Investigating the effect of overburden on the erodibility of gypsum and anhydrite layers

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Abstract

The presence of soluble layers in the foundation of important structures such as dams, bridges and high-rise buildings, in case of being left untreated, may cause severe problems. These layers may easily be dissolved due to contact with groundwater flow, causing some cavities in the soil and settlement of the structure which in severe conditions may highly damage or ultimately lead to failure of the structure. Since nearly all studies carried out on soluble layers so far, have been concentrated on different factors influencing the solubility of the layers under free field conditions, the effect of overburden which roots from the weight of the structure may have an important and influential role in the phenomenon in many engineering projects. Therefore, to fill the gap in past studies on this topic, investigating the effect of overburden on the rate and types of solubility of the susceptible layers is of great necessity and importance. In the present study, the effect of overburden pressures on solubility and erosion of soluble layers has been assessed and investigated. The circulation tests on cubical gypsum samples taken from a mine in Semnan province, west of Tehran, have been carried out. At the same time, they were subjected to different overburden pressures in a new apparatus developed for this study. Cylindrical holes of different initial diameters from 6.5 to 14.75 mm. were cut in the center of samples for the flow passing through and the final diameters of the holes were measured after the electrical conductivity of the flow getting stable during the circulation test. Different flow rates, different overburden pressures and different diameters of holes have been examined and the electrical conductivity was monitored during circulation continuously. Based on the testing results, for relatively large initial hole diameters (eg: 9 & 12.5 mm.), the electrical conductivity decreases as the overburden increases. For greater hole diameters the rate of decreasing the electrical conductivity decreases and nearly becomes constant by increasing the overburden. Nevertheless, the variations of electrical conductivity get an unspecific trend by increasing the initial hole diameter and the overburden pressure.

Keywords: gypsum, anhydrite materials, solubility, titration, circulation test, erodibility, overburden pressure, electrical conductivity
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1 Introduction

One of the critical aspects in the design of hydraulic structures, particularly dams and water supply facilities, is the investigation and assessment of subsidence. Settlement, whether immediate and elastic or long-term and plastic, depends heavily on the material properties of the foundation and abutments. In areas with underlying layers of soluble rocks, induced settlement is not only dependent on material properties but may also be influenced by the solubility of these layers. Consequently, settlements caused by dissolution cannot be simply treated as material creep, as they arise due to changes in the geometry of joints and cracks during the dissolution process.

Creep, or plastic settlement, is generally defined as the deformation of materials under constant loading. It represents an irreversible deformation over time, leading to ground densification and consolidation. In contrast, solution-induced settlement may persist and escalate until the collapse and complete destruction of the foundation, superstructures, and facilities. Therefore, a thorough understanding of the phenomenon, including its occurrence, progression, and cessation, is crucial.

This study examines the behavior and solubility characteristics of gypsum layers under free-field conditions, particularly under varying overburden pressures resulting from the weight of superstructures and facilities constructed above ground level. The study also comprehensively evaluates the primary and other significant factors influencing this phenomenon.

2 Literature review

2.1 Solubility studies of gypsum and anhydrite materials

One of the first studies on dissolution was conducted in 1904 by James and Lupton [12]. The presence of soluble materials behind dams and the consequent dissolution of these minerals in water flowing through the body has been studied by James and Kirkpatrick [11].

The first people to start relatively comprehensive studies on the solubility of rocks were James et al., who in 1981 studied the phenomenon of the solubility of sulfate rocks (gypsum and anhydrite) and discussed it from an engineering point of view [10].

James and Lupton considered the dissolution of gypsum fine crystals as a linear function of the normal concentration (C) and saturation concentration (C_s) of the gypsum-containing solution and expressed this phenomenon as Equation (2.1) [12].

$$\frac{dM}{dt} \propto (C_s - C) \tag{2.1}$$

where in:
dM: Mass or weight changes
dt: Time changes
C: Initial concentration of calcium ions
C_s: Concentration of calcium ions in the saturated state.

James and Lupton proposed equation (2.2) for the dissolution of anhydrite [12]:

$$\frac{dM}{dt} \propto (C_s - C)^2. \tag{2.2}$$

James and Lupton [12] presented a comprehensive study which, while summarizing previous studies, Based on theoretical and experimental methods for calculating the solubility of gypsum and anhydrite, they presented equations (2.3) and (2.4), respectively [12].

$$\frac{dM}{dt} = KA(C_s - C) \tag{2.3}$$

$$\frac{dM}{dt} = KA(C_s - C)^2 \tag{2.4}$$

K, dissolution rate constant and A, surface exposed to water. The value of K depends on the surface area of the flowing water and the velocity of the water flow, so that as the area of the flowing surface area and the flow velocity increase, the value of K increases. Therefore, in gypsum strip particles (with high contact surface) and high flow velocity, a constant amount of dissolution rate can be expected to increase [12].

Leaching can dissolve soluble materials in soil layers or in rock formations and the resulting dissolution can facilitate seepage, which increases dissolution in a progressive state [8]. In 2011, Al-Rawi et al. Conducted a study on gypsum stones under different conditions, which showed that at higher temperatures, the amount and rate of gypsum decomposition is higher. Also, the final concentration of gypsum decomposition increases with increasing flow rate. As the diameter of gypsum cavities increases, the dissolution concentration of gypsum increases [1]. During a laboratory study in 2018 by Hong et al., Studies showed that the dissolution of gypsum is a very important physicochemical property of the rock [9].

2.2 Stress and deformability studies of gypsum and anhydrite materials

In 1981, the geotechnical properties of several types of evaporative rocks were investigated, including gypsum and anhydrite, and the results showed that all of these rocks had very low porosity and usually showed many plastic deformations before breaking under axial load. And gypsum creep before failure is greater than anhydrite [3]. In 1995, Meer and Spiers conducted studies on the creep behavior of gypsum with different grain sizes, and the results showed that reducing grain size increases the amount of creep [6]. Then in 1999, the effects of pore water salinity on the behavior of such materials were investigated and the results showed that their creep behavior also depends on water salinity and with increasing salinity, the ductility of these materials increases and in some cases up to 50 times Gypsum materials creep more than in the absence of salt [7]. According to experiments conducted in 2000 on gypsum taken from the Sivas region of Turkey, gypsum was classified as an almost deformable rock and its tensile and compressive strength decreases when gypsum remains in water. When the samples were kept in water for 20 days, the gypsum resistance decreased by approximately 55%. Most specimens show plastic-elastic-plastic deformation [13]. In 2001, Blum examined the creep of crystalline materials both in the laboratory and in the existing mechanism. These studies showed that temperature can also have many effects on the creep of these materials. For some crystalline materials they introduced a hardening criterion and for others a softening criterion [4]. In 2005, gypsum grain deformation was investigated at high stresses and high temperatures. Observations showed that the deformations were usually uniform and that the deformation of the specimen was very large before breaking [2]. In 2009, the creep behavior of calcite rock in the presence of salt and CO2 gas was studied and the results showed that with increasing salinity in the presence of carbon dioxide, the itching rate is very high and sometimes increases up to 10 times [15]. In 2012, the mechanical properties of gypsum left in brackish water were investigated. These experiments showed that the presence of salinity at the right temperature weakens gypsum and increases its deformation and ultimately reduces its strength [14]. Research by Yu et al. in 2016 shows that an aqueous solution can significantly soften gypsum. After corrosion by the aqueous solution, the gypsum is severely damaged in terms of structure and the crystal clusters are transformed from attached joints to isolated joints [17]. Gypsum-salt evaporitic rocks play an important role in controlling the physical-mechanical performance of the upper Earth mantle as well as the formation of extensive hallokinetic structures that are directly related to rock hydrocarbon reservoirs and oil accumulation. Under many geological conditions, warm groundwater is saline and often penetrates the evaporative salt-gypsum sequences. However, the micro-mechanical behavior of salt-gypsum in these saline environments is less known and this behavior governs the mechanical behavior and overall deformation. In a study by Meng et al. in 2018, the microstructural evolution of gypsum-salt and its attenuation mechanisms under different saline conditions (or associated thermal-hydrological-chemical environments) were investigated. The results showed that for a given concentration, the porosity and fractal dimensions of the samples gradually increase with increasing temperature, while for a given temperature, with increasing salt water concentration, the porosity and fractal dimension decrease. The results confirm that water temperature significantly attenuates salt gypsum, while chlorine ions have a much weaker effect [16]. The micro-mechanisms involved in the deformation of gypsum have long been considered by the scientific world and are not yet fully understood. According to Caselle's research in 2020, the strange crystallographic structure of salt with layers of water molecules in the salt structure, contributes to the development of plastic structures in gypsum [5].

3 Research method

In this study, circulation test with overhead application on gypsum samples prepared from one of the mines of Semnan plain in different conditions to determine the solubility of gypsum under the effect of overhead has been done. An example of the materials extracted from the mine is shown in Figure 1.

Figure 1: Sample of gypsum materials extracted from Semnan Cement Factory mine

To perform the test, a vertical overhead application device and a circulation system were constructed according to Figure 3. In this system, the perforated samples are placed under the overhead application device and the water conduction pipes are connected to the sample in a completely sealed manner on both sides. The prepared samples were in the form of cubes and in different diameters as shown in Figure 2.
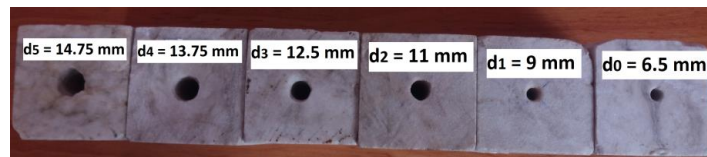

Figure 2: Prepared samples of perforated cubes for dissolution test by applying overhead

Figure 3: Apparatus for applying vertical overhead and circulation

In this system, by starting the circulation from the linear pump shown in Figure 3, which directs the water from the tank to the holes of the cubic sample, the circulation process and measuring the dissolution rate of the desired sample is performed. At the same time, a fixed vertical load is applied to the sample as an overhead by a device similar to a uniaxial device. This work continues for a fixed flow and a specific diameter of the sample until the amount of electrical conductivity of the circulating solution inside the tank is fixed and the amount of electrical conductivity and the time of the test are recorded. In the present study, by considering different samples with different diameters and different flow rates, as well as different overheads, and finally by adding the amount of salt (sodium chloride), the experiment was performed in 33 cases as presented in Table 1. As shown in Table 1, the primary sample diameter (d_1) and the secondary sample diameter (d_2) were recorded at each test step.

Table 1: Different test modes of simultaneous application of overhead and circulation

No.	F (kg)	Q (l/s)	d_1 (mm)	d_2 (mm)	S (g/l)	T (deg)
1	0	0.48	6.5	9	0	26.6
2	0	0.48	6.5	9	1	27.5
3	0	0.48	6.5	9	3	26.6
4	1500	0.48	6.5	9	0	26.4
5	3000	0.48	6.5	9	0	31.6
6	4500	0.48	6.5	9	0	30.1
7	1500	0.35	6.5	9	0	29.7
8	3000	0.35	6.5	9	0	29.4
9	4500	0.35	6.5	9	0	28.0
10	1500	0.48	9	11	0	28.0
11	3000	0.48	9	11	0	26.8
12	4500	0.48	9	11	0	25.9
13	1500	0.35	9	11	0	27.0
14	3000	0.35	9	11	0	26.3
15	4500	0.35	9	11	0	25.9
16	0	0.48	9	11	1	27.3
17	0	0.48	11	12.5	1	27.7
18	0	0.48	11	12.5	3	27.8
19	0	0.48	11	12.5	5	26.7
20	1500	0.48	9	11	1	26.9
21	1500	0.48	11	12.5	1	28.4
22	3000	0.48	11	12.5	3	24.7
23	4500	0.48	11	12.5	1	25.9
24	0	0.48	12.5	13.75	0	26.2
25	0	0.48	12.5	13.75	1	26.8
26	1500	0.48	12.5	13.75	1	24.7
27	3000	0.48	12.5	13.75	1	24.3
28	4500	0.48	12.5	13.75	1	25.4
29	0	0.35	13.75	14.75	0	26.5
30	0	0.35	13.75	14.75	3	26.9
31	1500	0.35	13.75	14.75	3	25.1
32	3000	0.35	13.75	14.75	3	25.9
33	4500	0.35	13.75	14.75	3	26.0

Based on the titration test, the maximum water-soluble gypsum is as shown in Figure 4. The maximum gypsum soluble in one liter of water is equivalent to the electrical conductivity of 4160 microsiemens and is equal to 1328 mg (1.328gr).
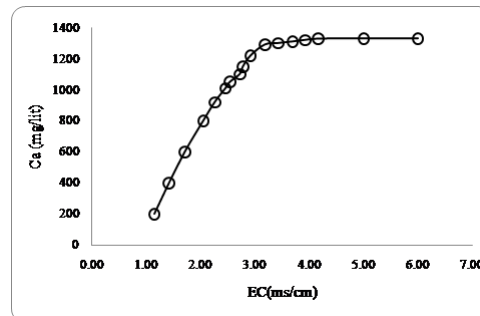

Figure 4: Maximum water-soluble gypsum based on titration test

4 Research results

According to Table 1, the test results in different modes are presented below. Each of the test modes is performed in a period of time and with the stabilization of the electrical conductivity against time for the desired mode. For example, changes in electrical conductivity versus time in the case without applying overhead and a hole diameter of 6.5 mm and without adding salt are shown in Figure 5. Accordingly, the maximum amount of electrical conductivity is equal to 2.59 ms/cm.
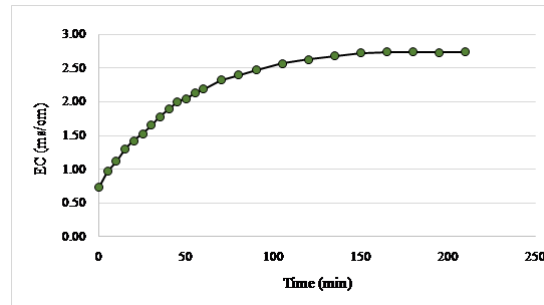

Figure 5: Changes in electrical conductivity over time in conditions without overhead and without salt and hole diameter of 6.5 mm

The following are the results of the overhead and circulation application test with respect to the maximum amount of electrical conductivity in each test.

4.1 No overhead ($F = 0$ Kg)
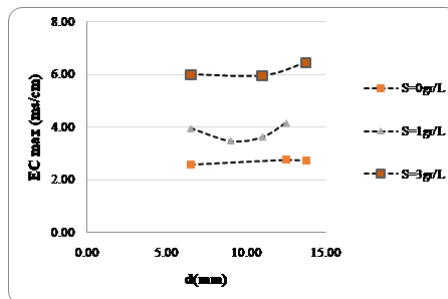
Figure 6: Changes in electrical conductivity versus hole diameter in different salt values under no-load conditions

According to the above diagram, in the case of no overhead application and without considering salt, the amount of electrical conductivity increases with increasing diameter, which increases with increasing the amount of salt, the rate of increase of electrical conductivity increases. In general, the base of a constant diameter increases the electrical conductivity by adding NaCl.

According to the above diagram for a fixed diameter, the amount of electrical conductivity increases with increasing salt content in conditions without applying overhead. In smaller hole diameters the changes in electrical conductivity are less than in NaCl and in larger diameters these changes are greater.

4.2 Overhead ($F = 1500$ Kg)

According to the above diagram, in the case of applying 1500 kg overhead and without considering salt, the amount of electrical conductivity increases with increasing diameter. Electricity is greatly increased by the addition of table salt.

According to the above diagram for a fixed diameter, the amount of electrical conductivity increases with increasing salt content under 1500 kg overhead conditions. At smaller hole diameters the changes in electrical conductivity are less than at NaCl and at higher diameters these changes are greater. The changes in electrical conductivity in this mode are not noticeable compared to the no-overhead mode.
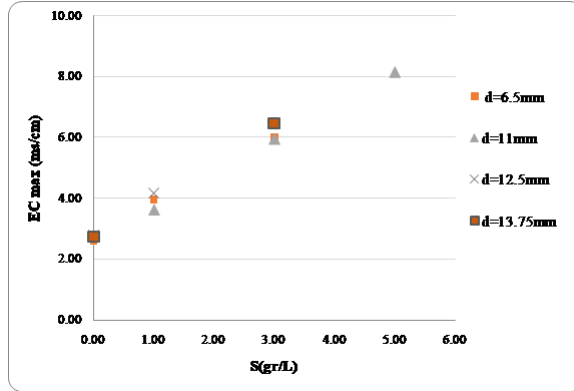
Figure 7: Changes in electrical conductivity versus the amount of salt added for different hole diameters under no-load conditions
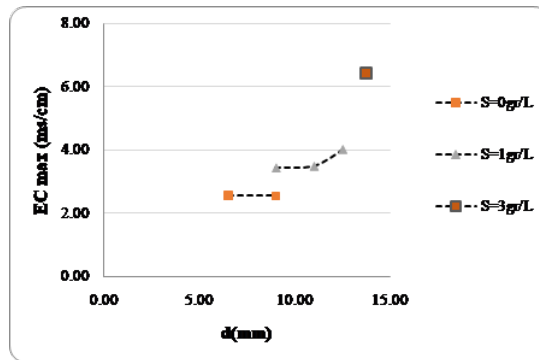

Figure 8: Changes in electrical conductivity versus hole diameter in different salt values under 1500 kg overhead
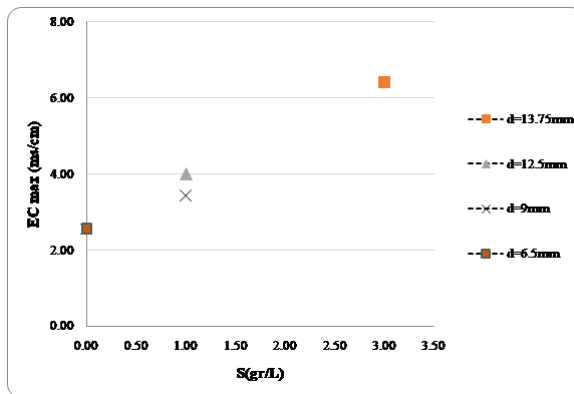

Figure 9: Changes in electrical conductivity versus the amount of salt added for different hole diameters under 1500 kg overhead

4.3 Overhead ($F = 3000$ Kg)

According to the above diagram, in the case of applying 3000 kg overhead and without considering salt, the amount of electrical conductivity decreases with increasing diameter and with increasing the amount of salt, this trend changes and the rate of increase of electrical conductivity increases and in general A constant diameter increases the electrical conductivity by adding NaCl.

According to the above diagram for a fixed diameter, the amount of electrical conductivity increases with increasing salt content under 3000 kg overhead conditions. In smaller hole diameters the changes in electrical conductivity are less than in NaCl and in larger diameters these changes are greater. The changes in electrical conductivity in this mode are not noticeable compared to the no-overhead mode and the 1500 kg overhead mode.
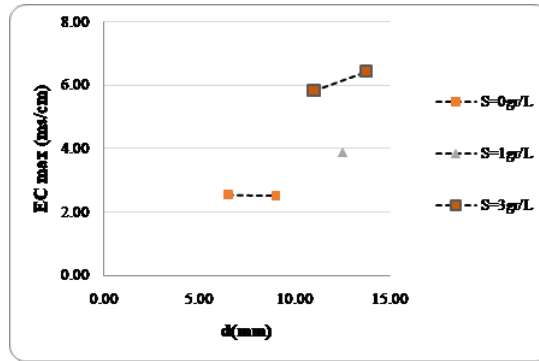
Figure 10: Changes in electrical conductivity versus hole diameter in different salt values under 3000 kg overhead
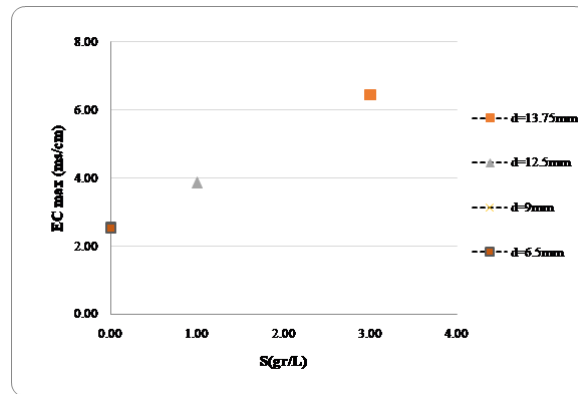

Figure 11: Changes in electrical conductivity versus the amount of salt added for different hole diameters under 3000 kg overhead

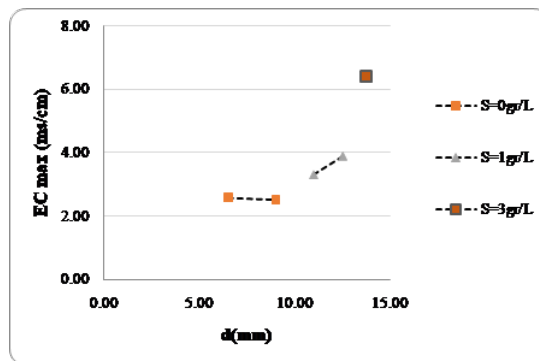## 4.4 Overhead ($F = 4500$ Kg)

Figure 12: Changes in electrical conductivity versus hole diameter in different salt values under 4500 kg overhead conditions

According to the above diagram, in the case of applying 4500 kg overhead and without considering salt, the amount of electrical conductivity decreases with increasing diameter and with increasing the amount of salt, this trend changes and the rate of increase of electrical conductivity increases and the slope of the diagram in This mode is more than the previous modes with overheads of 1500 and 3000 kg.

According to the above diagram for a fixed diameter, the amount of electrical conductivity increases with increasing the amount of salt under the conditions of applying an overhead of 4500 kg. In smaller hole diameters the changes in electrical conductivity are less than in NaCl and in larger diameters these changes are greater. The changes in electrical conductivity in this mode are slightly greater than the no-overhead mode and the 1500 and 3000 kg overhead mode.
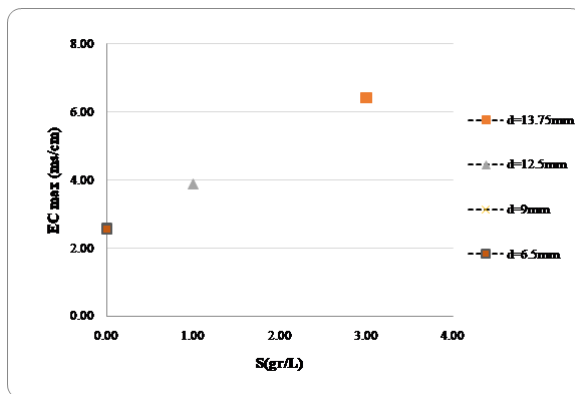
Figure 13: Changes in electrical conductivity versus the amount of salt added for different hole diameters under 4500 kg overhead

4.5 Compare the results of different overheads

For diameters of 9, 12.5 and 13.75 mm and flow rate and constant salt content, the changes in electrical conductivity relative to the vertical overhead load are presented below.
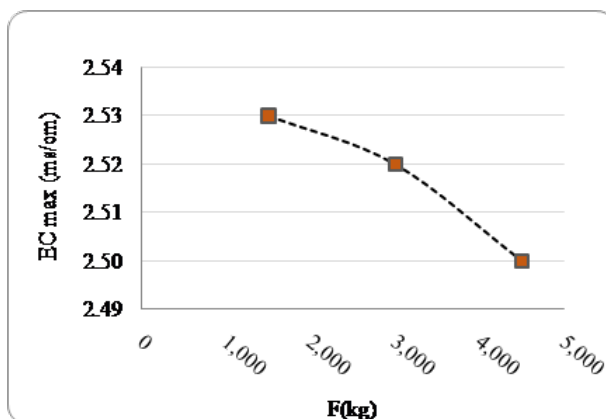

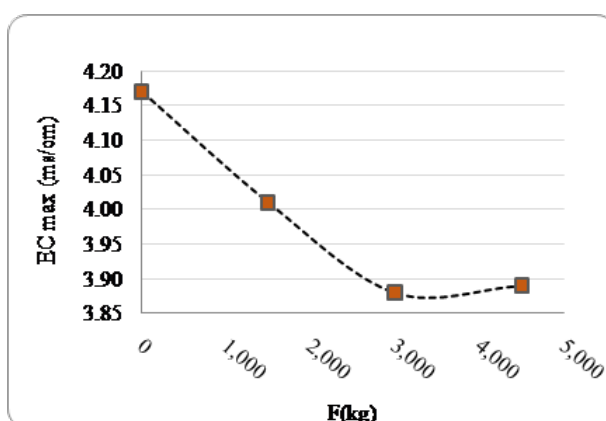Figure 14: Changes in electrical conductivity against different overheads for a hole diameter of 9 mm

Figure 15: Changes in electrical conductivity against different overheads for a hole diameter of 12.5 mm

As shown in Figures 10 to 12, for a fixed diameter (diameters 9 and 12.5 mm), the amount of electrical conductivity decreases with increasing overhead, and the electrical conductivity changes less and almost constant with increasing diameter and increasing overhead. And with further increase in the diameter of the hole, the changes in electrical conductivity relative to the overhead load become unpredictable and have an uncertain trend.
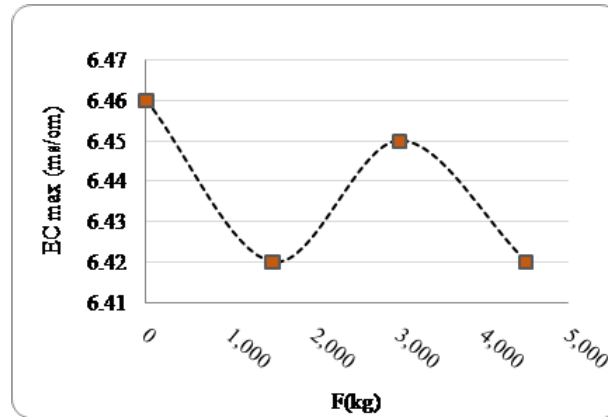
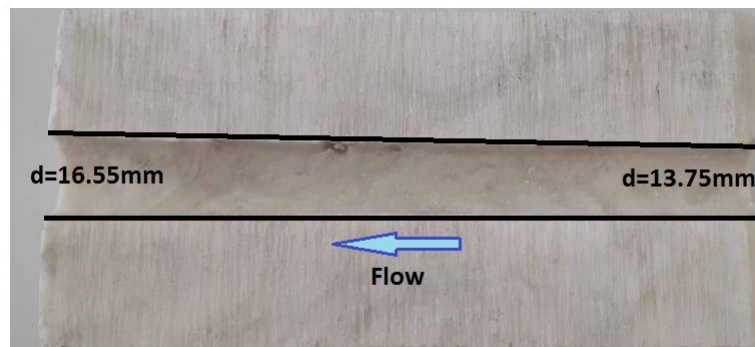Figure 16: Changes in electrical conductivity against different overheads for a hole diameter of 13.75 mm

Figure 17: Longitudinal section of the sample with a diameter of 13.75 mm after the test

The sample with a diameter of 13.75 mm was cut longitudinally after the experiment, as shown in Figure 4. As can be seen in the figure, the diameter of the hole created after the test in the output section of the current is equal to 16.55 mm. This indicates that in places where the flow velocity changes greatly, it leads to further dissolution of the gypsum.

5 Conclusion

The results indicate that:

- In the case of no and with the application of overhead and without considering the salt, the amount of electrical conductivity increases with increasing diameter, which increases with increasing the amount of salt, the rate of increase of electrical conductivity increases. In general, the base of a constant diameter increases the electrical conductivity by adding NaCl.

- For a fixed diameter, the electrical conductivity increases with increasing salt content under overhead and overhead application conditions. At smaller hole diameters the changes in electrical conductivity are less than at NaCl and at higher diameters these changes are greater.

- For a constant diameter (diameters 9 and 12.5 mm) with increasing overhead, the amount of electrical conductivity decreases and also with increasing diameter and increasing overhead the changes in electrical conductivity become less and almost constant and with increasing the diameter of the hole, the electrical conductivity changes The overhead load is unpredictable and has an uncertain trend.

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