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Development of a new creep testing equipment to obtain long-term deformation parameters of salt

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Abstract

Creep phenomenon in rock engineering plays a key role in the development of underground spaces as they must be stable enough for a long period of time. The study describes the main ideas of the design and manufacturing of a new creep testing machine that is set up at Shahrood University of Technology (SUT). The testing machine is capable of performing creep tests at low equivalent stresses on more than one cylindrical rock sample simultaneously at a very low cost. To evaluate the performance of the equipment, a series of creep tests were performed on salt rock samples and their axial and lateral deformations were measured by dial gauges. Measurements were taken under constant temperature, humidity and sustained loads. The results revealed that both axial and lateral creep behavior of specimens follow the same pattern with an idealized salt rock creep curve. The experiments also indicated that the steady state creep rate rises with increasing initial applied stress level.

Keywords: *Long-term creep; uniaxial creep test; salt rock; lever arm; rock testing standards.*

1.Introduction

The simulation of the long-term behavior of salt domes or salt layers and the behavior of caverns constructed in this rock require knowledge of the time-dependent deformational characteristics of rock salt such as creep and dilation. Creep in rock mechanics is defined as irreversible deformation under constant or sustaining stress without fracturing and is observed mainly in soft rocks and less in all other kinds of rocks within long enough time intervals [1]. The effect of time dependent deformation on the behavior of geologic material has long been recognized [2, 3, 4, 5, 6]. A common goal of previous studies is to determine creep properties of rocks that are essential for further development in the field of underground mining, storage caverns and structures in and on rocks [7].

In principal, rock deformation can be divided into recoverable and permanent components. Both can be observed when the load on a specimen is applied, removed or reduced. Furthermore, the time-dependent creep deformation process can be divided into three stages: primary, secondary and tertiary creep phase. The initial (time-independent) deformation can roughly be predicted by its stress-strain modulus. A material, which is capable of creep like salt, will continue to deform slowly with time indefinitely. It is possible if applied stresses are low or until rupture causes failure if the stressing is high enough. The primary region is the early stage of loading when the creep rate decreases rapidly over time. Then it reaches a steady state which is called the secondary creep stage followed by a rapid

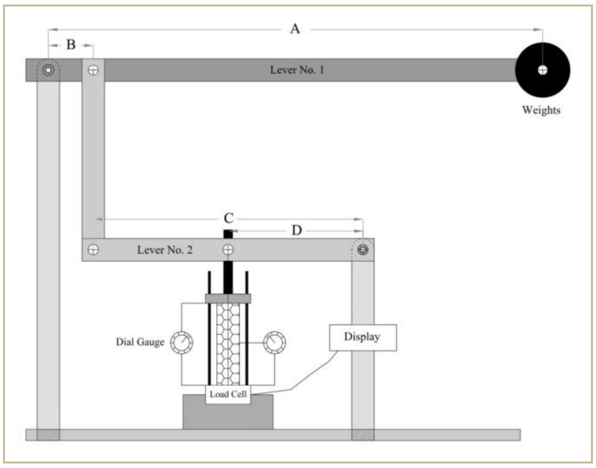
increase (tertiary stage) and fracture, if the applied stresses are high. The tertiary stage is always connected with the phenomenon of time-dependent failure [8].
Creep also depending on several factors, such as structural rock properties, magnitude of the applied load (stress), temperature and time. During decades, many efforts have been directed toward the study on time-dependent behaviors of salt rock and the parameters affecting it including the effect of stress and strain rate [9], temperature effects [9, 10, 11, 12], Humidity [13, 14], Inclusions and impurities [15, 16, 17]. More recently, there has been many achievements documented in the six conferences on the mechanical behavior of salt since 1984 and other publications. It is important that suitable creep behavior be evolved to find out the stability of existing as well as future openings in salt rocks which show deformation over time. Therefore, it was decided to establish the necessary laboratory facilities for studying the creep behavior of salt rocks.

2. Creep test principles

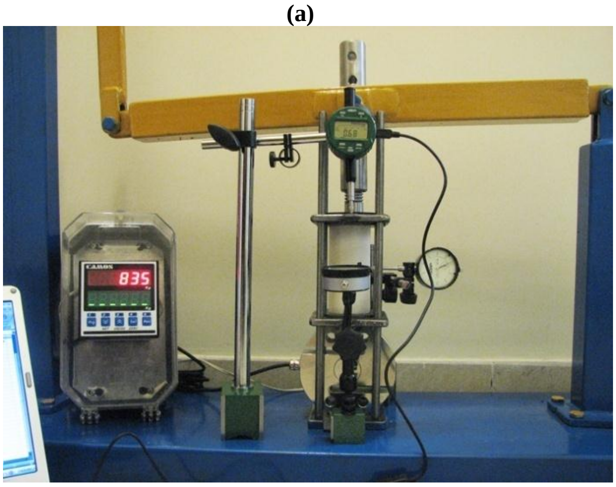
In principle, the creep deformation should be linked to an applied stress. Thus, as the sample deforms, the cross-sectional area varies and the load needs to be corrected to maintain a constant stress. For long-term creep testing, it makes experiments expensive as servo-controlled machines should be used. In practice, because of the associated experimental ease, constant load testing is recommended [18]. Therefore, when reporting creep test results, the initial applied stress is used.
The study of time-dependent strain has many experimental difficulties as it must be carried out under controlled conditions for temperature and humidity. Also, the sustained load should be applied throughout the experiment and the strain measuring system must be sensitive enough to show small strain in the samples.
Extensive laboratory investigations have been performed over the past several decades on mechanical creep behavior of soft rocks such as coal, salt rock and shale, as well as hard rocks, like granite and tuff, with the aid of servo-controlled hydraulic systems, conventional compression test machines and mechanical loading equipment including springs and levers. For long-term creep tests, simple mechanical testing machines cannot be used as they are not capable of sustaining the applied load constant while the sample is deformed. Servo-controlled testing machines have the advantages of ensuring constant stress and accurate measurements. Also, they can conduct both single and multi-step creep tests. This however involves comparatively higher costs for long-term creep tests.
Lever arm testing machines provide a more satisfactory condition for constant load, but are limited by their loading capacity. For the mechanical spring testing machine, the applied load level will decrease as the sample deforms To study the creep behavior of salt rocks, this study conducted uniaxial compression creep tests using newly developed testing machine as described in the section 2.1. Required facility for studying time-dependent deformation was manufactured by the research team at Shahrood University of Technology (SUT) as described below. The creep curves obtained from these tests were compared in terms of creep rates with values calculated using generally accepted creep laws for salt rocks.

2.1. Applying constant load

Creep testing programs can be performed using hydraulic, pneumatic or mechanical loading systems. Because of their higher loading capacity, Servo-Hydraulic units are best fitted for such tests. However, long-term testing of material can be very expensive using these machines while, mechanical instruments, in a relatively lower cost and loading capacity can be more preferable for soft materials such as salt and coal. Springs and levers are widely used in mechanical loading instruments to ensure constant loading in long enough time intervals. However, loading capacity of spring will decrease by it's lengthen; so, levers are more appropriate to use in mechanical loading equipments, especially in those used in creep test.
The facility is developed to perform creep tests by applying different loading scenarios to one or more cylindrical rock samples and measuring their deformation response. It works in combination of two second-type lever arms and dead weights as shown in Figure 1a and 1b. In the second-type levers load is applied on one side of the resistance and the fulcrum is located on the other side. Based on the law of the lever, the power into the lever equals the power out, and the ratio of output to input force is given by the ratio of the distances from the fulcrum to the points of application of these forces.
As shown in Figure 1, the ideal mechanical efficiency of the whole system can be multiplied by increasing the number of lever arms but, the moving intervals of the upper loading plate will be decreased dramatically instead. Currently the



(a)



(b)

Figure 1. Uniaxial creep Testing Equipment - a: Schematic layout, b: Measuring units including axial and lateral displacement gauges, load cell and display system

mechanical advantage of the system is ideally equal to 25.

To apply load on samples, at first, weights are placed at the end of lever number one. Mechanical advantage of the first lever (approximately equal to 12.6) will enhance applied force and transmit it through vertical connector between levers. Next, the mechanical advantage of the second lever (approximately equal to 2) will increase the applied force 2 times and transmit it to the sample with the aid of loading axis. Weights should be kept unchanged during each experiment. Also, humidity and temperature should be carefully monitored. Finally, to unload the sample, weights can be easily removed. The equipment facilitates repeating similar experiments by using different loading. The only thing that needs to be changed is weight.

2.2. Measuring devices

To measure strain in rock samples, a number of methods such as optical systems, strain gauges and dial gauges have been frequently used. In this investigation dial gauges were preferred due to their simplicity and economy. The INSIZE dial gauges used in this work were of 30 mm range and read to 0.01 millimeters. The dial gauges were installed on the system to collect axial and lateral deformation data.

The first set of gauges was used to measure vertical strain and placed between the two loading platens. The second set, including two gauges, was used to determine the lateral strain and were vertically connected to the sample. Since, load is applied using dead weights, a measuring device was required. To measure initial stress state, a LS300-5t load cell was mounted below the lower platen and connected via a relay to a display system. Load cell accuracy is equal to ±10N based on careful calibration. Also, a digital thermometer and a psychrometer were used to ensure constant physical conditions in the laboratory.

3. Experimental working

In the following section the experimental work including basic tests and uniaxial creep tests on salt rock samples are discussed. Particularly, the structure of salt rock mass requires special consideration during coring and cutting program as will be pointed out below.

3.1. Sample preparation

Sample preparation followed the ASTM D4543 standard practice as much as practical. Specimens, with length to diameter ratio equal to 2.5 were prepared for uniaxial compression and creep test. The core samples with a nominal diameter of 54mm were drilled from block samples obtained from Koohdasht-e-Kohan underground salt mine in Garmsar, Iran. The laboratory coring program on block samples consumed a great deal of time, effort and material. Most of the coring problems were directly related to the internal structure of the salt. It was a soft material with a crystalline structure, extremely brittle, especially when unconfined and subjected to high temperature and also severely soluble in water. It was not possible to use dry coring procedures as thermal stress in rock samples is caused thereby. Similarly, water could not be used since it dissolves the sample surface and changes its characteristics.

Final procedure for coring from salt rock was a combination of previous experiences and trial and error.

Most of the coring problems were directly related to the structure of salt. It was a soft material with a crystalline structure, extremely brittle, especially when unconfined and subjected to high temperature and also severely soluble in water. It was not possible to use dry drilling as it caused thermal stress in rock samples. In the final drilling procedure, cores were drilled using saturated brine as drilling fluid. Coring was conducted at low rotation speed of core barrel and small trust approximately equivalent to the self-weight of the barrel.

The saturated brine as drilling fluid was prepared from the same rock sample in order to have the least effect on specimens. It was also used as grinding fluid during the cutting. A recovery system was used to recycle brine to avoid producing much more saline water.

After the coring program, the sample dimensions were measured using a digital caliper. Finally, the specimens were labeled and wrapped with linen and plastic sheets.

3.2. Uniaxial compression test

A series of uniaxial compression test was conducted using INSTRON 8802 servo-controlled machine to determine the average ultimate uniaxial short-term strength of the specimens under uniaxial compression (Figure 2a and 2b). These tests were performed to determine stress level in uniaxial creep tests to avoid sudden failure of salt samples under in long time intervals. It can seriously damage measuring units in the creep testing equipment. This test procedure follows the ASTM D2938 standard as much as practical [19]. The axial compressive load is applied linearly to touch 10mm displacement in 5 to 10 minutes. The result of four UCS test is plotted in Figure 3. Based on these Based on these experiment results the average uniaxial compressive strength was calculated at 28.7MPa. So, long-term creep tests should be conducted at a lower stress level.

3.3. Long- term uniaxial creep test

In order to study the creep characteristic of the rock salt, the specimens were loaded continuously for a maximum period of 120 hours, while assuring constant stress in the specimen depending on the displacement results. This test procedure follows the ASTM D4405 standard as much as practical [18]. During the test, the axial and lateral deformations and time were recorded. The frequency of readings was much more at the beginning of the test and gradually decreased to once a day after the first few days of the test. This also depended on the deformation rate of each specimen. The results are presented by strain-time curves as shown in Figure 4 and 5. The initial applied stress varies from 3.6 to 7.3MPa for each test. As the applied loads were less than the uniaxial strength, a long-term deformation was expected and could be observed for each specimen. Experiments showed that the creep rate in lateral direction was more sensitive than in the axial direction. Another important observation is that both axial and lateral creep curves follow the same pattern with an idealized salt rock creep curve. However, lateral creep strain can touch the steady state faster than axial creep strain. Also, experiments indicated that the steady state creep rate grows with increasing initial applied stress state.

(a)

(b)

Figure 2. a: INSTRON 8802 servo-hydraulic testing equipment, b: Failure of the sample in UCS testing under ASTM D2938 standard condition

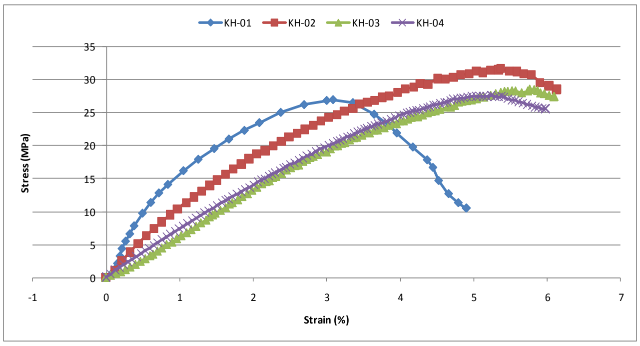


Figure 3. Uniaxial Compressive Strength of four samples

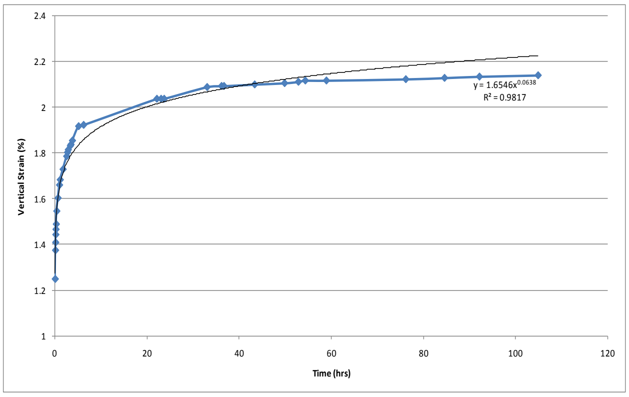


Figure 4. Axial strain of sample No. 1 under 3.6Mpa initial stress

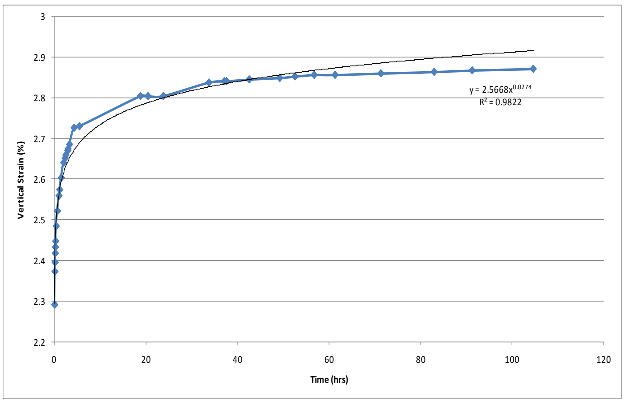


Figure 5. Axial strain of sample No. 2 under 7.3Mpa initial stress

4. Conclusion

A new creep testing machine was designed and developed in this research to conduct long-term uniaxial creep test in a very low cost. The testing machine is capable of performing simultaneous light-duty creep tests on more than one cylindrical rock sample. To evaluate the equipment performance, creep tests were conducted on salt rock since it has a distinctive rheological behavior. The facility is designed as simple as possible to achieve an easy-to-use machine for time-dependant studies. Dead weights along with mechanical advantage of the system apply a constant load by order of 25 to the sample(s). Experiments revealed that the equipment ensuring constant load on samples for long enough time period. However, a negligible tolerance in applied load is recorded by average of 1.8% on careful calibration of load cell basis. To perform accurate creep test, an especial method was introduced to conduct coring program in the laboratory because of salt unique characteristics. Saturated brine was prepared from the same salt rock to have the least effect on specimens.

The steady state creep rate was found to increase with the increasing initial applied stress in salt samples tested within the scope of presented investigations. Axial creep curves obtained in this study follow the principle patterns of a creep test when regarding the different stages of creep. A power law based curve was found to fit the creep curves of the tested salt specimens up to the steady state stage of creep. However, these curves do not describe the creep behavior of salt rock in general.

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