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Evaluation of solubility of gypsum-bearing piles and the role of water in its leakage off the pile in fifty-year return period: special case of Marash Dam

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Abstract

Gypsum and anhydrite in circumstances of fast water flux and high permeability is a manufacturing concern in the fifties. Experiences show that in low water flux zones, the solubility is less probable and it decreases if the environment is such that the water is saturated before getting in contact with gypsum-containing area. Hence evaluation of these materials towards the mentioned factors seems to be necessary. In current study the solubility of gypsum is measured in three solutions including distilled water, Marash Dam water, and distilled water plus 1% NaCl. Consequently, the values of solubility constant are measured and calculated using circulation analysis in the three solutions. Finally, the extent of fracture width during fifty years has been calculated and the amount of water leakage is assessed with high precision according to this value, regarding the water downfall (hydraulic gradient) in the dam's body and gypsum-bearing zones. Results of circulation analysis (with constant hydraulic gradient) show that the progress of fracture's radius decreases from the input towards the output. Additionally, along the water flow path, the growth of radius is more considerable in zones having purer gypsum in comparison with surrounding points.

Keywords: Gypsum material, solubility constant, permeability, hydraulic gradient, circulation analysis

Introduction

Engineering experiences show that besides the potential risk of gypsum and anhydrite solubility, another factor is necessary in order to enable the dissolution and its consequences. This factor is passing of water among the gypsum-bearing layers with appropriate velocity. During the process, soluble minerals are transferred by water as dissolved load and leave empty voids in the rock. The phenomenon will cause many problems in dam's pile stability.

It is absolutely essential for pile and dam abutment stability situated on these construction materials to prevent gypsum and anhydritic layers in hydraulic structures from solution due to water flow.

Continuous flow of water passing with high velocity may increase the rate of gypsum and anhydrite materials. This high solubility leads to increase in bedrock permeability caused by developing fractures and this could reduce the efficiency of dam's grout curtain .Development of pores caused by rock solution leads to uneven embedment of the structure (Memarian, 1992; Memarian, 1995).

Literature Review

James (1981) were the first to begin a relatively comprehensive study on solubility. They discussed the solution phenomenon of sulfate rocks (gypsum and anhydrite) from engineering point of view in 1967.

Liu and Nanculas (1971) found that the solution of tiny gypsum crystals is a linear function of normal concentration (C) and saturated concentration (Cs) of gypsum dissolution which can be expressed by James (1992), Dutton (1997), Henkels (1999), Mahir (1981), Gypsum Association (2001) and Harris (2001).

$$\frac{dM}{dt} \propto (c_s - c) \tag{1}$$

Where dM, dt, C and Cs are variation of mass, variation of time, initial concentration of calcium ion, and concentration of calcium ion in saturation mode, respectively.

James and Lupton (1978) introduced expression 2 for dissolution of anhydrite.

$$\frac{dM}{dt} \propto (c_s - c)^2 \tag{2}$$

According to the study by James and Lupton (1978), the expression turns into equation if both sides are multiplied by A (exposed surface of water) and K (solubility constant).

James (1992) has studied the solubility of carbonated rocks and suggested the following equation for calculating the solubility coefficient (dissolution rate constant):

$$\frac{V}{A} \cdot \frac{dc}{dt} = K(C_s - C)^n \tag{3}$$

Where V is water flow volume, $\frac{dc}{dt}$ is variations of calcium concentration with respect to time, and n is the order of reaction.

James (1981) presented a research paper entitled “Design of soluble rocks bearing piles” studied calcite and halite minerals besides gypsum and anhydrite.

Materials and methods

In current study, two types of experiments including determination of maximum dissolved gypsum in water and circulation, have been carried out on gypsum material.

Determination of maximum dissolved gypsum in distilled water, Marash Dam water, and %1 NaCl-containing water

In order to determine the maximum solubility of gypsum in certain amount of water, gypsum powder prepared from Marash dam is gradually added to the water and stirred. Variations in water electrical conductivity has been measured via conductivity meter (Figure 1). The electrical conductivity of the solution was found to increase by addition of the powder; however, the electrical conductivity levelled off at a certain value so that addition of more powder did not increased the value anymore. This was checked by adding more powder and agitating the system for several hours. The value was constant during the whole time and this was because the solution had reached its saturation limit. The measured values was detected and electrical conductivity variation curves has been plotted versus %gypsum w/w. The tests have been tripled using the above waters (Figures 2, 3, and 4).

a b

Figure 1: Steps in determination of maximum dissolved gypsum test in different waters: a) Addition of gypsum powder, and b) Measuring the electrical conductivity

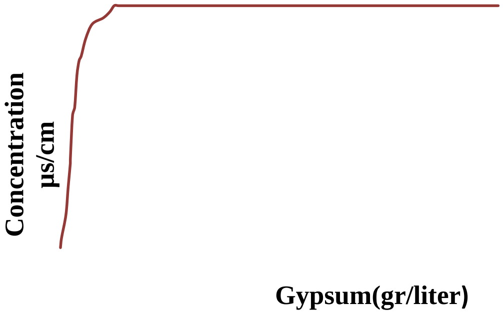

Figure 2: Electrical conductivity versus %gypsum in distilled water solution

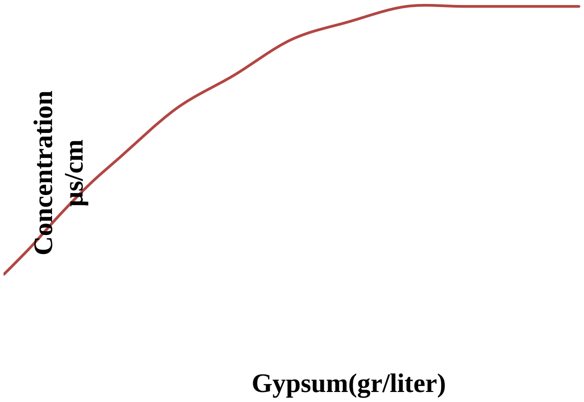

Figure 3: Electrical conductivity versus %gypsum in Marash dam water solution

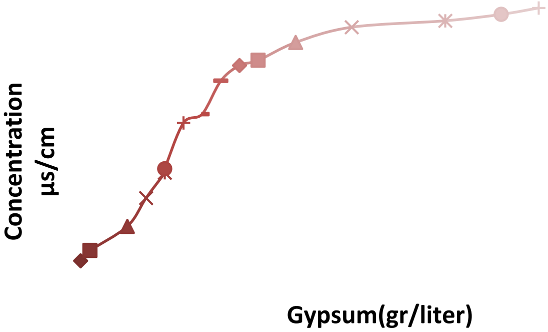

Figure 4: Electrical conductivity versus %gypsum in water solution containing %1 NaCl

Table 1, carries the maximum values of electrical conductivity and dissolved gypsum in the three different waters.

Table 1: Saturated calcium ion concentration in gypsum solution of different waters.

Type of solution	Maximum electrical conductivity (µs/cm)Ec	Maximum dissolved gypsum (gr/lit)Cs
Distilled water	2200	6.25
Marash dam water	3100	3.5
Water containing %1 NaCl	29750	12.5

Circulation test

Cylindrical specimens with about 10 cm and cubic specimens with 10 ×30 ×30 cm dimensions were collected from drilling cores of Marash dam abutment and pile. The two ends of the specimens were cut in parallel and small 3.3 mm diameter holes were made around their axis. In cubic sample, 3.5 mm diameter hole with 31 cm length was made using electrical driller. In order to precisely measure the average diameter, the hole was filled with mercury, the weight of mercury was measured, and then the average diameter of the hole was calculated using weight of mercury and sample's length (Figure 5).

The cycle of circulation test is demonstrated in Figure 5.

a b

Figure 5: Piercing and preparation of gypsum specimens: a) cylindrical specimen, b) cubic specimens having 3 holes.

The circulation test has been performed in 3 modes including distilled water, Marash dam water, and distilled water containing %1 NaCl. In all the three modes, the value of electrical conductivity has been measured in each second (C). The solubility constant could be calculated by determining the value of C, the maximum dissolved gypsum (Cs), flowing water volume (V) (500 cc for Marash water and 1000 cc for other solutions), and the area of flow (A) which is equal to lateral surface of the hole (31.10 cm2 for cylindrical and 47.12 cm2 for cubic specimen). This can be done by obtaining solubility constant (K) and n for each solution by numerical solution of the equation

$$\frac{dM}{dt} = KA(C_s - C)^n .$$

Results and discussion

Results of circulation test using distilled water

Figure 6 shows the variation of gypsum electrical conductivity versus time in circulation test using distilled water. The amount of circulating water has been 1 liter.

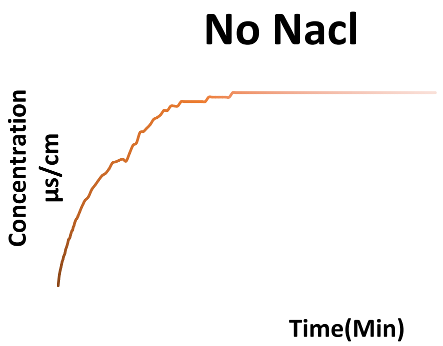

Figure 6: Variation curve of electrical conductivity versus time (distilled water)

The variations of calcium ion concentration in solution versus time (Figure 7) can be obtained using standard diagrams (corresponding to determination of maximum dissolved gypsum) and electrical conductivity variation diagrams versus time (resulted from circulation test).

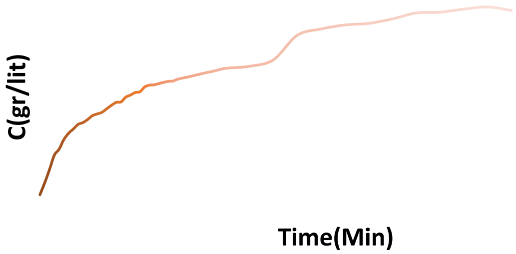

Figure 7: Variations of calcium ion concentration versus time (distilled water)

Regarding Figure 7 and expression 3, it is possible to calculate the parameters K and n. The values are tabulated in Table 2 for distilled water and 0.5 m/s testing rate.

The amount of error for the calculated K and n values is shown in Figure 8.

Table 2: Values of K and n for distilled water

Cs (g/lit)	n	K((m/s)×10-5)
6.25	1.975	1.13

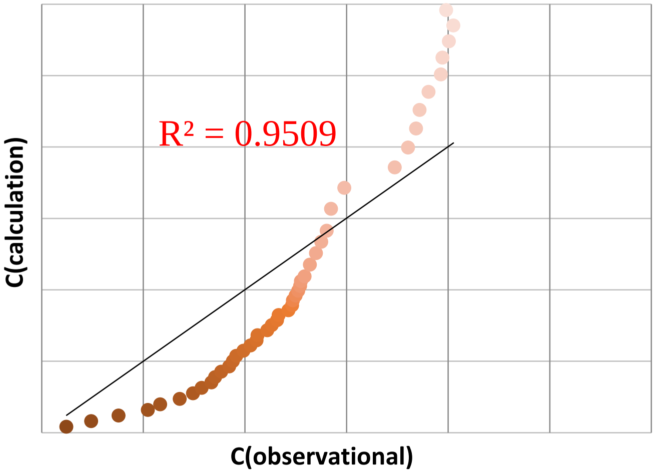

Figure 8: Correlation between observed and calculated values of calcium ion concentration (dissolved gypsum) in distilled water

Results of circulation test using distilled water

Figure 9 shows the variation of gypsum electrical conductivity versus time in circulation test using Marash dam water. The amount of circulating water has been 0.5 liter.

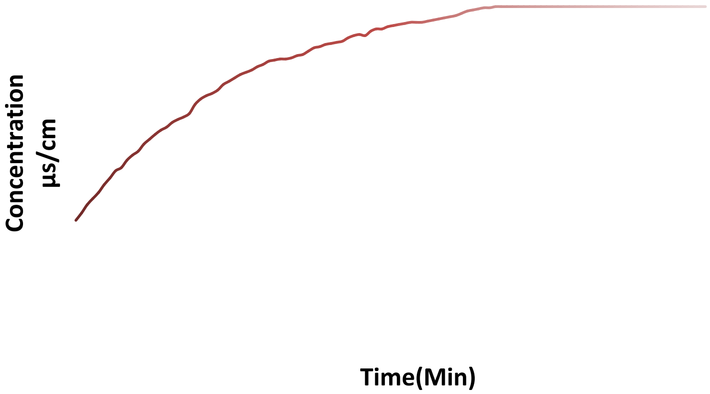

Figure 9: Variation curve of electrical conductivity versus time (Marash dam water)

Again, the variations of calcium ion concentration in solution versus time (Figure 11) can be obtained using standard diagrams (corresponding to determination of maximum dissolved gypsum) and electrical conductivity variation diagrams versus time resulted from circulation test (Figure 10).

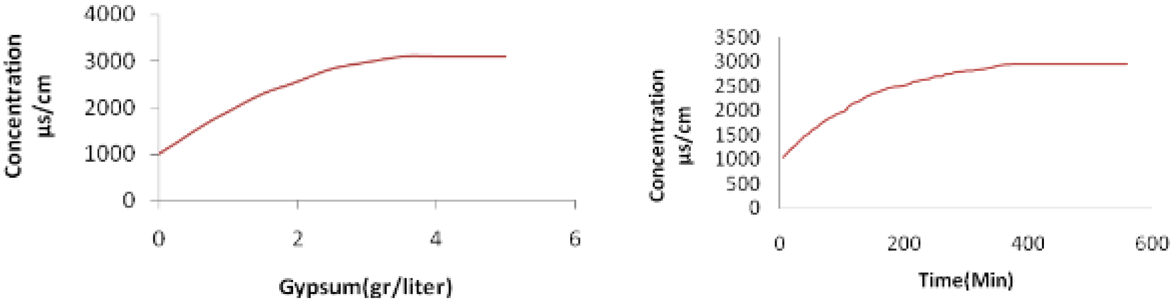

Figure 10: Curves obtained from a) circulation test and b) determination of maximum dissolved gypsum

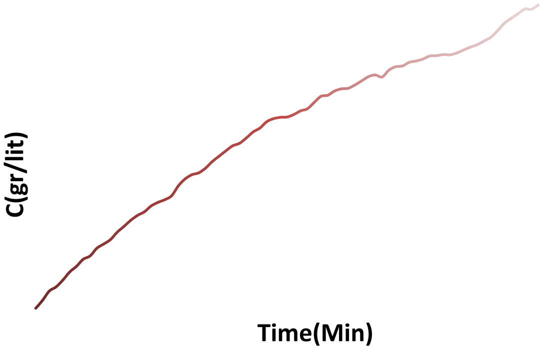

Figure 11: Variations of calcium ion concentration versus time for Marash dam water

Regarding Figure 11 and expression 3, it is possible to calculate the parameters K and n. The values are tabulated in Table 3 for Marash dam water and 0.1 m/s testing rate.

Table 3: Values of K and n for Marash dam water

Cs (g/lit)	n	K((m/s)×10-5)
3/5	1/5	1/02

The amount of error for the calculated K and n values are shown in Figure 12.

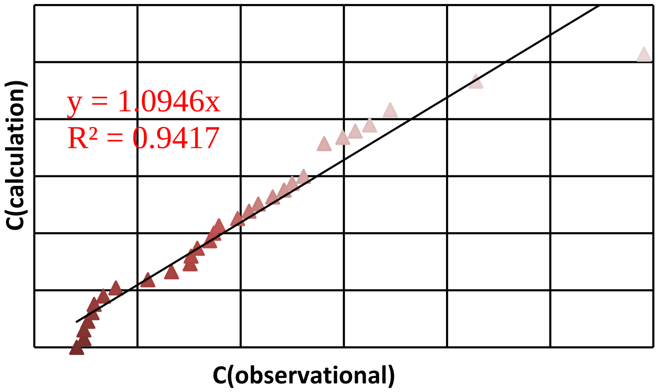

Figure 12: Correlation between observed and calculated values of calcium ion concentration (dissolved gypsum) in Marash dam water

The dissolution of gypsum in Marash water is illustrated in Figure 13.

Figure 13: Dissolution of gypsum in Marash water

Results of circulation test using distilled water containing %1 NaCl

Figure 14 shows the variation of gypsum electrical conductivity versus time in circulation test using distilled water containing %1 NaCl. The amount of circulating water has been 1 liter.

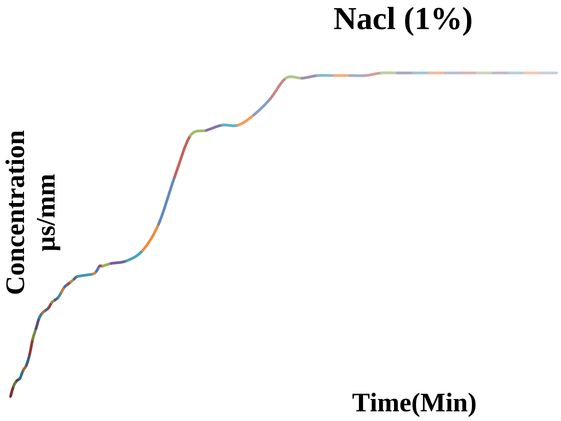

Figure 14: Variation curve of electrical conductivity versus time (distilled water containing %1 NaCl)

Just like the previous two modes, the variations of calcium ion concentration in solution versus time (Figure 15) can be obtained using standard diagrams (corresponding to determination of maximum dissolved gypsum) and electrical conductivity variation diagrams versus time (resulted from circulation test).

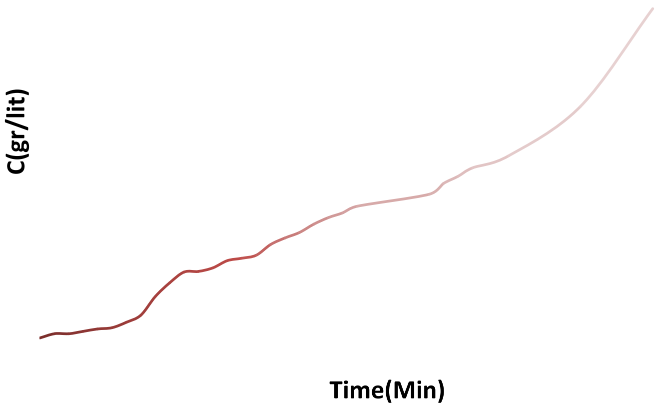

Figure 15: Variations of calcium ion concentration versus time (distilled water with %1 NaCl)

Regarding Figure 15 and expression 3, it is possible to calculate the parameters K and n. The values are tabulated in Table 4 for distilled water containing %1 NaCl and 0.5 m/s testing rate.

Table 4: Values of K and n for distilled water with %1 NaCl

Cs (g/lit)	n	K((m/s)×10-5)
12.5	1.8	1.98

The amount of error for the calculated K and n values are shown in Figure 16.

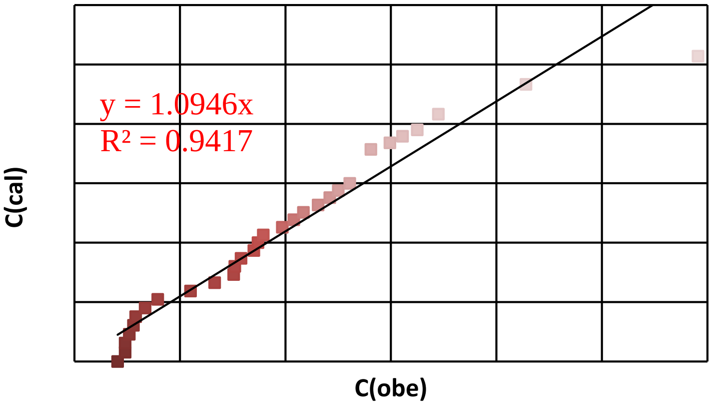

Figure 16: Correlation between observed and calculated values of calcium ion concentration (dissolved gypsum) in distilled water with %1 NaCl

Calculation of maximum fracture width

Among the boreholes drilled in Marash dam constructing zone, those having gypsum and their Lojan values were greater than 1, were considered.

Informations on borehole specifications including borehole number, depth, Lojan value, and permeability coefficient are carried in Table 5.

Table 5: Results of Lojan test in Marash dam with Lojan values greater than 1

Bore number	Bore depth	Lojan amount	Permeability $cm/s \times 10^{-4}$ (K)
50	16.80-14	6.6	0.79
50	19.80-17.2	3.1	0.37
58	26.55-26.40	27.76	3.3
60	13-12.20	5.4	0.65
56	64.45-63.10	2.8	0.34
56	73.30-72.45	1.5	0.18

The variations of fracture width versus time is calculated:

$$\rho \frac{dw}{dt} = 2k(C_s - C)^n \quad (4)$$

Where ρ is gypsum density, w is fracture width, and k is solubility constant.

Variations of fracture width could be determined if calcium concentration at various times and solubility constant is known. In current study, values of solubility constant are obtained for various Marash dam water flow rates. An expression could be developed between solubility constant and water flow rate using the recorded experimental data (Figure 17).

Table 6: Flow rate values for initial permeability coefficient for various boreholes

Bore number	$k_0 (m/s) \times 10^{-6}$	$w_0 (mm)$			$V_0 (m/s) \times 10^{-6}$			
		b=1m	b=0/5m	b=0/33m	i=0/1	i=0/4	i=0/8	i=1
50	0.79	0.099	0.079	0.069	0.079	0.316	0.632	0.79
50	0.37	0.077	0.061	0.053	0.037	0.148	0.292	0.37
58	3.3	0.16	0.127	0.11	0.33	1.32	2.64	3.3
60	0.65	0.093	0.074	0.064	0.065	0.26	0.52	0.65
56	0.34	0.075	0.059	0.052	0.034	0.136	0.272	0.34
56	0.18	0.06	0.048	0.042	0.018	0.072	0.144	0.18

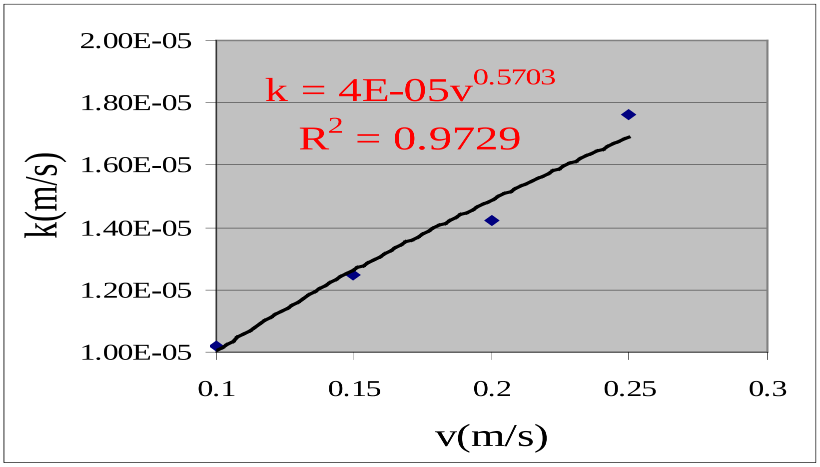

Figure 17: Variations of solubility constant versus flow rate in case of Marash water

In order to obtain solubility constant in real conditions, flow rate should be known for the real conditions. This could be done by performing the Lojan test. According to Table 6, the flow rate in the desired cross section is calculated by Darcy's expression for the underground flows using permeability coefficient (K) and hydraulic gradient (i) in certain depths (Table 7). Additionally, initial width of the fractures are calculated by

$$k = \frac{gw^3}{12vb} \tag{5}$$

Where
g: gravity acceleration
b:fractures interval
v: water viscosity (0.0101 cm2/s)
k: permeability coefficient in Lojan test
w: initial width of the fractures

According to Figure 17, the solubility constants are calculated as follows in Table 7.

Table 7: Values of solubility constant

Bore number	$k_0 (m/s) \times 10^{-6}$	$K(m/s) \times 10^{-9}$			
		i=0/1	i=0/4	i=0/8	i=1
50	0.79	3.56	7.85	11.65	13.24
50	0.37	2.31	5.09	7.56	8.59
58	3.3	8.05	17.74	26.34	29.92
60	0.65	3.18	7.02	10.43	11.84
56	0.34	2.2	4.85	7.2	8.2
56	0.18	1.53	3.38	5	5.7

According to Table 7, the greatest solubility constant is related to borehole no.58 with hydraulic gradient of 1, and the minimum is related to borehole no.56 with 0.1 hydraulic gradient. The amount of fracture width extension in fifty-year period is calculated using expression (4). In order to estimate the maximum fracture width extension in predetermined time intervals, the maximum concentration variation is considered and it is assumed that the amount of dissolved calcium in the flow passing through the desired section is minimum at that specific time, and therefore, maximum washing and dissolution would occur.

The calculated values of fracture extension with various hydraulic gradients in fifty-year period are given in Table 8.

Table 8: Values of fracture width extension for fifty year period

Bore number	$k_0 (m/s) \times 10^{-6}$	$w(mm)$			
		i=0/1	i=0/4	i=0/8	i=1
50	0/79	8/03	17/70	26/27	29/84
50	0/37	5/21	11/48	17/05	19/36
58	3/3	18/14	39/99	59/38	67/44
60	0/65	7/18	15/83	23/51	26/70
56	0/34	4/96	10/94	16/25	18/45
56	0/18	3/45	7/61	11/30	12/84

According to Table 8, in fifty-year period, the maximum fracture width extension is related to borehole no.58 (67.44 mm) with hydraulic gradient of 1, and the minimum extension is related to borehole no.56 (3.45 mm) with hydraulic gradient of 0.1.

Calculation of leakage amount

Having calculated the maximum fracture width, the leakage amount can be calculated by

$$Q = V.A \tag{6}$$

Since $A = w.b$, for unit width, the above equation can be rewritten as

$$q = V.w \tag{7}$$

Using the above expression, the leakage amount is calculated for various hydraulic gradients and velocities inside the dam.

It should be noted that in this research, the values of hydraulic gradients and flow rate are hypothesized and their limits are in a way that covers nearly the whole governing hydraulic conditions in a dam. Thus, id the hydraulic specification of the dam is completely known, one could assess the leakage values according to the calculations regarding the gypsum-bearing zone width.

Variations of leakage versus flow rate are tabulated in Tables 9-12 for different boreholes considering the various hydraulic gradients.

According to Tables 9, 10, 11, and 12, leakage and its rate versus flow rate increases with flow rate. Moreover, these variations are less in case of low hydraulic gradients.

Table 9: Leakage values after fifty year with 0.1 hydraulic gradient

$w(mm)$	$q(m^3/s/m)\times 10^{-5}$			
	$V = 0.1m/s$	$V = 0.5m/s$	$V = 1m/s$	$V = 5m/s$
17/70	177	884	1769	8847
11/48	115	574	1150	5740
39/99	400	1999	4000	20000
15/83	158	791	1583	7916
10/94	109	547	1094	5470
7/61	76	380	761	3806

Table 10: Leakage values after fifty year with 0.4 hydraulic gradient

$w(mm)$	$q(m^3/s/m)\times 10^{-5}$			
	$V = 0.1m/s$	$V = 0.5m/s$	$V = 1m/s$	$V = 5m/s$
17/70	177	884	1769	88/47
11/48	115	574	1150	5740
39/99	400	1999	4000	20000
15/83	158	791	1583	7916
10/94	109	547	1094	5470
7/61	76	380	761	3806

Table 11: Leakage values after fifty year with 0.8 hydraulic gradient

$w(mm)$	$q(m^3/s/m)\times 10^{-5}$			
	$V = 0.1m/s$	$V = 0.5m/s$	$V = 1m/s$	$V = 5m/s$
26/27	263	1314	2627	13137
17/05	170	852	1704	8524
59/38	593	2969	5938	29689
23/51	235	1175	2315	11754
16/25	162	812	1624	8122
11/30	113	565	1130	5651

Table 12: Leakage values after fifty year with hydraulic gradient of 1

$w(mm)$	$q(m^3/s/m)\times 10^{-5}$			
	$V=0.1m/s$	$V=0.5m/s$	$V=1m/s$	$V=5m/s$
29/84	298	1492	2984	14920
19/36	194	968	1936	9680
67/44	674	3371	6744	33712
26/70	267	1335	2670	13349
18/45	184	922	1845	9225
12/84	128	642	1284	4618

The maximum leakage obtained for fifty-year period for the greatest fracture is 0.34 m3/s in width unit, with hypothetical maximum hydraulic gradient (1) and flow rate (5 m/s).

Conclusion

The conclusions drawn from this research are as follows:

1) Existence of dissolved ions in Marash dam water has led to decrease in gypsum solubility, while the maximum dissolved gypsum water is greater in distilled than in Marash dam water.

2) According to experimental observations, the amount of increase in volume of the zone exposed to water in circulation test using Marash dam water and 0.1 m/s testing rate, has been %30.

3) Regarding the experimental observations, the prepared samples contained %39 gypsum and %31 anhydrite. Hence the order of reaction was expected to be between 1 and 2.

4) The greatest correlation between observed and calculated concentrations has been for Marash dam water (%99).

5) According to the obtained results from circulating test with constant hydraulic gradient shows that the fracture diameter grow rate decreases from the input toward the output. Additionally, the increase in diameter has been greater in zones having purer gypsum along the water flow path.

6) According to the obtained results from circulating test, if the water is unsaturated, the fractures show increase in water passing, while they do not show this behavior in calcium sulfate ion saturated water. Thus there would be no width grow below the calcium ion saturated dam foundation. If the water reaches the calcium ion super saturation mode, gypsum sedimentation and subsequently fractures width reduction occurs.

7) The leakage increases with flow rate and the leakage rate versus flow rate increases for the fifty-year period. Moreover, these variations are less in case of low hydraulic gradients.

8) The maximum leakage in fifty-year period for the greatest fracture is 0.34 m3/s in width unit, with maximum hydraulic gradient and flow rate.

References

Dutton, J. (1997). Global growth for gypsum, Lime & Building Products. Gypsum.

Gypsum Association. (2001). Annual gypsumboard shipments & industry capacity: Washington, DC.

Harris, P. (2001). Wallboard wonderland—The North American gypsum market: Industrial Minerals, no. 400.

Henkels, P.J. (1999). Synthetic gypsum use in wallboard. Chicago: IL, U.S. Gypsum Co.

James, A.N. (1992). Soluble materials in Civil Engineering, Ellis Horwood.

James, A.N. Lupton, A.R.R. (1978). Gypsum and anhydrite in foundations of hydraulic structures, Geotechnique, 28(3): 249-272.

James, A.N. (1981). Solution parameters of carbonate rocks". Bulletin of the International Association of Engineering Geology-Bulletin de l'Association Internationale de Géologie de l'Ingénieur, 24(1): 19-25.

Mahir, M. (1981). Investigation and Study of gypsum and anhydrites of Dejleh’s dam. PhD thesis in geotechnical engineering, Istanbul University.

Memarian, H. (1992). Geology for engineers. Tehran: Tehran University Press.

Memarian, H. (1995). Geology for geotechnics. Tehran: Tehran University Press.