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# Swelling problems and triaxial swelling behavior of claystone: A case study in Tire, Turkey

Mehmet Erdinc Bilir

Department of Mining Engineering, Engineering Faculty, Zonguldak Karaelmas University 67100 Zonguldak, Turkey.  
E-mail: mbilir29@hotmail.com. Tel: (90-372) 257 40 10 / 1251 ext. Fax: (+90-372) 257 40 23.

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**Increase in the volume of rocks containing swelling minerals like montmorillonite and anhydrite due to physico-chemical reaction with water is defined as swelling. If increase in the volume is prevented, a swelling problem which harms engineering structures occurs. In the design of these structures the data obtained from swelling tests should be used. Triaxial swelling test is important in terms of the success of the design. In this study swelling problem caused by claystone containing smectite group clay mineral in Tire Lignite Enterprise (Izmir, Turkey) was investigated and triaxial swelling behavior of the claystone was determined.**

**Key words:** Swelling, triaxial, stress, strain, claystone, smectite.

## INTRODUCTION

One of the most important properties of soft and disintegrated rocks is that they have high strength when they are dry and low strength when wet. These kinds of rocks exhibit swelling behaviour in case they contain anhydrite and smectite group minerals such as montmorillonite.

Increase in the time-dependent volume of rocks containing swelling minerals like montmorillonite and anhydrite due to physico-chemical reaction with water is defined as swelling (ISRM, 1983). Swelling mechanism is expressed as the combination of physico-chemical reaction with water and stress relief. This reaction usually plays the most important role but swelling can only take place simultaneously with or following stress relief.

A number of researchers like Asai (1994), Egger (1996), Einstein (2000), Hawlader et al. (2005), Kovari et al. (1988), Madsen et al. (1995), Schwingenschloegl and Lehmann (2009), Tu et al. (2005) and Vrkljan et al. (1991) has studied the problems associated with the tunnels driven in swelling rocks in different countries. Of course, there exist swelling rocks in Turkey as well. However, the number of studies reporting swelling problems in under-ground engineering structures is very few. In the studies performed by Aydin (1986), Dalgic and Gozubol (1995), Ozcelik and Kulaksiz (1995), Yilmaz and Karacan (1995) and Unver and Kargi (1995) problems in galleries, gateroads and tunnels driven in swelling rocks were investigated.

The topic of this study is about swelling behaviour of claystone in underground lignite mine located in Tire, Izmir, Turkey. The purpose of the study is to quantitatively determine the swelling stress and strain by triaxial swelling test and to propose a triaxial swelling equation. In this paper, swelling problems in Tire Lignite Enterprise were specified first, then swelling data were obtained and conclusions were drawn and comments were made accordingly.

## MATERIALS AND METHODS

### Swelling problems

Tire is a town 80 km far from Izmir and situated in southeast of the city (Figure 1). It is surrounded by Kucuk Menderes Plain and Bayindir in the north, Odemis in the east, Selcuk and Torbali towns in the west and Aydin Mountains in the south. Tire Lignite Enterprises Co. is located near Akcasehir Village, Karagol region of Tire.

Neogene aged cover rocks of the region have been unconformably lied upon to the Paleozoic aged marble and schist of the Menderes Massif (Gemici et al., 1992). The stratigraphic section of the region is given in Figure 2. Neogene sediment accumulation called as Ayaklikiri formation starts with pebbles derived from metamorphic rocks at the basement and continues with sandstone and mudstone inter-beddings containing claystone at the middle levels of the sequence. In Akcasehir region coal formation is observed as 3 seams in claystone. These seams are Buyuk seam



Figure 1. Location map.

AGE	LITHOLOGY	EXPLANATION
NEOGENE MIDDLE MIOCENE	[Horizontal dashed lines]	Claystone
	[Alternating horizontal solid and dashed lines]	Coal Seams
	[Horizontal dotted lines]	Sandstone
	[Horizontal dash-dot lines]	Mudstone
	[Horizontal dotted lines with small circles]	Pebblestone
PALAEO-MESOZOIC	[Wavy lines]	Schist
	[Horizontal lines with vertical dashes]	Marble
NO SCALE		

Figure 2. Generalized stratigraphic section of Akçesehir-Tire (Gemici et al., 1992)

(10 to 12 m), Orta seam (5 to 6 m) and Kucuk seam (1.5 to 2.0 m).

Mining area lays over a syncline having direction of northeast-southwest (MENR, 2007). Mining method employed in the mine is retreated longwall method. Coal production is made by Cardox

system. Cardox system is based on the principle that the pressure resulted from the expansion of liquid CO<sub>2</sub> penetrates into the fissures and fractures inside the coal and breaks the coal into pieces. Wooden supports are primarily preferred due to their low cost (E. Tuncer, Tire Lignite Enterprise, personal communication). In case of instability problems, then steel and concrete supports are used. The level of ground water exceeds the production level due to excess rain between December and March. Since coal seams are in claystone containing smectite group minerals swelling problems are encountered in galleries and gateroads. These problems are; cracking and breaking in concrete supports, inward moving sidewalls, bending and buckling of steel arches and closure in the cross-section of galleries, embedded wooden timbers, and breakage in centre props and floor heave in gateroads. These problems were investigated in 9 locations shown in the plan of the mine and presented in Figure 3. These locations and associated problems are summarized in Table 1. Furthermore, Figures 4 to 8 are the examples of the swelling problems in the mine.

In order to solve swelling problem in regions where steel and wooden supports are available shaving off method which is a passive design approach is employed. Shaving off is required in every 6 months. As a result of swelling behaviour there occurs a closure in cross-section and shaving off is needed when it starts to ruin hauling shaving off is done to achieve original cross-sectional area. Swelling occurs again after a while due to moisture in the air or water leaking from surrounding rock mass since as a result of this process surfaces having relatively lower water content are created. This vicious circle is a disadvantage of shaving off application in regions where swelling problems occur.

In cases where shaving off is not adequate to solve the problem concrete support is used. Figure 9 shows the concrete support applied in Location 4. Thickness of the concrete in this 25 m-section is 70 cm and it goes 1.20 m further down from the floor. However, fractures started to occur in the sidewalls. Flat floor geometry

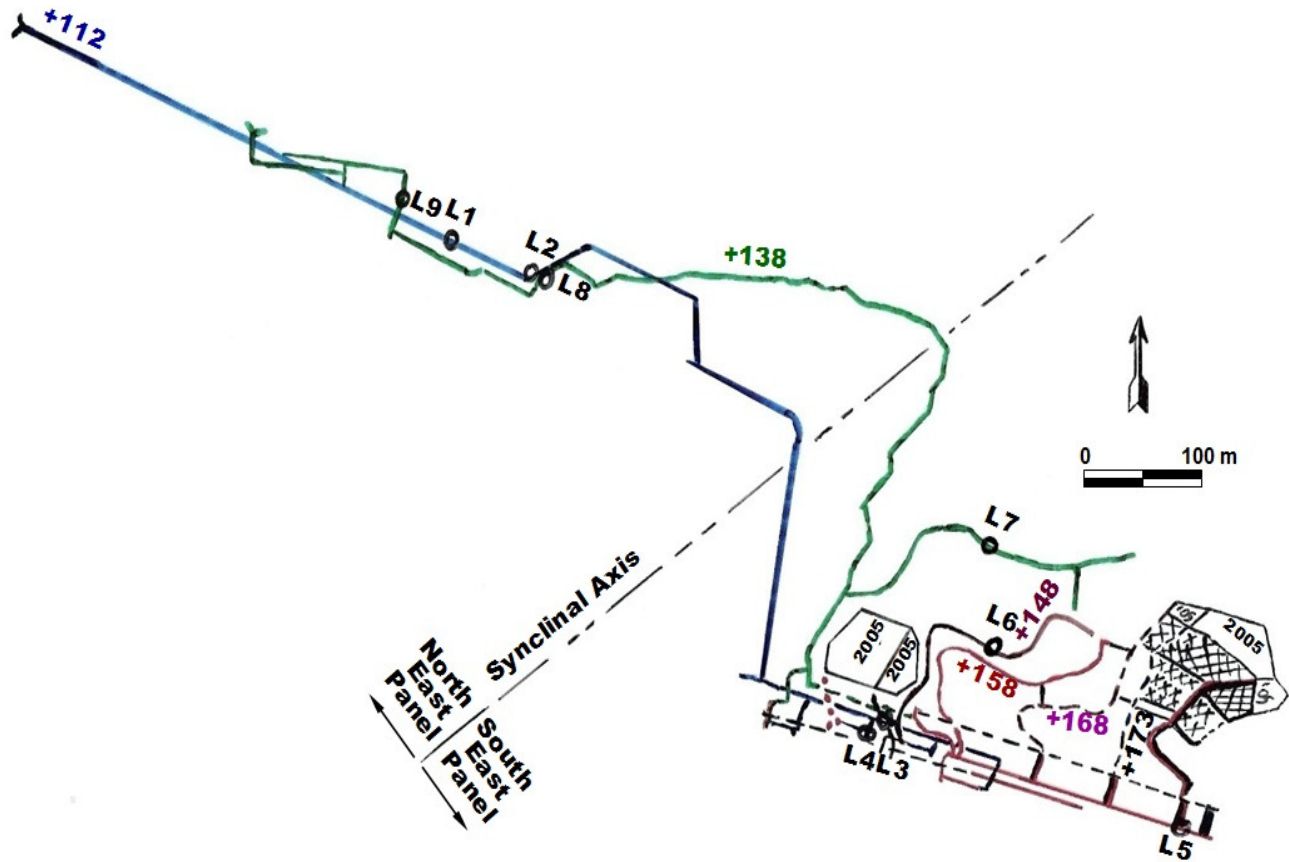


Figure 3. Plan of Tire lignite mine.

causes stress relief region to be bigger and occurrence of small counter stresses.

### Sample preparation

Swelling tests were performed on cylindrical core samples with a diameter of 54 mm and a height of 2 cm obtained from block samples taken from Tire Lignite Enterprise, but no swelling is reported. Then, the samples were ground and pressed by a special apparatus developed by Yesil (1991) with the same density ( $1.77 \text{ g/cm}^3$  dry) and cylindrical samples with a diameter of 54 mm were obtained. Sample height and diameter/height (D/H) ratio were determined as 20 mm and 2.7, respectively by taking recommendations in ISRM (1979) and ISRM (1989) into account. Although it was designed to press whole samples to have a density of  $1.77 \text{ g/cm}^3$  and a D/H ratio of 2.7 it is very difficult in practice. Hence, it was attempted to approach these values as much as possible.

### Triaxial swelling test apparatus

Computer controlled triaxial swelling apparatus was designed taking setups developed by Yesil (1991) and Bilir (2001) into account (Figure 10). Depending on the confining pressure swelling load and swelling displacements can be measured by this apparatus with a sensitivity of 0.001 kN and 10  $\mu\text{m}$ , respectively. Apparatus is connected to an uninterrupted power supply (UPS) against electricity cut-offs. The apparatus is composed of main

frame, a confining pressure unit and a data acquisition and control unit.

Main frame is composed of a triaxial cell and an axial loading unit. The triaxial swelling cell is composed of upper and lower loading platens containing porous stones, a rubber jacket, a seating cylinder, lower and top end caps mounting the cell and a water container (Figure 11). The sample is placed into the jacket and the jacket is put into the seating cylinder. There is a 1 cm circumferential gap between the wall of the seating cylinder and the wall of the rubber jacket. The oil fills this gap and applies pressure to the sample. The gap also allows the sample to swell laterally. Swelling occurs by the contact of water passing through upper and lower platens with the sample. The axial loading unit is composed of two columns, a loading piston, a load cell, a displacement transducer and a motor. It controls swelling by applying or removing the load onto/from the sample.

The components of the confining pressure unit are; 0.37 kW electric motor, a manometer, a spherical valve, a pressure relief valve and a speed (frequency) control device. The purpose of confining pressure unit is to provide a continuous and constant confining pressure in a desired level by oil.

The data acquisition and control unit is composed of a computer, data acquisition unit, a communicator, an interface (input/output) card and speed control device. Software developed by Visual Basic records data coming from the apparatus in definite intervals and does some controls to make motor load or unload. The software is composed of a Displacement Control Program by which swelling load is defined (the motor applies load) and a Load Control Program by which maximum displacement is defined (the motor unloads). Working principles of these programs are based on

**Table 1.** Swelling problems in Tire Lignite Enterprise.

Location	Surrounding rock	Roof height (cm)			Floor width (cm)			Type of support	Swelling problem
		O	F	SD	O	F	SD		
1 (+112 level)	Claystone	200	173	27	260	177	83	Concrete	Exfoliation in lining, closure in cross-section
2 (+112 level)	Claystone	200	187	13	260	250	10	Steel	Closure in cross-section
3 (+112 level)	Adjacent rock: coal, Floor: claystone	200	200	0	260	260	0	Steel	Floor heave
4 (+112 level)	Adjacent rock: coal, Floor: claystone	200	170	30	260	256	4	Steel	Closure in cross-section
5 (+158 level)	Adjacent rock: coal, Floor: claystone	200	165	35	260	215	45	Steel	Closure in cross-section, deformation in railways
6 (+148 level)	Adjacent rock: coal, Floor: claystone	200	170	30	260	210	50	Wood	Closure in cross-section, breakage and embedding of timbers
7 (+131 level)	Adjacent rock: coal, Floor: claystone	200	160	40	260	205	55	Wood	Deformation in gateroads and railways due to floor heave
8 (+131 level)	Clayish sandstone	200	160	40	260	220	40	Steel	Floor heave, deformation in steel arches and railways
9 (+131 level)	Claystone	200	120	80	260	180	80	Concrete	Closure in cross-section (inward moving sidewalls)

O: Original height; F: Final height at the measurement time; SD: Swell displacement

swelling test methods suggested by ISRM (1989) and Yesil (1991).

**Test method**

The purpose of the test method is, after applying confining pressure, to define axial swelling stress first by triggering Displacement Control Program and then uses Load Control Program a few times by which the load over the sample is reduced in certain amounts to define axial swelling strains. The test method is described in detail below:

(a) Swelling cell is placed into the water container, and water container is placed over the piston so that contact between the loading cell and the swelling cell is provided. Then confining pressure is applied to the sample. Displacement transducer is reset.

(b) The sample is allowed to swell up to 50 µm by starting the Displacement Control Program. The program makes the motor work at every time swelling exceeds 50 µm and applies load onto the sample so that swelling reduces down to 50 µm. After a while the sample starts swelling again and comes to 50 µm. The program sends signal to the motor to load the sample again. This loop continues until the displacement stays below 50 µm. As a result maximum swelling load is obtained in the Displacement Control Phase.

(c) The Displacement Control Program is stopped and information such as ports, recording interval, maximum

load obtained from Displacement Control phase are entered into the Load Control Program.

(d) By entering maximum load the Load Control Program calculates the level to which it lowers the load. This load, called “reduced load”, is usually the half of the maximum load. When the program is run the motor starts in reverse direction and removes the load over the sample and stops just below the reduced load. When the half of the load over the sample is unloaded the sample starts to swell. The program, now, controls whether the reduced load is exceeded or not. Load increases when the sample tries to swell and after some time exceeds the reduced load. The motor runs again and reduces the load below the reduced load and swelling occurs. This loop continues until the load stays below the reduced load. As a result, maximum swelling at a certain reduced load is defined and program is stopped.

(e) Swelling strain corresponding to axial swelling stresses is found by running the Load Control Program as much as desired. Every time the Load Control Program is run load in the former phase is entered into the program as maximum swelling load and reduced load levels are calculated. In general, it is enough to run the Load Control Program three or four times.

**RESULTS**

The variations in swelling stresses and swelling

strains of Tire claystone with time obtained from triaxial swelling tests under confining pressures of 0.5, 1 and 2 MPa and geotechnical properties are given in Figures 12 to 15 and Table 2, respectively.

The test performed with a confining pressure of 0.5 MPa lasted in 10 days and the axial swelling stress was 1.41 MPa. The axial swelling strain ranges from 0.05 to 2.91%. The test done with a confining pressure of 1.0 MPa lasted in 23 days and the axial swelling stress was 1.76 MPa and the axial swelling strain ranges from 0.10 to 1.81%. The test performed with a confining pressure of 2.0 MPa lasted in 18 days and the axial swelling stress was defined as 2.06 MPa and the axial swelling strain ranges from 0.10 to 2.77%. Water content variation changes between 24.20 and 27.80%. In addition, liquid limit and plastic limit were found as 57.50 and 37.51%, respectively.

According to the results of XRD (X-ray diffraction) semi-quantitative mineralogical analysis done in Earthsciences Application and Research Centre of Hacettepe University, it was found that the whole rock contains 66% clay minerals and 19% of this clay mineral is composed of smectite.



**Figure 4.** Location 1 (+ 112 level).



**Figure 5.** Location 2 (+ 112 level).



**Figure 6.** Location 4 (+ 112 level).



Figure 7. Location 6 (+ 148 level).



Figure 8. Location 9 (+ 131 level).

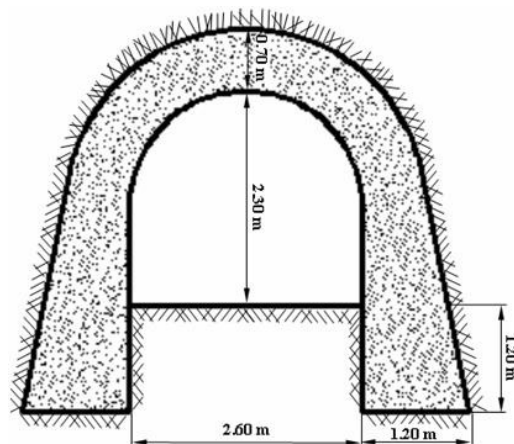


Figure 9. Cross-section of concrete support applied against swelling on Location 4.

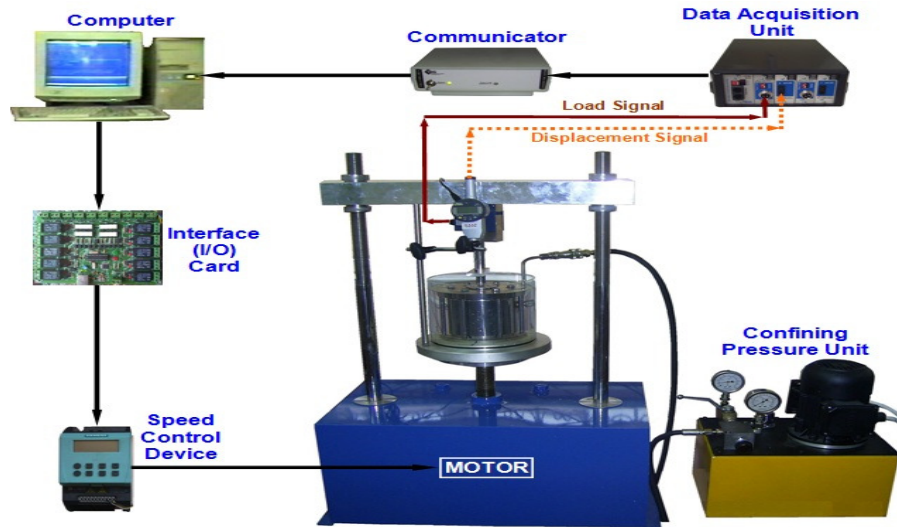


Figure 10. Triaxial swelling test apparatus.

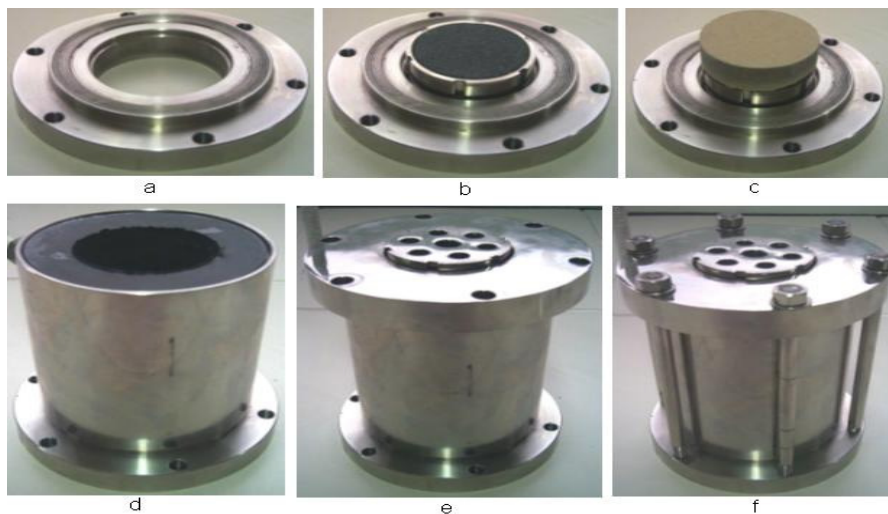


Figure 11. Installation steps of triaxial swelling cell.

The relationship between axial swelling stress ( $\sigma_s$ ) and axial swelling strain ( $\epsilon_s$ ) under each confining pressure ( $\sigma_3$ ) obtained from triaxial swelling tests for Tire claystone is given in Figure 16 and obtained equations are given in Equations (1 to 3).

$$\sigma_3 = 0.5 \text{ MPa for } \epsilon_s = -2.84 \ln(\sigma_s) + 0.88 \quad R^2 = 0.98 \quad (1)$$

$$\sigma_3 = 1.0 \text{ MPa for } \epsilon_s = -3.04 \ln(\sigma_s) + 1.74 \quad R^2 = 0.97 \quad (2)$$

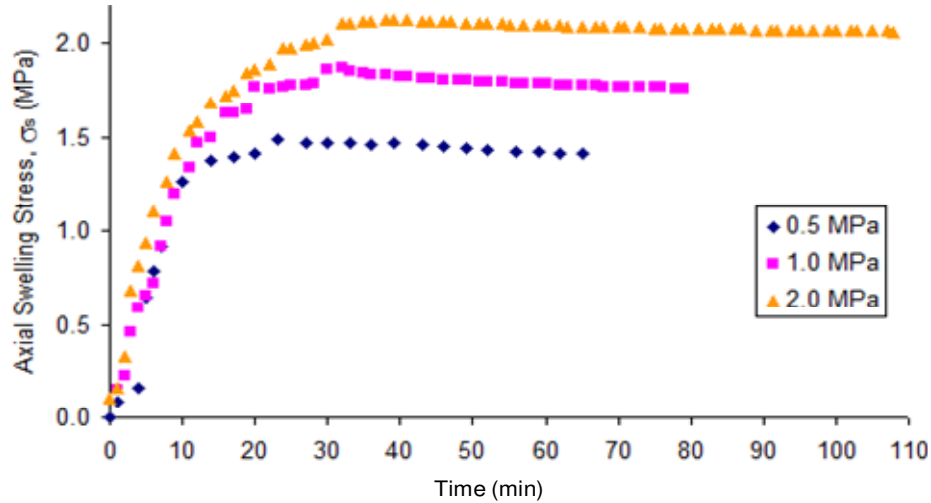
$$\sigma_3 = 2.0 \text{ MPa for } \epsilon_s = -3.84 \ln(\sigma_s) + 2.75 \quad R^2 = 0.99 \quad (3)$$

In order to express the triaxial swelling behaviour mathematically multiple regression analysis was

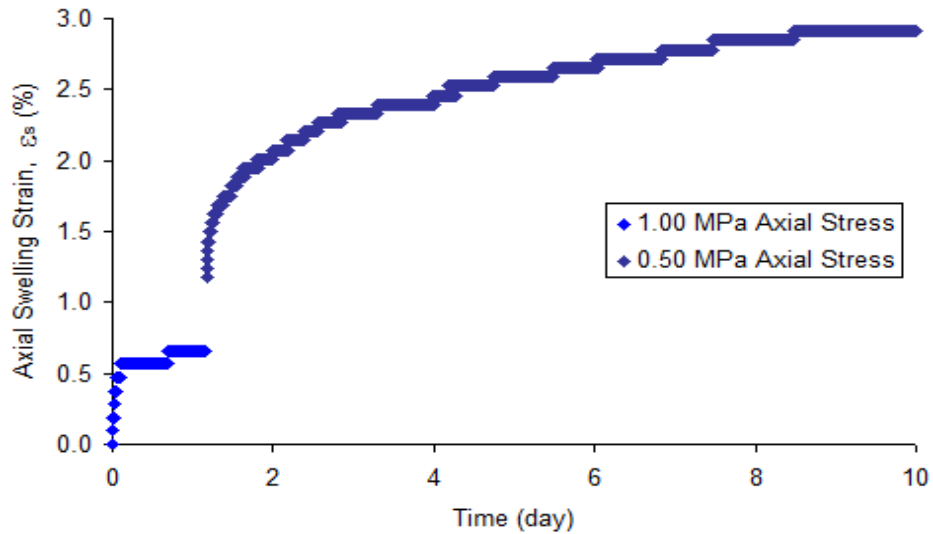
performed and triaxial swelling correlation of Tire claystone was found as in Equation (4). T test is statistically significant in 95% confidence interval for axial swelling strain ( $\epsilon_s$ ) and confining pressure coefficients ( $\sigma_3$ ). Furthermore, F test is also statistically significant in the same confidence interval.

$$\sigma_s = 1.17 \cdot 1.38 \sigma_3 \cdot 0.73 \epsilon_s \quad R^2 = 0.95 \quad SE = 0.10 \quad (4)$$

The tests were stopped since the rubber jacket was burst in reduced loads at which the load over the sample is lower than the confining pressure in each of the three confining pressure levels, thus maximum swelling strains were not obtained. However, the maximum swelling



**Figure 12.** The variation of axial swelling stress with time at different confining pressures.



**Figure 13.** The variation in axial swelling strain with time under different axial stresses at a confining pressure of 0.5 MPa.

strain is estimated from Equations (1 to 3) and Equation (4) by assuming  $\sigma_s$  equal to 0.025 MPa (seating load) and found as 11.36 and 16.92%, and 12.73 and 14.26%, respectively (Table 3).

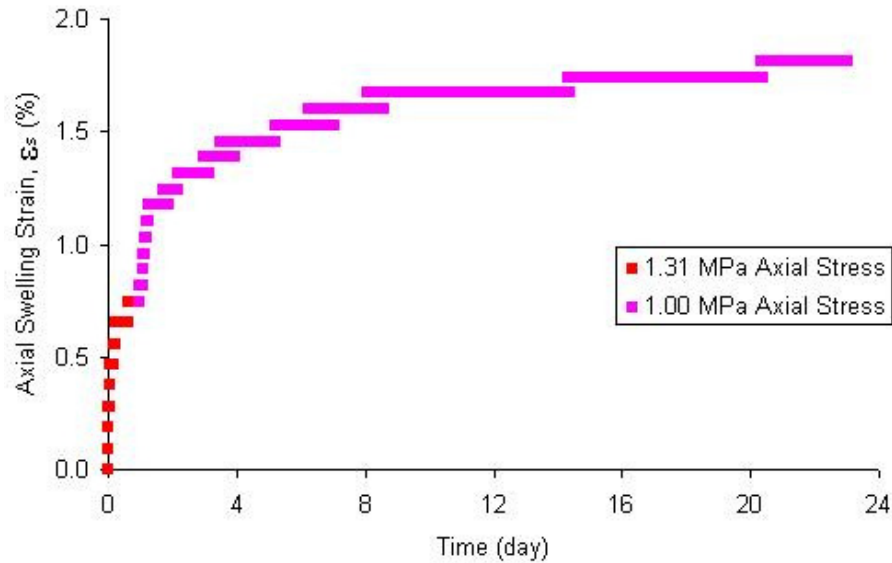
## DISCUSSION

The main reasons of swelling problems occurred in Tire Lignite Enterprise are; maximum swelling stress obtained and ranging from 1.41 and 2.06 MPa (Figure 16), maximum swelling strains calculated in between 11.36 and 16.92% and smectite type clay which accounts for 19% of the clay fraction. Claystone below the water table in places where there is no stresses applied against the

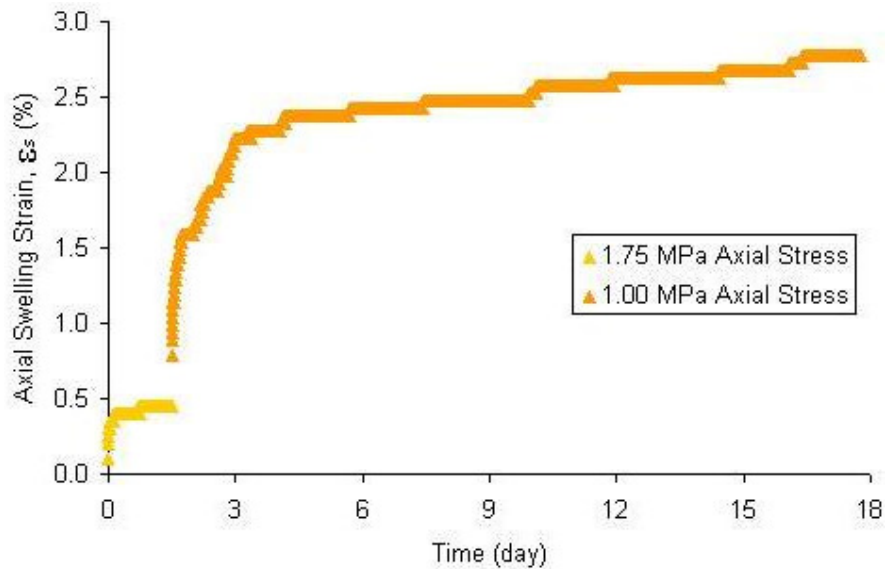
surface of the opening was freely swelled, and in places where there is a counter-stress excess swelling stresses caused timbers, steel arches and concrete supports to be deformed. As Figures 12 to 15 were analyzed it was determined that most of the swelling stress and strain develops shortly after the contact of claystone with water and then they slow down since claystone is saturated with water. Moreover, swelling stresses were defined in shorter times than swelling strains.

The reason that the shaving off method applied to prevent swelling strains is unsuccessful is that the counter-stresses were prevented and fresh surfaces unsaturated by water were created by shaving off the swollen parts. More swelling occurs cumulatively because of continuous shaving off. Although it seems





**Figure 14.** The variation in axial swelling strain with time under different axial stresses at a confining pressure of 1 MPa.



**Figure 15.** The variation in axial swelling strain with time under different axial stresses at a confining pressure of 2 MPa.

that the cost of individual shaving off process is low increasing number of shaving off makes the method more expensive. Cracks occurred in 70 cm-thick concrete indicates high swelling stresses. Since stress relief region is greater in the flat floor and there is no counter-stresses preventing the swelling of claystone, it is highly possible that more swelling strains will be encountered in the future.

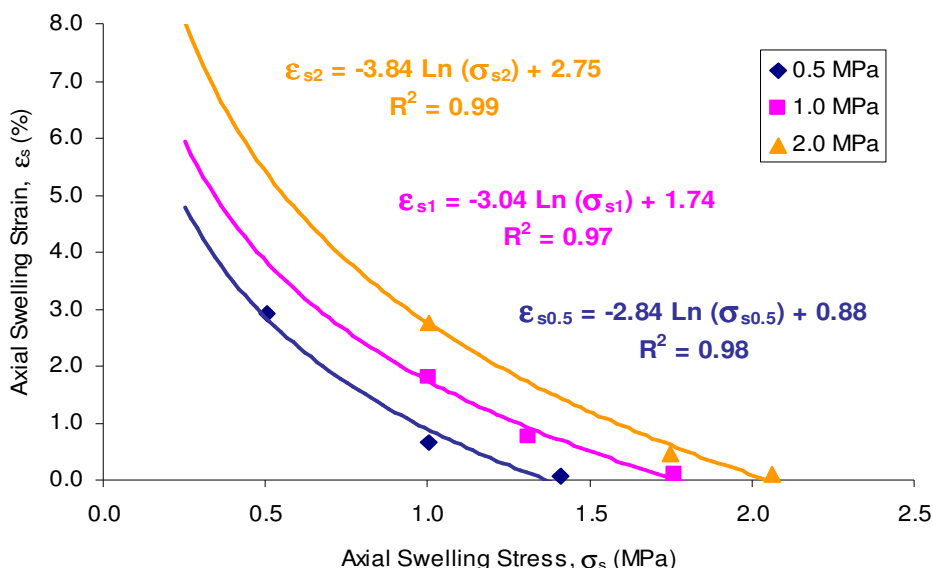
In solving the swelling problems encountered in the mine either active-passive or intermediate approaches recommended by ISRM (1994) can be used. Maximum

swelling stress is used in the active design in which the rock is not allowed to swell freely. In passive design in which there is no swelling stress, maximum swelling strain is taken into account. Moreover, swelling stress and strain lower than the maximum values and higher than the minimum values are used in intermediate approach. These values should be determined by Figure 16 and/or Equation (4).

The tests to determine the triaxial swelling behaviour of the claystone continued 51 days. During this period swelling displacement and load were continuously

**Table 2.** Geotechnical properties of Tire claystone.

Confining pressure, $\sigma_3$ (MPa)	0.5		1.0		2.0				
Axial swelling stress, $\sigma_s$ (MPa)	1.41	1.00	0.50	1.76	1.31	1.00	2.06	1.75	1.00
Axial swelling strain, $\epsilon_s$ (%)	0.05	0.66	2.91	0.10	0.75	1.81	0.10	0.45	2.77
Density, $d$ (g/cm <sup>3</sup> )	1.79		1.75		1.75				
Height, $H$ (cm)	1.975		2.013		2.020				
Weight, $m$ (g)	80.782		80.783		80.986				
D/H	2.73		2.68		2.67				
Initial water content, $W_i$ (%)	0.23		0.62		0.65				
Final water content, $W_f$ (%)	28.03		24.82		25.91				
Water content variation, $W_v$ (%)	27.80		24.20		25.26				
Diameter, $D$ (cm)	5.40								
Liquid limit, LL (%)	57.50								
Plastic limit, PL (%)	37.51								
Smectite content $S_c$ (%)	19								
Clay content, $C_c$ (%)	66								



**Figure 16.** The relationship between axial swelling stress and axial swelling strain of Tire claystone depending on the confining pressure.

**Table 3.** Maximum swelling strains estimated by equations.

Equation	$\sigma_s$ (MPa)	$\sigma_3$ (MPa)	$\epsilon_s$ (%)
1 and 4	0.025	0.5	11.36 and 12.73
2 and 4	0.025	1.0	12.95 and 13.23
3 and 4	0.025	2.0	16.92 and 14.26

checked by the computer-controlled triaxial swelling apparatus equipped with digital measurement transducers, and the data were frequently recorded. Hence, performing tests became easier and high-precision

measurements were taken.

Another difficult step in swelling tests is sample preparation. Because of the breakage and cracking of samples while taking cores from rock blocks, obtaining

intact cores are usually not possible. Thus, the samples are ground and then pressed again to be used in the tests. However, grinding disturbs the mineralogical structure of the rock. Swelling stresses and swelling strains of disturbed samples are usually higher than those of the intact ones. The reason is that the water can penetrate into disturbed samples more easily. Thus, using disturbed samples are considered as a disadvantage in triaxial swelling tests.

## CONCLUSIONS

The determination and solving of swelling problems in underground openings requires knowledge and a detailed investigation covering *in-situ* observation and measurements, and design. The results of the current study in which the problems experienced in Tire Lignite Enterprise due to swelling claystone are analyzed and the determination of the data to be used in design is listed below:

(a) The swelling problems encountered either in the gateroads supported by timbers and the galleries supported by steel arches or concrete supports are resulted from the contact of ground water exceeding the production level in rainy seasons and claystone containing smectite group clay minerals.

(b) In order to prevent the problems, 70 cm-thick concrete support are applied and shaving off method is employed. Since the design is not done taking swelling stress and strain into account the problems are faced again after a short time.

(c) Swelling stresses were found as a function of axial swelling strains by applying confining pressures of 0.5, 1 and 2 MPa to disturbed samples in triaxial swelling tests. According to these data "Triaxial Swelling Equation" was derived for Tire claystone. Maximum measured axial swelling stress is found as 2.06 MPa and maximum axial swelling strain estimated from Equation (4) is found as 14.26%.

(d) It is considered that using triaxial swelling equation in support design may minimize the swelling problem in the mine. Moreover, utilization of drainage channels for surface waters and lowering the ground water level below production level by drilling may prevent the contact of water with minerals having a swelling potential.

(e) Swelling tests should be performed under triaxial conditions. Since the tests take long time the equipment to be used should be computer-controlled which enable the researchers to make precise measurements and obtain swelling data close to the practical values.

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