated by various studies, which showed that the gypsum rock can experience various notable problems, such as forming karst features (caves and sinkholes) due to continuous dissolution (Yılmaz, 2001; Johnson, 2005; Shafiei et al., 2008). The conversion of anhydrite to gypsum may cause 60% increase in the volume of a solid phase, which brings numbers of engineering problems. The dissolution efficiency of water type on gypsum was studied by Chen and Wu (1983), who reported that the solubility of gypsum is greater in distilled water than in water containing more Ca^{2+} and SO_4^{2-} ions. In the water saturated with $CaSO_4$, the gypsum solubility was found to be about 1.83–2.5 g/L at 20 °C, which is approximately 1/160 of the average value (2.2 g/L) compared to the solubility of ordinary salt (360 g/L) and 1.5 times the solubility of $CaCO_3$ (1.5 mg/L) (Gumusoglu and Ulker, 1982; Bell, 1994; Yılmaz, 2001). Gypsum is susceptible to a rapid dissolution whenever there is an active motion of groundwater unsaturated

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with calcium sulfate (Mohammed and Vipulanandan, 2015). As the gypsum dissolution is recognizable compared with the limestone dissolution, its dissolution causes karst. This is the result of chemical solution in the existing discontinuities enhancing collapse process as a result of karstification. Karstic gypsum presented in dam abutment or reservoir-impoundment area causes a number of problems such as loss of reservoir water or catastrophic loss of the dam (Johnson, 2005). The dissolution of gypsum is dependent on the exposed surface area to water. Furthermore, it is also associated with the flow velocity of water passing over the mineral surfaces and the salinity of the water (James and Lupton, 1978). Some other natural factors, such as temperature, applied pressure and grain size, were also recognized to control the process of gypsum dissolution (Porter et al., 2000). Gypsum, such as $CaCO_3$ and salt, dissolves reversibly, but anhydrite does not. When anhydrite is dissolved, it forms a solution of calcium sulfate which, at common temperatures and pressures, is in equilibrium with the solid phase of gypsum, but not with anhydrite. If disequilibrium of the solid-solvent system occurs, gypsum precipitates. This is due to the instability of anhydrite under normal surface and shallow subsurface thermobaric conditions (Klimchouk, 1996).

To the authors' knowledge, there is no information in the literature concerning the evaluation and quantification of the effects of soaking time and confined water pressure on the gypsum dissolution and mechanical behavior of gypsum rock.

In this study, the nonlinear model was used to predict the long-term stress–strain behavior of the gypsum rock subjected to different confined water pressures. The effect of the confined water pressure on the gypsum dissolution was also studied. At least three samples were tested for each condition.

2. Materials and methods

A series of laboratory tests on the gypsum rock was conducted to evaluate the influences of the soaking time and confined water pressure on the gypsum dissolution and UCS of the gypsum rock.

2.1. X-ray diffraction characterization

X-ray diffraction (XRD) was used to characterize the chemical composition of gypsum rock. The air-dried sample ($\sim$2 g) was placed in an acrylic sample holder which was about 3 mm deep. The sample was analyzed by using parallel beam optics with CuKα radiation at 40 kV and 30 mA. The sample was scanned for reflections (2θ) in the range from 0° to 80° with a step size of 0.02° and a 2 s count time per step (Vipulanandan and Mohammed, 2015a).

2.2. Rock samples

In this study, an area in Sulaymaniyah City (elevation = 966 m, 35.557°N, 45.4359°E) in the northern Iraq (Kurdistan Region) where is rich in gypsum rock was selected. Sufficient block samples for all the laboratory tests were collected. The site is characterized by a massive gypsum rock layer overlain by green marl, on which a clay substrate lies. The gypsum rock locally contains marl or clay impurities within cracks. Gypsum rock samples were collected from the mined layer of gypsum. The collected samples were cored in NX size (54 mm in diameter) and the height/diameter ratio (L/D) was selected to be 2.5 (ASTM D7012-10, 2010). The samples were washed to remove the fine materials and kept in the oven at 25 °C for 48 h in order to obtain constant weight. Oven-dried samples at 25 °C were kept inside a vacuum desiccator to be evacuated for 3 h in the air-dry condition. Then they were fully saturated using distilled water according to the procedure mentioned in Hawkes and Mellor (1970). Subsequently, the submerged samples were evacuated for 24 h (Ali, 1979; Rauh et al., 2006). Three samples with the same size, color and origin were considered for each time interval. The second step was to use pressure vessels to saturate the gypsum rock samples and to apply four levels of confined water pressures of 0, 0.2 MPa, 0.35 MPa and 0.5 MPa on the pre-saturated rock samples at three soaking times of 35 d, 70 d and 105 d.

Confined water pressure of 0.5 MPa is equivalent to 50 m high water column over the sample, simulating field gypsum rock in the reservoir of the hydraulic projects, which directly affects the gypsum-rich substrates near the surface under the foundation.

2.3. Pressure vessels

Steel pressure vessels were used to allow the simulation of water pressures. The pressure vessels are cylindrical containers; the base and side walls were made of stainless steel while the top was made of the specific plastic material suitable for vessel conditions, as shown in Fig. 1. One inlet valve located on the top surface was used to introduce air and pressurize the vessel. An outlet valve was used to extract the water from the vessel. Samples could be placed into and removed from the vessel through the removable gate located in the top center of the vessel. Plastic pipes, special connections and a pressure meter were used with the vessels in order to smoothly extract the saturation water, apply pressure on the samples and check the pressure, respectively. All the tests were performed at room temperature of (24 ± 1) °C.

2.4. Electrical conductivity

For measuring the amount of dissolved gypsum, the electrical conductivity of the distilled water with dissoluble gypsum was regularly measured using conductivity probe. The conductivity measuring range was from 0.1 μS/cm to 1000 μS/cm. The device was calibrated using different standard solutions.

2.5. Compression test

The cylindrical samples of 54 mm in diameter and 135 mm in height were tested at a predetermined controlled loading rate (ASTM D7012-10, 2010). Compression tests were performed on the normal gypsum rock and pre-saturated samples at 35 d, 70 d and 105 d of soaking time using a hydraulic compression testing machine (Instron, UK, 5584 universal testing machine) with a displacement rate of 1 mm/min and a loading rate of 0.5 mm/min. A circumferential extensometer was also used to measure the axial strain of the samples, as shown in Fig. 2.

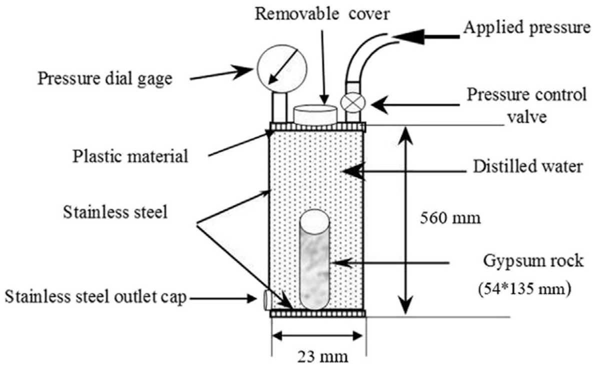

Fig. 1. Schematic representation of gypsum rock saturation system.

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