Cite this article

Mohammed A and Salih N (2019)
Vipulanandan p - q model to predict the effect of pressurised water on the strengths of gypsum rock in Kurdistan Region, Iraq.
Geotechnical Research 6(2): 78–90,
<https://doi.org/10.1680/jgere.18.00014>

Research Article

Paper 1800014

Received 21/02/2018; Accepted 30/08/2018
Published online 02/10/2018
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Keywords: rocks/rock mechanics/
strength & testing of materials/stress
analysis

Vipulanandan p - q model to predict the effect of pressurised water on the strengths of gypsum rock in Kurdistan Region, Iraq

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In this study, the effects of soaking time and confining water pressure on the compressive and flexural strengths of rock due to the dissolution of gypsum content in rock samples with 96% gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) content collected from northern Iraq (Kurdistan Region) were investigated. Experiments on compressive strength and flexural strength were performed on gypsum rock samples in normal and pre-saturated conditions. The pre-saturated samples were submerged in distilled water for 35, 70 and 105 d and subjected to confined pressures of 0–0.5 MPa. Thermogravimetric analyses showed a notable reduction in the weight of gypsum rock between 25 and 120°C. Also, the total weight loss at 800°C for the field rock sample was 7.53%. The weight loss of the gypsum rock increased with increasing soaking time and confining water pressure. The gypsum content decreased by 11% under a soaking time of 105 d and a confining water pressure of 0.5 MPa with respect to the natural samples. The compressive strength of the normal gypsum rock was 19.6 MPa, and it decreased by 68 and 90% after 105 d of soaking under confining water pressures of 0 and 0.5 MPa, respectively. The flexural strength of the normal gypsum rock was 10.8 MPa, and it decreased by 65 and 91% after 105 d of soaking under confining water pressures of 0 and 0.5 MPa, respectively. Two non-linear constitutive models were used to simulate the experimental stress–strain relationships in various conditions. The constitutive model parameters were sensitive to the gypsum content. Based on the methods of the coefficients of determination (R^2) and root mean square errors, the non-linear constitutive model (Vipulanandan p - q model) predicted the stress–strain behaviour for the gypsum rock very well.

Notation

a, b, c	linear model parameters
b	width of the tested beam
d	depth of the tested beam
E_i	initial modulus of elasticity
k	initial model parameter for gypsum rock
L and D	length and thickness of a sample, respectively
N	number of experimental data points
P	confining water pressure
$P_{\max}$	load at a given point (maximum)
p and q	material parameters
R^2	coefficient of determination
t	soaking time
$\bar{x}$	mean of calculated data
x_i	calculated data from the model
$\bar{y}$	mean of the actual test data
y_i	actual test data
ε	axial strain: %
σ	compressive stress
σ_c	compressive strength
σ_f	flexural strength
σ_{f0}	initial flexural strength

Introduction

Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) rocks cover more than 20% of the earth's surface, with 7 million km^2 covered by highly soluble gypsum-

bearing rocks (Dreybrodt *et al.*, 2002). Construction failures and geological problems have globally resulted from the presented properties of gypsum content (GC), two examples being the surface collapse of roads and bridge in Ripon, UK (Cooper and Saunders, 2002) and the 400 m^3 sinkhole and 5.5 m land surface drop in the north-eastern side of Mosul in Iraq (Al-Layla and Thabet, 1990). Gypsum is a soluble mineral deposit resulting from evaporation of natural water. It can transform to anhydrite by losing its hydration water, or anhydrite can transform to gypsum by the addition of water (Ingebritsen and Sanford 1999; Jaworska, 2010). The conversion of anhydrite to gypsum may cause over 60% increase in the volume of the solid phase, which causes lots of engineering problems (Salih *et al.*, 2015). The average uniaxial compressive strength of gypsum rock has been found to be in the range 9–16 MPa (HaiFei *et al.*, 2009; Liang *et al.*, 2012; Shafiei *et al.*, 2008) as shown in Figure 1. The influence of saturation on the compressive properties of gypsum rock has been considered by several research studies; usually with increasing soaking time (i.e. increasing degree of saturation), the strength of gypsum rock decreases (Heidari *et al.*, 2012; Salih *et al.*, 2015; Vászrhelyi and Ván, 2006). Water is suggested to be a significant factor influencing the stability and mechanical properties of gypsum rock (Dusseault, 2011; Mohammed and Mahmood, 2018a, 2018b; Salih *et al.*, 2015). Among the various notable problems investigated by various research studies, gypsum rock can experience formation of karst features (caves

Figure 1. Variation in compressive strength with density for rocks

and sinkholes), due to continuous dissolution (Johnson, 2005; Shafiei *et al.*, 2008; Yilmaz, 2001). The dissolution of gypsum is dependent on the surface area exposed to water. The solubility of gypsum is greater in distilled water than in water containing more calcium (Ca^{2+}) and sulfate (SO_4^{2-}) ions (Fengxiang *et al.*, 1983). In water saturated with calcium sulfate (CaSO_4), gypsum solubility was found to be about 1.83–2.5 g/l at 20°C, the average of which (2.2 g/l) is approximately 1/160 of the solubility of ordinary salt (360 g/l) and 1.5 times the solubility of calcium carbonate (CaCO_3) (1.5 mg/l) (Bell, 1994; Gumusoglu and Ulker, 1982; Yilmaz, 2001). Gypsum is susceptible to rapid dissolution whenever there is an active movement of groundwater, which is unsaturated with calcium sulfate (Salih *et al.*, 2015). Gypsum, like calcium carbonate 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).

Leaching of gypsum is an essential point for the dissolution process, which has been also studied. Unbonded gypsum leaches out quickly due to the water percolating through the fissures at the boundary between gypsum and the surrounding rock. Rock collapse in the roofs of tunnels and mines often occurs in bending conditions (Fengxiang *et al.*, 1983). Elizzi (1976) and Ali (1979) studied the difference between compression and tension strain in four-point mode bending tests for gypsum rock. The studies showed that the compressive strain from the four-point bending test for a gypsum rock sample was greater than the tension strain. Efimov (2009) highlighted the method of bending testing. The result showed that the three-point bending test for gypsum rock showed higher tension compared with the four-point bending test. Based on the information from various research studies performed on different types of rock, the size (L/D , where L and D are the length and thickness of the sample, respectively) for the

compression test varied from 0.5 to 3. The different beam sizes ($L \times W \times D$) used for flexural strength tests found in the literature are summarised in Table 1.

In this study, non-linear models were used to predict the long-term stress–strain behaviour of gypsum rock subjected to different confining water pressures. The effect of the confining water pressure on the dissolution of the GC was also studied. At least three samples were tested for each condition.

Vipulanandan *p-q* model

The stress–strain behaviours of strain-softening materials such as concrete, glass-fibre-reinforced polymer concrete, fine sand grouted with sodium silicate, sulfate contaminated clay soil and cement mortar were predicted using the Vipulanandan *p-q* model (Mebarkia and Vipulanandan, 1992; Mohammed and Vipulanandan, 2014; Vipulanandan and Paul, 1990). Vipulanandan and Usluogullari (2011) modelled the stress–strain behaviour of Portland cement-stabilised sand using the *p-q* model. Vipulanandan and Mohammed (2015a) used the Vipulanandan *p-q* model for predicting the piezoresistive behaviour of smart cement modified with iron oxide nanoparticles. Also, the Vipulanandan *p-q* model was used to predict the electrical resistivity against curing time of smart oil well cement (Mohammed and Vipulanandan, 2015; Vipulanandan and Mohammed, 2015b).

Aims and objectives

The overall objective of this study was to investigate the effect of long-term soaking time and confining water pressure on the compressive and flexural strengths of gypsum rock. The specific objectives are as follows

- investigation of the effect of the soaking time and confined water pressure on the dissolution of GC
- the long-term compressive strength and flexural strength behaviour of normal gypsum rock samples and pre-saturated samples subjected to different confining water pressures
- quantification of the long-term stress–strain relationship of gypsum rock under different confining water pressures
- correlation between the compressive strength and flexural strength of gypsum rock.

Materials and methods

X-ray diffraction characterisation

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

Table 1. Literature review of the dimensions of samples for compression and flexural strength tests

Compression test				Flexural test		
Reference	Type of rock	Size of sample	Length/ diameter (<i>L/D</i>)	Reference	Type of rock	<i>L × W × D</i> : mm
Lundborg (1967)	Granite	20, 30, 40 and 60 mm dia.	1	Xeidakis <i>et al.</i> (1996)	Marble, calcite and dolomitic	180 × 40 × 20
Bieniawski <i>et al.</i> (1967), Singh and Singh (1993), Yilmaz and Sendir (2002), Brady and Brown (2013)	Gypsum rock	NX (52 mm dia.)	2	Biolzi <i>et al.</i> (2001)	Granite	240 × 40 × 30
Ali (1979)	Gypsum rock	38.1 mm dia. × 114.3 mm high and 50.8 mm dia. × 152.4 mm high	3	Coviello <i>et al.</i> (2005)	Calcarene	130 × 50 × 40
Whittles <i>et al.</i> (2006)	Sandstone	25 mm dia. × 50 mm high	2	Biolzi <i>et al.</i> (2011)	Sandstone	180 × 40 × 40
Agustawijaya (2007)	Sandstone and siltstone	54 mm dia.	1.6–2.5	Aliha <i>et al.</i> (2009)	Granite	220 × 40 × 20
Özkan <i>et al.</i> (2009)	Rock salt	25, 50, 75, 100 and 125 mm dia.	0.5–2.5	Moonen (2009)	Sandstone	240 × 48 × 24
Cho <i>et al.</i> (2010)	Sulfaset synthetic rock	55 mm dia. × 110 mm high	2	Efimov (2009)	Granite	120 × 20 × 20
Liang <i>et al.</i> (2012)	Salt rock	50 mm dia. × 100 mm high	2	Chen and Azzam (2007)	Sandstone	250 × 50 × 50
Current study	Gypsum rock	54 mm dia.	2.5	Current study	Gypsum rock	140 × 40 × 20
Remarks	Different types of rock were used	Diameters varied from 20 to 55 mm	<i>L/D</i> varied from 0.5 to 3	Remarks	Different types of rock were used	Different <i>L × W × D</i> values were used

Thermogravimetric analysis

Thermogravimetric analysis (TGA) curves, % weight loss with temperature (TGA) and its derivative (% weight change/°C – derivative thermogravimetry (DTG)), were recorded using Setaram TGA 500 apparatus at a heating rate of 10°C/min for a sample of about 20 mg (Khalil and Gad, 1972). TGA and DTG curves for the field gypsum rock were obtained. The test sample was loaded in a platinum pan (three-quarters full). This was followed by introduction of nitrogen (N₂) gas into the TGA compartment for 5 min to purge the likely oxygen in the environment of the system. After purging, the sample was heated in the nitrogen atmosphere from room temperature to the maximum of 800°C (Vipulanandan and Mohammed, 2015b).

Compression test (ASTM D 7012-10)

In this study, an area in northern Iraq (Kurdistan Region) in Sulaymaniyah City (elevation = 966 m, 0495932 38S and 3945243 UTM) that is rich with massive layers of gypsum rock was selected. Sufficient block samples for all the laboratory tests were collected. The site features a massive gypsum rock layer. The gypsum rock locally contains marl or clay impurities within cracks. Gypsum rock samples were collected from the mined layer of gypsum. Based on the information from the literature (Table 1), the collected samples were cored in NX size (54 mm dia.) and *L/D* was selected to be 2.5

(ASTM D 7012-10 (ASTM, 2010a)). The field rock samples were washed to remove the fine materials and were kept in an oven at 25°C for 48 h in order to obtain constant weight. Oven-dried (25°C) compression and flexural samples were kept inside a vacuum desiccator to be evacuated for 3 h. The sample preparation and testing procedures are explained in Figure 2.

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 from a specific plastic material suitable for vessel conditions as shown in Figure 3. One inlet valve located on the top surface was used to introduce air to pressurise 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 at the top centre of the vessel. Plastic pipes, special connections and a pressure meter were prepared to be used with the vessels as shown in Figure 3. All the tests were performed at the room temperature of 24 ± 1°C.

Saturation process

A specific procedure for saturating the normal gypsum rock samples was considered (Hawkes and Mellor, 1970). Distilled

Figure 2. Flow diagram of laboratory testing

Figure 3. Schematic representation of the gypsum rock saturation system

water was added into the desiccator, and the evacuation process was continued for 24 h (Ali, 1979; Rauh *et al.*, 2006). The weight of the samples was measured in real time every 6 h using a

0.001 g electronic balance to check if a constant weight for the samples was obtained. After 12 h, the samples' weight was constant. The first step involved saturating the gypsum rock samples under atmospheric pressure in containers with a known volume of water. The samples were soaked inside the containers for durations of 35, 70 and 105 d; the change in the samples' weight and the electrical conductivity (EC) of the water-dissolved gypsum were recorded at 7 d intervals. Three samples with the same size, colour and origin were considered for each time interval. Then, the second step was conducted by using pressure vessels to saturate the samples and applying three different levels of confining water pressures of 0.2, 0.35 and 0.5 MPa to the pre-saturated samples.

A confining water pressure of 0.5 MPa is equivalent to a 50 m high water column above the sample, simulating the conditions in the reservoir of hydraulic structure projects, which directly affects the gypsum-rich substrates near the surface under the foundation. The flow diagram of the laboratory programme is shown in Figure 2.

Compressive strength test (ASTM D 7012-10)

Cylindrical specimens 54 mm in diameter and 135 mm high (2.13 inches dia. × 5.30 inches high) were tested at a predetermined controlled loading rate. Compression tests were performed on the normal gypsum rock and pre-saturated samples at 35, 70 and 105 d of soaking 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 used to measure the radial strain of the specimens as shown in Figure 4.

Flexural test (ASTM D 6272-10)

Based on the various research studies performed on the flexural beam rock samples, various dimensions ($L \times W \times D$) of the flexural rock samples were used (Table 1). In this study, the four-point bending test (ASTM, 2010b) with dimensions ($L \times W \times D$) of 140 mm × 40 mm × 20 mm was performed as shown in Figure 4(b). The loading rate was selected to be 0.075 MPa/s. The flexural strength (σ_f) of the samples was calculated using the equation

$$\sigma_f = \frac{P_{\max} \times L}{4 \times b \times (d)^2}$$

where σ_f is the flexural strength (MPa); $P_{\max}$ is the load at a given point (maximum) on the load-deflection curve (N); L is the support span (mm); b is the width of the tested beam (mm); and d is the depth of the tested beam (mm) as shown in Figure 4(b).

Electrical conductivity

A conductivity probe was used to measure the conductivity of the contaminated distilled water with dissolvable gypsum. The conductivity measuring range was from 0.1 to 1000 $\mu\text{S}/\text{cm}$. The device was calibrated using different standard solutions.

Figure 4. Experimental set-up for the (a) compression test and (b) four-point bending test for the gypsum rock samples (cylinders and beams)

Comparison of model predictions

In order to determine the accuracy of the model predictions, both the coefficients of determination (R^2) and the root mean square error (RMSE) for the model predictions as defined in Equations 2 and 3 were quantified.

$$2. \quad R^2 = \left[\frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} \times \sqrt{\sum_i (y_i - \bar{y})^2}} \right]^2$$

$$3. \quad \text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_i - x_i)^2}{N}}$$

where y_i are the actual test data; x_i are the calculated data from the model; $\bar{y}$ is the mean of the actual test data; $\bar{x}$ is the mean of calculated data; and N is the number of experimental data points.

Results and discussion

X-ray diffraction

The field rock sample contained gypsum (2θ peaks at 14.96° , 21.00° , 26.80° , 36.68° , 39.64° , 42.52° , 50.28° and 55.48°) and quartz (SiO_2) (2θ peaks at 60.02° and 76.21°) as shown in Figure 5. Similar results were obtained by Koukouzas and Vasilatos (2008). Based on the XRD test results, the GC in the field sample was 96%.

Thermogravimetric analysis

Using TGA, the weight loss at the rate of weight change with temperature was obtained for field gypsum rock. Weight loss in gypsum rock was analysed in four temperature ranges as shown in Figure 6. The hemihydrate was formed between 100 and 200°C when the heating rate was $10^\circ\text{C}/\text{min}$, but complete conversion below 100°C occurred when heating was very slow. A few minutes of heating above 250°C or longer between 100 and 125°C resulted in the formation of soluble anhydrite ($\gamma\text{-CaSO}_4$); further heating around 360°C gave anhydrite (Khalil and Gad, 1972). Weight loss for the

Figure 5. XRD pattern of the gypsum rock

Figure 6. Weight loss obtained using TGA and DTG for the gypsum rock

field gypsum rock between 25 and 120°C was 5.70%, and it was 0.75% when the temperature changed from 120 to 400°C. The weight loss for gypsum rock was 0.39% when the temperature changed from 400 to 600°C as shown in Figure 7. The total weight loss for the gypsum rock at 800°C was 7.53%, as shown in Figure 6.

Gypsum content (%)

The EC is a good tool to measure the capacity of water to conduct electrical current; it is related to the concentration of gypsum dissolved in 1 litre of distilled water as shown in Figure 8. The EC of the water was used to determine the amount of the gypsum (g/l) dissolved in the distilled water. Distilled water does not contain dissolved gypsum so it does not conduct electricity and has an EC of zero, as shown in Figure 8. The EC of the distilled water contaminated with dissolved gypsum was recorded every 7 d. The process of dissolution started from 0 up to 3 g of gypsum powder mixed with 1 litre of distilled water using an electrical blender. Based on the experimental data shown in Figure 8, the relationship in Equation 4 was used to predict the GC in grams per litre from the EC ($\mu\text{S}/\text{cm}$).

Figure 7. TGA test results for the gypsum rock

Figure 8. GC-EC relationship

$$GC(\text{g/l}) = 6 \times 10^{-4} \times (\text{EC})^2 + 4 \times 10^{-4} \times \text{EC} + 0.08$$

$$R^2 = 0.99 \quad \text{for } (0 \leq GC(\text{g/l}) \leq 3)$$

4.

According to the conducted relationship in Figure 8, the measured conductivity amount will be deducted from the total GC of soaked samples. After that, the remaining GC is achieved due to the measured dissolved gypsum per cent.

Weight loss due to saturation (%)

Using the 0.001 g electrical balance, the gypsum loss at the rate of weight loss with soaking time for pre-saturated samples at various confined water pressures was measured. GC (%) decreased with increasing soaking time and confined water pressure as shown in Figure 9. GC decreased from 96 to 89.5%, a 6.8% reduction, when the sample was soaked for 105 d under 0 MPa of confined water pressure as shown in Figure 9. GC decreased from 96 to 85%, an 11.5% reduction, when the rock sample was soaked for 105 d in distilled water under 0.5 MPa of confined water pressure as shown in Figure 9. The weight loss represented by the amount of gypsum lost increased by 37, 43 and 70% when the confining water pressure increased to 0.2, 0.35 and 0.5 MPa at 105 d of soaking, respectively, as shown in Figure 9. This also indicates that the rate of the gypsum dissolved increased with increasing confining water pressure.

Compressive strength

The compressive strength and the density of the normal gypsum rock samples were compared with 102 data for the different types of rock collected from literature as shown in Figure 2. With an increase in the soaking time, the compressive strength decreased. For example, it decreased from 19.6 MPa (2843 pounds per square inch (psi)) to 12.1 MPa (1755 psi), which is a 38% reduction, at 35 d of soaking at 0 MPa of confined water pressure as summarised in Table 2. The compressive strength decreased from 19.6 MPa

Figure 9. Variation in weight loss for the gypsum rock plotted against soaking time for compression test samples with different confined water pressures

(2843 psi) to 6.3 MPa (914 psi), which is a 68% reduction, at 105 d of soaking at 0 MPa of confined water pressure as summarised in Table 2. With the increase in the water pressure, the compressive strength decreased. The compressive strength decreased from 6.3 MPa (914 psi) to 2 MPa (290 psi), which is a 68% reduction, at 105 d of soaking when the confined water pressure increased from 0 to 0.5 MPa (73 psi), as shown in Figure 10.

With the increase in soaking time, the initial modulus of elasticity decreased. It decreased from 5297 to 3335 and 1600 MPa, 37 and 70% reductions, at 35 and 105 d of soaking, respectively, at 0 MPa of confined water pressure, as shown in Figure 11. Increasing the confined water pressure from 0 to 0.5 MPa decreased the initial modulus of elasticity of the samples by 43 and 50% at 35 and 105 d

of soaking, respectively, as shown in Figure 11. The initial modulus of elasticity of the gypsum rocks decreased with increasing soaking time and confined water pressure, as shown in Figure 11.

Stress-strain behaviour modelling

In this study, the pre-saturated gypsum rock with four different confining water pressures after various soaking times exhibited a strain-softening behaviour, as shown in Figures 12 and 13.

Vipulanandan *p*-*q* model

Based on experimental results, the model proposed by Vipulanandan and Paul (1990) was used to predict the stress-strain behaviour of gypsum rock with four different confining water pressures at different soaking times (Equation 5). The model is defined as follows

Table 2. Stress-strain model parameters for the gypsum rock

			Vipulanandan p - q model (Equation 5)						β model (Equation 6)				
Confined water pressure: MPa	Soaking time: d	GC: %	σ_c : MPa	ϵ_c : %	p	q	RMSE: MPa	R^2	σ_c : MPa	ϵ_c : %	β	RMSE: MPa	R^2
Field sample	0	96.0 $\pm$ 0.4	19.6 $\pm$ 0.9	0.38 $\pm$ 0.01	1.81 $\pm$ 0.2	0.84 $\pm$ 0.02	0.204	0.99	19.8 $\pm$ 1.3	0.38 $\pm$ 0.02	3.38 $\pm$ 1	0.443	0.99
0	35	93.6 $\pm$ 0.6	12.1 $\pm$ 1	0.53 $\pm$ 0.02	1.5 $\pm$ 0.1	1.13 $\pm$ 0.01	0.134	0.99	12.4 $\pm$ 1.5	0.55 $\pm$ 0.03	3.12 $\pm$ 1.3	0.330	0.99
	105	89.5 $\pm$ 0.4	6.3 $\pm$ 1.5	0.41 $\pm$ 0.01	1.1 $\pm$ 0.1	1.30 $\pm$ 0.02	0.051	0.99	5.2 $\pm$ 1.6	0.42 $\pm$ 0.01	2.55 $\pm$ 1.2	0.237	0.98
0.20	35	93.0 $\pm$ 0.5	7.8 $\pm$ 2	0.49 $\pm$ 0.03	1.3 $\pm$ 0.2	0.67 $\pm$ 0.03	0.066	0.99	7.8 $\pm$ 2.1	0.46 $\pm$ 0.05	3 $\pm$ 1.1	0.190	0.99
	105	87.1 $\pm$ 0.6	4.2 $\pm$ 1.3	0.33 $\pm$ 0.01	1 $\pm$ 0.12	0.47 $\pm$ 0.04	0.054	0.99	4.2 $\pm$ 1.6	0.32 $\pm$ 0.03	2 $\pm$ 1.12	0.111	0.99
0.35	35	92.9 $\pm$ 0.8	6.4 $\pm$ 2	0.40 $\pm$ 0.03	1.32 $\pm$ 0.14	0.87 $\pm$ 0.02	0.068	0.99	6.4 $\pm$ 2.1	0.41 $\pm$ 0.04	2.57 $\pm$ 1.3	0.146	0.98
	105	86.7 $\pm$ 0.4	3.6 $\pm$ 1.3	0.34 $\pm$ 0.01	1.2 $\pm$ 0.2	0.97 $\pm$ 0.03	0.025	0.99	3.6 $\pm$ 1.7	0.35 $\pm$ 0.03	2.41 $\pm$ 1.5	0.103	0.99
0.50	35	92.4 $\pm$ 0.2	4.9 $\pm$ 1.6	0.35 $\pm$ 0.02	1.70 $\pm$ 0.1	0.70 $\pm$ 0.01	0.058	0.99	4.9 $\pm$ 1.8	0.36 $\pm$ 0.02	2.22 $\pm$ 1.3	0.133	0.98
	105	85.0 $\pm$ 0.6	2.0 $\pm$ 1.3	0.31 $\pm$ 0.01	0.8 $\pm$ 0.15	0.56 $\pm$ 0.02	0.039	0.99	3.2 $\pm$ 1.5	0.30 $\pm$ 0.02	2.35 $\pm$ 1.4	0.065	0.99

Figure 10. Variation in compressive strength of the gypsum rock plotted against soaking time with different confined pressures

Figure 11. Variation in initial compressive modulus of the gypsum rock plotted against soaking time for compression test samples with different confined pressures

Figure 12. Comparison of experimental stress-strain and model predictions for the gypsum rock

$$5. \quad \sigma = \left[\frac{\varepsilon/\varepsilon_c}{q + (1 - p - q)(\varepsilon/\varepsilon_c) + p(\varepsilon/\varepsilon_c)^{(p+q)/p}} \right] \times \sigma_c$$

Figure 13. Comparison of experimental stress-strain and models prediction for the gypsum rock with different confined water pressures: (a) $P = 0$ MPa; (b) $P = 0.2$ MPa; (c) $P = 0.35$ MPa; (d) $P = 0.5$ MPa

where σ is the compressive stress, ε is the axial strain (%), σ_c and ε_c are the compressive strength and the corresponding strain, respectively, and p and q are material parameters.

The parameter q was defined as the ratio of the secant modulus at peak stress to the initial tangent modulus. The parameter p was obtained by minimising the error in the predicted stress-strain relationship. Hence, the parameters p and q in Equation 5 were determined based on the stress-strain behaviour of gypsum rock with different soaking times, confined water pressures, RMSEs and coefficients of determination R^2 and are summarised in Table 2. The parameters p and q are influenced by GC (%), as summarised in Table 2. The shape of the stress-strain curve can be changed based on the p and q values as shown in Figure 14(a).

PARAMETER p

For gypsum rock with different percentages of GC, the parameter p was in the range 0.80–1.81, as summarised in Table 2. Hence, the descending part of the strain-softening stress-strain relationship for the saturated samples was steeper compared to that for the normal gypsum rock samples. For the normal gypsum rock samples with

Figure 14. Compressive stress–strain relationships: (a) Vipulanandan p - q model and (b) β model

96% GC, p was 1.81 and was reduced to 0.8 when the GC was 85%, as summarised in Table 2. The parameter p and GC were correlated using Equation 8, and model parameters, RMSE and coefficients of determination (R^2) are summarised in Table 2.

PARAMETER q

This parameter represents the non-linear behaviour of the gypsum rock up to the peak stress. For gypsum rock with different percentages of GC, the parameter q was in the range 0.47–1.30, as summarised in Table 2, and indicates that the material behaviour is more linear with soaking time and confining water pressure. For the normal gypsum rock sample with 96% GC, q was 0.84 and was reduced to 0.56 when the GC was 85%, as summarised in Table 2. The parameter q and GC were correlated using Equation 8, and model parameters, RMSE and coefficient of determination (R^2) are summarised in Table 2.

β method

Ezeldin and Balaguru (1992) proposed an analytical equation (Equation 7) to generate the stress–strain curve for the normal strength of steel-fibre-reinforced concrete based on the equation proposed by Carreira and Chu (1985) for uniaxial compression of plain concrete. This equation involves the material parameter β , which is the slope of the inflection point at the descending branch of the shear stress relationship.

$$6. \quad \sigma = \left[\frac{\beta(\epsilon/\epsilon_c)}{\beta - 1 + (\epsilon/\epsilon_c)^\beta} \right] \times \sigma_c$$

where σ is the compressive stress, σ_c and ϵ_c are the compressive strength and the corresponding strain, respectively, and β is a material parameter.

The stress–strain relationship for gypsum rock in different soaking times and four different confined water pressures and the model predictions are shown in Figures 11 and 12.

PARAMETER β

For the normal gypsum rock sample, parameter β was 3.38. It decreased to 2.55 when the sample was kept in distilled water for 105 d, as summarised in Table 2. The parameter β varied from 2 to 3 when the soaking time varied between 0 and 105 d under confined water pressure varying from 0 to 0.5 MPa, as summarised in Table 2. The shape of the stress–strain curve can be changed based on the β value, as shown in Figure 14(b).

Compressive strength (σ_c)

Normal gypsum rock

The compressive strength (σ_c) of the normal gypsum rock sample with a density of 2.3 g/cm³ and GC of 96% was 19.6 MPa, as shown in Figure 11. The compressive stress–strain behaviour of the normal gypsum rock sample was modelled using the Vipulanandan p - q model (Equation 5). The coefficient of determination (R^2) was 0.99, as summarised in Table 1. The RMSE was 0.204 MPa, as summarised in Table 2. The model parameters p and q for normal gypsum rock were 1.81 and 0.84, respectively, as summarised in Table 1. The Vipulanandan p - q model (Equation 5) predicted the stress–strain behaviour of the normal gypsum rock sample very well, as shown in Figure 12.

Pre-saturated samples

CONFINED WATER PRESSURE OF 0 MPa

The compressive stress–strain behaviour of the pre-saturated gypsum rock with three different soaking times of 35, 70 and 105 d was modelled using the Vipulanandan p - q model (Equation 5). The coefficients of determination (R^2) were 0.99, as summarised in Table 2. The RMSE varied between 0.051 and 0.134 MPa, as summarised in Table 2. The model parameter p for pre-saturated gypsum rock with three different soaking times varying between 1.1 and 1.5 is summarised in Table 2. The model parameter q for pre-saturated gypsum rock with three different soaking times varying between 1.13 and 1.30 is summarised in Table 2.

CONFINED WATER PRESSURE OF 0.5 MPa

The compressive strength (σ_c) of the pre-saturated gypsum rock sample decreased by 50% when the sample was soaked in distilled water for 35 d under 0.5 MPa of confined water pressure, as summarised in Table 2. The compressive stress–strain behaviour of the pre-saturated gypsum rock with three different soaking times of 35, 70 and 105 d was modelled using the Vipulanandan *p*–*q* model (Equation 5). The coefficients of determination (R^2) for all samples were 0.99, as summarised in Table 2. The RMSE varied between 0.025 and 0.068 MPa, as summarised in Table 2. The model parameter *p* for gypsum rock with three different soaking times varied between 0.8 and 1.7, as summarised in Table 2. The model parameter *q* for the pre-saturated gypsum rock with three different soaking times varied between 0.58 and 0.97, as summarised in Table 2. The Vipulanandan *p*–*q* model (Equation 5) predicted the stress–strain behaviour of the pre-saturated gypsum rock very well (Figure 12(d)).

LINEAR MODEL PARAMETERS

The model parameters σ_c , ϵ_c , *p*, *q* and β and initial modulus of elasticity (E_i) were influenced by the GC (%). It is being proposed to relate the model parameters to the independent variables (GC (%)), soaking time (*t*) (d) and confining water pressure (*P*) (MPa)) using a linear relationship as proposed.

The effects of GC, soaking time and confining water pressure were separated as follows

$$\text{model parameters } (\sigma_c, \epsilon_c, p, q, \beta, E_i) \\ 7. \quad = k + a \times (\text{GC}) + b(t) + c(P)$$

where *k* is the initial model parameter for gypsum rock (normal gypsum rock) and *a*, *b* and *c* are the linear model (LM) parameters. The LM parameters were obtained from multiple regression analyses using the least-squares method. The LM parameters and coefficient of determination (R^2) and RMSE are summarised in Table 3.

Stress–strain data from all the finished tests in Table 2 are utilised to produce the corresponding *p* and *q* values by regression analysis following Equation 5. Then, these *p*, *q*, σ_c and ϵ_c values are used to train Equation 7 to get the value of the parameters *k*,

a, *b* and *c*. Secondly, for any other untested gypsum sample provided with GC, soaking time and confining water pressure, the *p*, *q*, σ_c and ϵ_c values of that untested gypsum sample will be derived by applying those values of *k*, *a*, *b* and *c* obtained in the first step into Equation 7. Finally, these new *p*, *q*, σ_c and ϵ_c values can be used to predict the stress–strain curve of that untested gypsum sample by following Equation 5.

Flexural strength test

Volume loss (%)

A 0.01 mm digital vernier calliper was used to measure the volume of the flexural gypsum rock beams with dimensions ($L \times W \times D$) of 140 mm $\times$ 40 mm $\times$ 20 mm. The rate of volume change with soaking time for pre-saturated samples at various confined water pressures was measured. Volume loss in saturated gypsum rock at different confined water pressures was evaluated in three time interval ranges, as shown in Figure 15. The volume reductions (%) of the gypsum rock at 0 MPa confined water pressure were 2.2, 4.7 and 7.3 after 35, 70 and 105 d of soaking, respectively, as shown in Figure 13. The volume loss of the samples increased with increasing confining water pressure at the same soaking time, as shown in Figure 16. Based on the test results, the flexural strength of the samples decreased by 33% for a soaking time of 105 d at 0.5 MPa of confined water pressure, as shown in Figure 16.

Figure 15. Variation in volume reduction of the gypsum rock plotted against soaking time for flexural test samples with different confined water pressures

Table 3. Linear compression and flexural strength model (Equation 8) parameters for the gypsum rock

Model parameters		<i>k</i>	<i>a</i>	<i>b</i>	<i>c</i>	Number of data	RMSE	R^2
Equation 5	<i>p</i>	2.1	−0.003	−0.007	−0.41	12	0.081	0.88
	<i>q</i>	−12.9	0.14	0.013	−0.27	13	0.079	0.87
	σ_c : MPa	81.7	−0.73	−0.11	−11.5	12	0.311	0.96
	ϵ_c : %	2.22	−0.017	−0.003	−0.35	11	0.018	0.89
	E_i : MPa	42 974	−398	−57	−4684	13	230	0.95
Equation 6	σ_c : MPa	109	−1.0	−0.13	−13.2	12	0.380	0.94
	ϵ_c : %	1.76	−0.012	−0.002	−0.36	11	0.020	0.88
	β	22.5	−0.20	−0.02	−2.26	12	0.060	0.97

Figure 16. Relationship between flexural strength of the gypsum rock plotted against soaking time with different confined water pressures

Two- and three-parameter hyperbolic relationships (Equation 8) have been used for decades to correlate the changes in material properties with and without additives (Vipulanandan and Krishan, 1993; Vipulanandan and Mohammed, 2015a, 2015b).

The variation in flexural strength with soaking time was represented using the proposed hyperbolic model (Equation 8) and the parameters; the coefficient of determination (R^2) and RMSE are summarised in Table 4.

$$8. \quad \sigma_f - \sigma_{f0} = \frac{GC(\%)}{A + B \times GC(\%)}$$

where σ_f is the flexural strength (MPa), σ_{f0} is the initial flexural strength (normal gypsum rock sample) (MPa) and A and B are the flexural strength hyperbolic model parameters.

Correlation between compressive and flexural strength

Based on the test results of the variation in flexural strength (σ_f) with the compressive strength (σ_c), Figure 17 is represented by the following non-linear hyperbolic relationship between flexural strength and compressive strength for the gypsum rocks.

$$9. \quad \sigma_f = \frac{\sigma_c}{1.40 + 0.02 \times \sigma_c} \quad R^2 = 0.98$$

Table 4. Non-linear flexural strength model parameters (Equation 8) for the gypsum rock

Confined water pressure: MPa	σ_{f0}	A	B	RMSE	R^2
0	10.8	0.09	7.83	0.180	0.99
0.2	10.8	0.08	3.72	0.213	0.99
0.35	10.8	0.08	3.12	0.127	0.99
0.50	10.8	0.07	2.60	0.016	0.99

Figure 17. Relationship between compression strength and flexural strength of the gypsum rock

Conclusions

In this study, the effect of soaking time and confined water pressure of pre-saturated gypsum rock was characterised and quantified. Based on the experimental and analytical data and the compressive and flexural strength behaviour of the gypsum rocks, the following conclusions are advanced.

- Based on the TGA test results, the highest weight loss of the sample was observed between 25 and 120°C, which was 5.7%. The total weight loss of the gypsum rock was 7.53% at 800°C.
- GC decreased with increasing soaking time and confined water pressure. The GC decreased by 11% when the sample was subjected to 0.5 MPa confined water pressure for 105 d of soaking.
- The compressive strength of gypsum rock decreased by 50 and 68% when the samples were subjected to 0.5 MPa of confined water pressure for 35 and 105 d, respectively.
- The initial modulus of elasticity of gypsum rock decreased by 70% when the samples were subjected to 0 MPa of confined water pressure for 105 d of soaking. The initial modulus of elasticity of gypsum rock decreased by 43 and 50% when the samples were subjected to 0.5 MPa of confined water pressure for 35 and 105 d, respectively.
- The flexural strength of gypsum rock decreased by 61 and 91% when the samples were subjected to 0.5 MPa of confined water pressure for 35 and 105 d, respectively.
- GC decreased with increasing soaking time and confined water pressure. The GC decreased by 11% when the samples were subjected to 0.5 MPa confined water pressure for 105 d of soaking.
- Based on the RMSE and R^2 , the non-linear Vipulanandan model (*p-q* model) predicted the stress-strain behaviour of gypsum rock at different soaking times and confined water pressures very well. The model parameters were sensitive to the GC.

- The compressive strength and flexural strength of the normal gypsum rock decreased with increasing soaking time and confined water pressure.

REFERENCES

- Agustawijaya DS (2007) The uniaxial compressive strength of soft rock. *Civil Engineering Dimension* **9(1)**: 9–14, <https://doi.org/10.9744/ced.9.1.pp.%209-14>.
- Ali SA (1979) *Creep Properties of Evaporite Rocks with Particular Reference to Gypsum*. PhD thesis, University of Sheffield, Sheffield, UK.
- Aliha MRM, Ayatollahi MR and Kharazi B (2009) Numerical and experimental investigations of mixed mode fracture in granite using four-point-bend specimen. In *Damage and Fracture Mechanics: Failure Analysis of Engineering Materials and Structures* (Boukharouba T, Elboudjaini M and Pluvillage G (eds)). Springer, Dordrecht, the Netherlands, pp. 275–283.
- Al-Layla MT and Thabet KM (1990) Formation of cavities in the alluvial deposits in Mosul City. *Proceedings of the 2nd Science Conference of Mosul Dam Research Centre, Mosul, Iraq*, pp. 172–185.
- ASTM (2010a) D 7012-10: Standard test method for compressive strength and elastic moduli of intact rock core specimens under varying states of stress and temperatures. ASTM International, West Conshohocken, PA, USA.
- ASTM (2010b) D 6722-10: Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials by four-point bending. ASTM International, West Conshohocken, PA, USA.
- Bell FG (1994) A survey of the engineering properties of some anhydrite and gypsum from the north and midlands of England. *Engineering Geology* **38(1–2)**: 1–23.
- Bieniawski ZT (1967) Stability concept of brittle fracture propagation in rock. *Engineering Geology* **2(3)**: 149–162.
- Biolzi L, Cattaneo S and Rosati G (2001) Flexural/tensile strength ratio in rock-like materials. *Rock Mechanics and Rock Engineering* **34(3)**: 217–233.
- Biolzi L, Labuz JF and Muciaccia G (2011) A problem of scaling in fracture of damaged rock. *International Journal of Rock Mechanics and Mining Sciences* **48(3)**: 451–457.
- Brady BH and Brown ET (2013) *Rock Mechanics: for Underground Mining*. Springer, Dordrecht, the Netherlands.
- Carreira DJ and Chu KH (1985) Stress-strain relationship for plain concrete in compression. *Journal of the American Concrete Institute* **82(6)**: 797–804.
- Chen YL and Azzam R (2007) Creep fracture of sandstones. *Theoretical and Applied Fracture Mechanics* **47(1)**: 57–67.
- Cho N, Martin CD, Segure DC and Jeon J (2010) Dilation and spalling in axially compressed beams subjected to bending. *Rock Mechanics and Rock Engineering* **43(2)**: 123–133.
- Cooper AH and Saunders JM (2002) Road and bridge construction across gypsum karst in England. *Engineering Geology* **65(2)**: 217–223.
- Coviello A, Lagioia R and Nova R (2005) On the measurement of the tensile strength of soft rocks. *Rock Mechanics and Rock Engineering* **38(4)**: 251–273.
- Dreybrodt W, Romanov D and Gabrovsek F (2002) Karstification below dam sites: a model of increasing leakage from reservoirs. *Environmental Geology* **42(5)**: 518–524.
- Dusseault MB (2011) Geomechanical challenges in petroleum reservoir exploitation. *KSCE Journal of Civil Engineering* **15(4)**: 669–678.
- Efimov VP (2009) The rock strength in different tension conditions. *Journal of Mining Science* **45(6)**: 569–575.
- Elizzi MAS (1976) *The Time Dependent Behaviour of Some Evaporite Rocks*. PhD thesis, University of Sheffield, Sheffield, UK.
- Ezeldin AS and Balaguru PN (1992) Normal-and high-strength fiber-reinforced concrete under compression. *Journal of Materials in Civil Engineering* **4(4)**: 415–429.
- Fengxiang C and Mingjiang W (1983) Investigation of the engineering properties of a dam foundation containing gypsum seams. *Rock Mechanics and Rock Engineering* **16(4)**: 275–280, <https://doi.org/10.1007/BF01042361>.
- Gumusoglu MC and Ulker R (1982) The investigation of the effect of gypsum on foundation design. *Bulletin of the International Association of Engineering Geology – Bulletin de l'Association Internationale de Géologie de l'Ingénieur* **25(1)**: 99–105, <https://doi.org/10.1007/BF02603199>.
- Haifei Z, TiYu D, Yuan L and Qiang S (2009) Abrupt solubility of gypsum in water at high pressure and ambient temperature and its implication. *Acta Petrologica Sinica* **25(5)**: 1288–1290.
- Hawkes I and Mellor M (1970) Uniaxial testing in rock mechanics laboratories. *Engineering Geology* **4(3)**: 179–285.
- Heidari M, Khanlari GR, Torabi Kaveh M and Kargarian S (2012) Predicting the uniaxial compressive and tensile strengths of gypsum rock by point load testing. *Rock Mechanics and Rock Engineering* **45(2)**: 265–273.
- Ingebritsen SE and Sanford WE (1999) *Groundwater in Geologic Processes*. Cambridge University Press, Cambridge, UK.
- Jaworska J (2010) An oxygen and sulfur isotopic study of gypsum from the Wapno Salt Dome cap-rock (Poland). *Geological Quarterly* **54(1)**: 25–32.
- Johnson KS (2005) Subsidence hazards due to evaporite dissolution in the United States. *Environmental Geology* **48(3)**: 395–409.
- Khalil AA and Gad GM (1972) Gypsum plasters: I. preparation of β -hemihydrates. *Journal of Applied Chemistry and Biotechnology* **22(6)**: 697–701.
- Klimchouk A (1996) The dissolution and conversion of gypsum and anhydrite. *International Journal of Speleology* **25(3–4)**: 21–36, <https://doi.org/10.5038/1827-806X.25.3.2>.
- Koukouzias N and Vasilatos C (2008) Mineralogical and chemical properties of FGD gypsum from Florina, Greece. *Journal of Chemical Technology and Biotechnology* **83(1)**: 20–26, <https://doi.org/10.1002/jctb.1770>.
- Liang W, Zhang C, Gao H et al. (2012) Experiments on mechanical properties of salt rocks under cyclic loading. *Journal of Rock Mechanics and Geotechnical Engineering* **4(1)**: 54–61.
- Lundborg N (1967) The strength-size relation of granite. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* **4(3)**: 269–272.
- Mebarkia S and Vipulanandan C (1992) Compressive behavior of glass-fiber reinforced polymer concrete. *Journal of Materials in Civil Engineering* **4(1)**: 91–105.
- Mohammed A and Mahmood W (2018a) Vipulanandan failure models to predict the tensile strength, compressive modulus, fracture toughness and ultimate shear strength of calcium rocks. *International Journal of Geotechnical Engineering*, <https://doi.org/10.1080/19386362.2018.1468663>.
- Mohammed A and Mahmood W (2018b) Statistical variations and new correlation models to predict the mechanical behavior and ultimate shear strength of gypsum rock. *Open Engineering* **8(1)**: 213–226.
- Mohammed AS and Vipulanandan C (2014) Compressive and tensile behavior of polymer treated sulfate contaminated CL soil. *Geotechnical and Geological Engineering* **32(1)**: 71–83.
- Mohammed A and Vipulanandan C (2015) Testing and modelling the short-term behavior of lime and fly ash treated sulfate contaminated CL soil. *Geotechnical and Geological Engineering* **33(4)**: 1099–1114.
- Moonen P (2009) *Continuous–Discontinuous Modelling of Hygrothermal Damage Processes in Porous Media*. PhD thesis, Delft University of Technology, Delft, the Netherlands.
- Özkan I, Özarslan A, Geniş M and Özşen H (2009) Assessment of scale effects on uniaxial compressive strength in rock salt. *Environmental & Engineering Geoscience* **15(2)**: 91–100.

- Rauh F, Spaun G and Thuro K (2006) Assessment of the swelling potential of anhydrite in tunnelling projects. *Proceedings of the 10th IAEG Congress, Nottingham, UK*, paper no. 473.
- Salih NB, Collins PE and Kershaw S (2015) Dissolution influences on gypsum rock under short and long-term loading: implications for dams. In *Engineering Geology for Society and Territory – Volume 6: Applied Geology for Major Engineering Projects* (Lollino G, Giordan D, Thuro K *et al.* (eds)). Springer, Cham, Switzerland, pp. 779–783.
- Shafiei A, Dusseault MB and Baghdadokht Z (2008) Geotechnical properties of soluble rocks from a dam site in Iran. *Proceedings of the 42nd US Rock Mechanics Symposium (USRMS), San Francisco, CA, USA*.
- Singh VK and Singh DP (1993) Correlation between point load index and compressive strength for quartzite rocks. *Geotechnical and Geological Engineering* **11**(4): 269–272.
- Vásárhelyi B and Ván P (2006) Influence of water content on the strength of rock. *Engineering Geology* **84**(1): 70–74.
- Vipulanandan C and Krishnan S (1993) XRD analysis and leachability of solidified phenol–cement mixtures. *Cement and Concrete Research* **23**(4): 792–802.
- Vipulanandan C and Mohammed A (2015a) Smart cement modified with iron oxide nanoparticles to enhance the piezoresistive behavior and compressive strength for oil well applications. *Smart Materials and Structures* **24**(12): 125020.
- Vipulanandan C and Mohammed A (2015b) XRD and TGA, swelling and compacted properties of polymer treated sulfate contaminated CL soil. *Journal of Testing and Evaluation* **44**(6): 2270–2284, <https://doi.org/10.1520/jte20140280>.
- Vipulanandan C and Ozgurel HG (2009) Simplified relationships for particle-size distribution and permeation groutability limits for soils. *Journal of Geotechnical and Geoenvironmental Engineering* **135**(9): 1190–1197.
- Vipulanandan C and Paul E (1990) Performance of epoxy and polyester polymer concrete. *Materials Journal* **87**(3): 241–251.
- Vipulanandan C and Usluogullari OF (2011) Stress–strain behavior and California bearing ratio of artificially cemented sand. *Journal of Testing and Evaluation* **39**(4): 637–645.
- Whittles DN, Kingman S, Lowndes I and Jackson K (2006) Laboratory and numerical investigation into the characteristics of rock fragmentation. *Minerals Engineering* **19**(14): 1418–1429.
- Xeidakis GS, Samaras IS, Zacharopoulos DA and Papakaliatakis GE (1996) Crack growth in a mixed-mode loading on marble beams under three point bending. *International Journal of Fracture* **79**(2): 197–208.
- Yilmaz I (2001) Gypsum/anhydrite: some engineering problems. *Bulletin of Engineering Geology and the Environment* **60**(3): 227–230.
- Yilmaz I and Sendir H (2002) Correlation of Schmidt hardness with unconfined compressive strength and Young’s modulus in gypsum from Sivas (Turkey). *Engineering Geology* **66**(3–4): 211–219.

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