IJMGE

Int. J. Min.& Geo-Eng.
Vol.47, No.2, Dec. 2013, pp.91-102

Effects of Pregnant Leach Solution Temperature on the Permeability of Gravelly Drainage Layer of Heap Leaching Structures

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Received: 12 March 2013; Received in revised form 9 May 2013; Accepted: 26 May 2013
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Abstract

In copper heap leaching structures, the ore is leached by an acidic solution. After dissolving the ore mineral, the heap is drained off in the acidic solution using a drainage system (consisting of a network of perforated polyethylene pipes and gravelly drainage layers) and is, then, transferred to the leaching plant for copper extraction where the copper is extracted and the remaining solution is dripped over the ore heap for re-leaching. In this process, the reaction between the acidic solution and copper oxide ore is exothermal and the pregnant leach solution (PLS), which is drained off the leaching heap, has a higher temperature than the dripped acidic solution. The PLS temperature variations cause some changes in the viscosity and density which affect the gravelly drainage layer's permeability. In this research, a special permeability measuring system was devised for determining the effects of the PLS temperature variations on the permeability coefficient of the gravelly drainage layer of heap leaching structures. The system, consisting of a thermal acid resistant element and a thermocouple, controls the PLS temperature, which helps measure the permeability coefficient of the gravelly drainage layer. The PLS and gravelly drainage layer of Sarcheshmeh copper mine heap leaching structure No. 1 were used in this study. The permeability coefficient of the gravelly soil was measured against the PLS and pure water at temperatures varying between 3°C to 60°C. Also, the viscosity and density of the PLS and pure water were measured at these temperatures and, using existing theoretical relations, the permeability coefficient of the gravel was computed. A comparison between the experimental and theoretical results revealed a good conformity between the two sets of results. Finally, a case (Taft heap leaching structure, Yazd, Iran) was studied and its gravelly drainage layer was designed based on the results of the present research.

Keywords: *heap leaching structure, gravelly drainage layer, permeability coefficient, pregnant leach solution, temperature, viscosity*

1. Introduction

Heap leaching structures play an important role in the processing and extraction of copper from the oxidized and low grade copper mines. To construct such structures, an area of about several hundred thousand square meters with a low slope (5 to 15 percent) is selected and insulated with some natural (compacted clay and composite soil) and geo-synthetic (Geo-membrane, Geo-textile, Geo-net and GCL) layers [1]. The main insulating layer of the heap leaching structure bed is the Geo-membrane liner. This is a polymeric material that varies from 1 to 2 mm in thickness. It is very sensitive to punching; if punched, the PLS will leak in the ground [2, 3, and 4]. To protect the Geo-membrane liner from getting punched, a layer of sandy soil, called Cushion, is placed over it. The drainage system, consisting of the gravelly layer and a network of perforated polyethylene pipes, is constructed over the Cushion. To prevent the drainage system from clogging, a layer of filter is spread over the system and then the ore is placed in steps [5, 6, and 7]. The ore steps are leached by acidic solution. The solution dissolves the copper and sends the solution out through the drainage system (Figure 1) [8]. The solution leaving the leaching heap carries copper, which is called the pregnant leach solution (PLS). The PLS is sent to the solvent extraction electro-winning (SX-EW) plant where it delivers its copper and then returns to the heap for re-leaching. The reaction between the copper oxide ore and acidic solution is exothermal, increasing increases the temperature of the PLS. Research suggests that, in some cases, such reactions increase the temperature of the pregnant solution up to 50°C [9]. Since the PLS temperature variations cause changes in the solution's viscosity and density, the permeability coefficient of gravelly drainage layer will be considerably affected. In this research, by using a special permeability measuring system, the effects of temperature variations of the PLS on the permeability coefficient of the gravelly drainage layer were measured and the results were compared with those of the theoretical relations.

Figure 1. Drainage of PLS through a gravelly drainage system (Sarcheshmeh copper heap leaching structure No.1).

2. Literature review

In 1851, carrying out some experimental studies, Darcy presented an empirical relation for the determination of water discharge passing sandy soils through [10]. This relation was used for the design of the thickness of sandy and gravelly drainage systems for many years. In 2000, Giroud developed an analytical relation to find the thickness of gravelly drainage systems for landfills [11]. In 2007and 2009, taking advantage of Giroud's analytical relation, Majdi et al. offered relations for the design of heap leaching structures drainage systems [12,13]. According to Majdi et al.'s approach, the thickness of the gravelly drainage system for heap leaching structures is determined as follows:

$$H = \frac{j * (\sqrt{1+4\lambda} - 1) * L * Tan\beta}{2Cos\beta} * F_S \qquad (1)$$

$$j = 1 - 0.12Exp\left[-\left[Log\left(\frac{8\lambda}{5}\right)^{\frac{5}{8}} \right]^2 \right],$$

$$\lambda = \frac{q_h}{K_{Lt} * Tan^2\beta}, K_{lt} = \frac{k_{La}}{RF_{PC} * RF_{CC} * RF_{BC}}$$

where

H : Gravelly drainage thickness (m)

$\mathbf{j}, \lambda$: Non-dimensional parameters

L : Distance between the perforated pipes of the heap drainage system (m)

β : Bed slope angle (degrees)

q_h : Acidic solution dripped over the heap (m3/s/m2)

K_{lt} : Long term permeability coefficient of gravelly drainage layer (m/s)

K_{la} : Laboratory permeability coefficient of gravelly drainage layer (m/s)

RF_{PC} : Reduction factor due to physical clogging

RF_{CC} : Reduction factor due to chemical clogging

RF_{BC} : Reduction factor due to biological activities clogging

As seen in equation (1), K_{la} has a considerable effect on the determination of the thickness of a gravelly drainage layer. This parameter depends on the solution, the temperature and the particle size distribution of gravel; it is mostly measured by using pure water at 22°C. But, as mentioned earlier, in heap leaching structures, the solution passing the gravelly drainage layer is PLS and its viscosity and density are different from those of water [14]. Also, the temperature of the PLS leaving the heap is higher than that of the dripped acidic solution, due to the reaction between the acid and the copper oxide soil. Therefore, there will be a considerable error, if the results of ordinary tests (i.e. with pure water at 22°C) are used in the design of drainage system of heap leaching structures. In this study, through the use of a special permeability measuring system, the permeability coefficient of the gravelly drainage layer for heap leaching structures was measured against pregnant leach solutions at different temperatures (3°C to 60°C).

3. Field measurements

To carry out this research, the temperature of the acidic solution at the moment of dripping, the temperature of the PLS leaving the heap, and the environment temperature were measured for one year at a fixed location in Sarcheshmeh heap No. 1 and Darezar bio-heap (Kerman, Iran). The results are shown in Figure 2. In Sarcheshmeh heap No. 1, the temperature of the dripping acidic solution was equal to that of the environment, but in Darezar bio-heap, the temperature of the dripping acidic solution was constant and equal to 16°C , because of the presence of some bacteria. The environment temperatures were the same for both cases because both locations were in the same site.

Figure 2. Measuring the temperature of PLS in Sarcheshmeh heap No. 1.

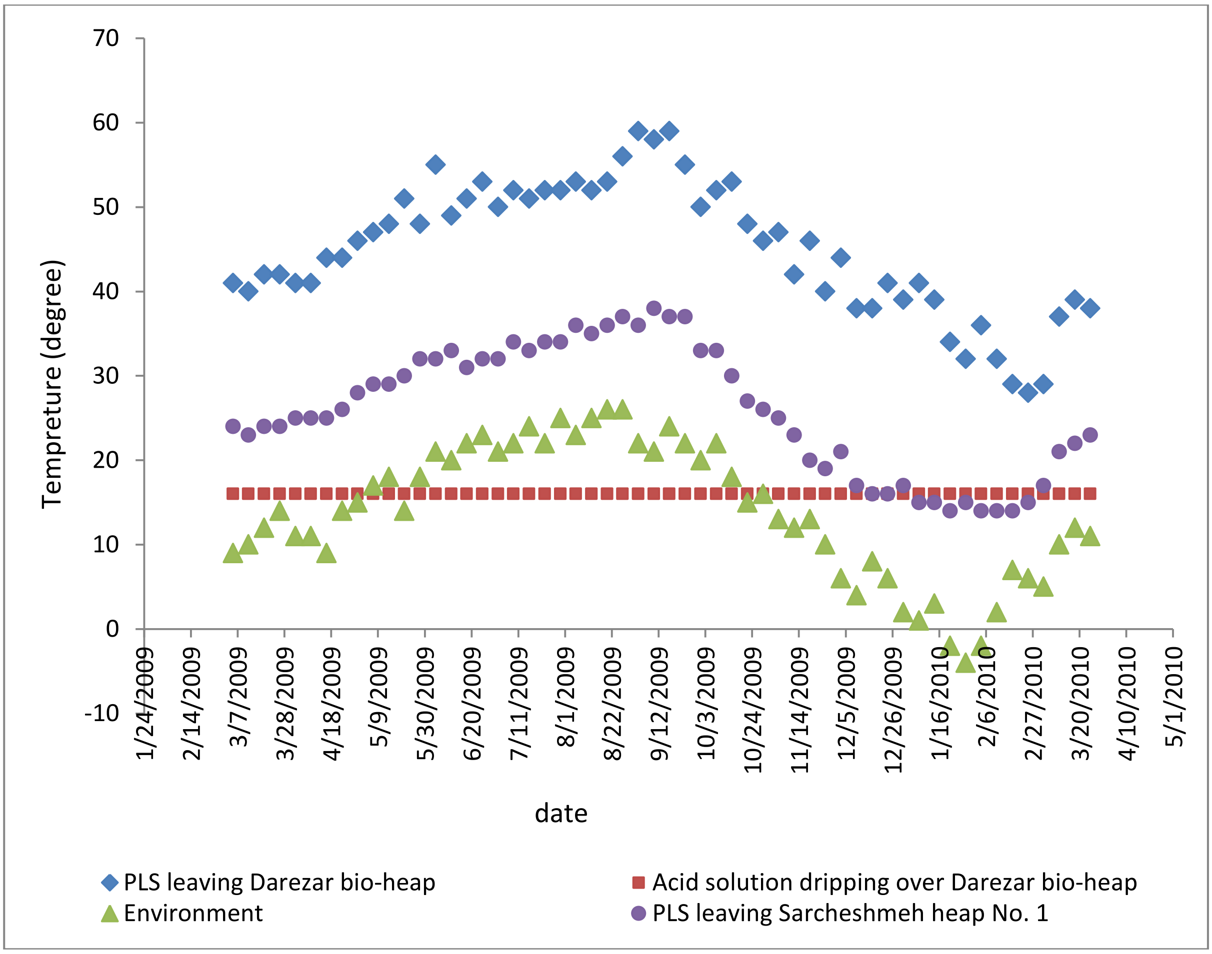


Figure 3. Temperature variations of the dripping acidic solution, the PLS leaving the heap and the environment in different days of the year (Sarcheshmeh heap No. 1 and Darezar bio-heap).

The following results can be drawn from the graphs:

- In all the measurements in both cases, the temperature of the PLS is higher than that of the dripping acidic solution;
- Due to the bacterial activities in the bio-leaching process, the temperature of the PLS leaving the bio-heap is higher than that of the solution leaving the ordinary heap;
- In this site, temperature variations of the solutions leaving the bio and ordinary heaps are 3°C to 60°C and 12°C to 40°C, respectively.
- Over the one-year period, mean temperature of the PLS of Darezar bio-heap, Sarcheshmeh heap No. 1 and Sarcheshmeh site environment temperature are 45°C, 25°C and 14°C, respectively.

4. Permeability tests

Figure 4 shows the system for measuring the permeability coefficients of the gravelly drainage layer against the PLS and water. In this system, the gravelly soil sample is placed inside a transparent acid resistant cylindrical cell, called sample cell, 20 cm in diameter and 54 cm in height. The top and bottom of the sample cell are connected to two tanks where the fluid height remains constant. To store the acid, there is a main storage tank installed under the system. By starting the pump, the PLS enters the upper tank from the main storage tank and moves into the sample cell. Then, passing through the gravel, it enters the lower tank and pours into the main storage tank. The additional solution remained in the upper tank returns to the main tank through a spillway after reaching a constant height. The permeability coefficient of the gravelly drainage layer of the heap leaching structure against the PLS can be computed using the described system and Darcy's relation as follows:

$$K = \frac{l}{h} \cdot \frac{Q}{A} \qquad (2)$$

where

k: Permeability coefficient of gravelly soil (m/s)

f: Length of the soil sample or sample cell (m)

h: Distance between the upper and the lower tanks spillways (m)

Q: Discharge of the PLS passing through the gravelly soil

A: Sample cell cross-sectional area

An acid resisting thermal element was fixed in the upper tank, connected to a digital thermostat as to change the temperature of the PLS. With this thermal system, it is possible to maintain a constant temperature of the PLS and measure the permeability of the gravelly soil at different temperatures.

For more reliable test results, the samples of the gravelly drainage layer and the PLS were selected from a real case (Sarcheshmeh heap leaching structure No. 1) and transferred to the laboratory. Figure 5 shows the particle size distribution curve and Table 1 presents the gradation parameters of the selected gravelly soil sample. As shown in Figure 5, the tested sample is poorly graded, whose uniformity and gradation coefficients are 1.29 mm and 0.965 mm, respectively.

The permeability coefficient of the selected gravelly soil was measured against the PLS and pure water at different temperatures using the system. The results of these tests are shown in Figure 6. The following results can be deduced from the figure:

- A temperature rise in the fluid (PLS and pure water) causes an increase in the permeability coefficient of the gravelly soil because the fluid viscosity decreases which causes more solution to pass according to Equation (2);

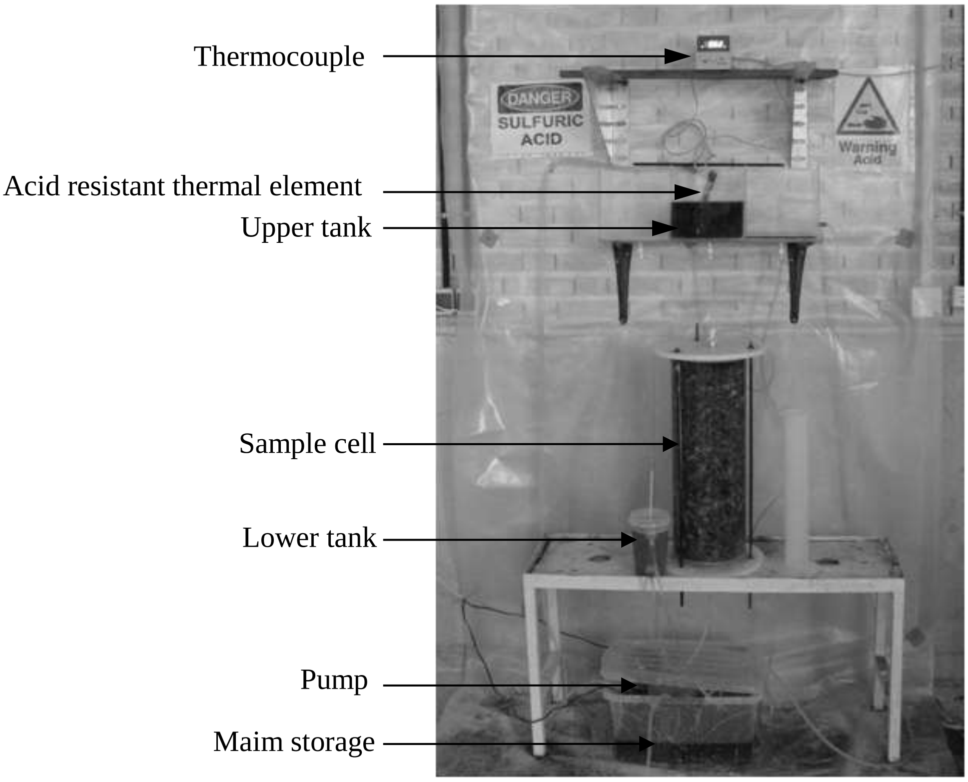


Figure 4. Special system for determining the permeability coefficient of gravelly drainage layer of heap leaching structures against PLS.

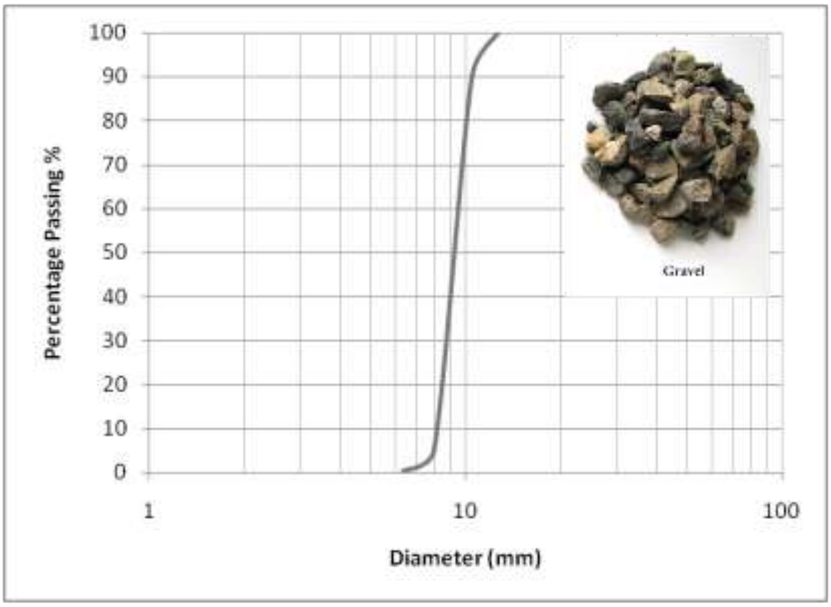


Figure 5. Particle size distribution curve of gravelly soil sample .

Table 1. Gradation specifications of the gravelly soil .

D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	D_{100} (mm)	C_u	C_c	PI	LL
8.5	8.8	9.4	12.7	1.29	0.965	NPI	NLL

- It is possible to predict the relation between the temperature and permeability of the gravelly drainage layer of the heap leaching structure against PLS and pure water with the help of the following exponential relations:

$$K_{PLS} = 4.45T^{0.105} \quad (3)$$

$$K_{Water} = 10.39T^{0.06} \quad (4)$$

where T is the fluid temperature.

- Comparing the results of the tests shows that the permeability coefficient of the gravelly drainage layer against pure water is higher than that against the PLS because the latter is more viscous than the former and its passing through the drainage system is more difficult.

5. Theoretical prediction of the permeability coefficient of the gravelly drainage layer against PLS

Permeability coefficient of different soils can be calculated by the following relation [15]:

$$K = \frac{\kappa \gamma}{\mu} \quad (5)$$

where

κ : Absolute permeability coefficient of soil (m^2)

γ : Unit weight of fluid (N/m^3)

μ : Viscosity of fluid (cp)

Therefore, permeability coefficients of the gravelly drainage layer against the PLS and pure water can be obtained, respectively, as follows:

$$K_{Water} = \frac{\kappa \gamma_{Water}}{\mu_{Water}} \quad (6)$$

$$K_{PLS} = \frac{\kappa \gamma_{PLS}}{\mu_{PLS}} \quad (7)$$

Dividing Equation (7) by Equation (6) results in the permeability coefficient of the gravelly drainage layer against the PLS as follows:

$$K_{PLS} = \frac{\mu_{Water}\, \gamma_{PLS}}{\mu_{PLS}\, \gamma_{water}} K_{Water} \quad (8)$$

To find the theoretical value of the permeability coefficient of the gravelly drainage layer of heap leaching structures against the PLS, the viscosities of pure water and the PLS were measured by viscometer at temperatures between 3°C and 60°C.

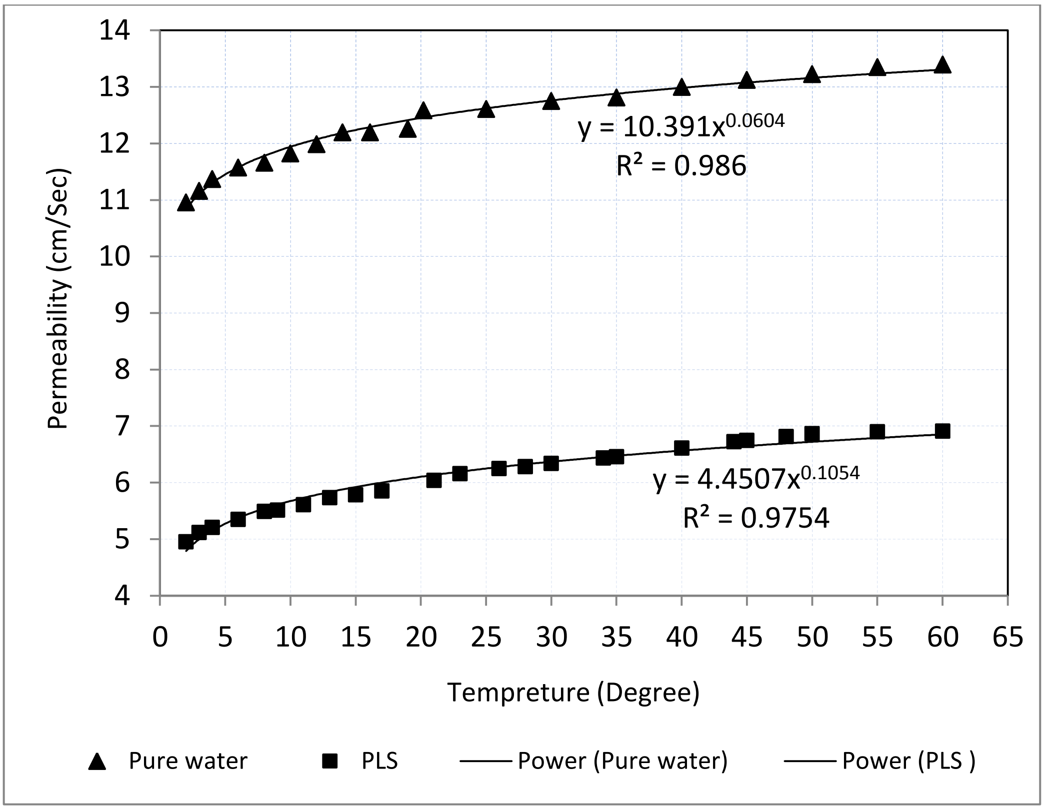


Figure 6. PLS and pure water permeability coefficient variations with respect to temperature.

The results are shown in Figure 7. Also, the densities of the two fluids (the PLS and pure water) were measured at different temperatures. The test results suggested that these densities at different temperatures remain almost unchanged and equal to $\gamma_{PLS} = 1.202\ gr/cm^3$ and $\gamma_{PLS} = 1.001\ gr/cm^3$. By substituting these values in Equation (8), the following relation can be expressed as:

$$K_{PLS} = \frac{1.2\,\mu_{Water}}{\mu_{PLS}} K_{Water} \qquad (9)$$

Therefore, according to Equation (9), Figure 7 and the permeability coefficient of the gravelly drainage layer against pure water, it is possible to predict the permeability coefficient of the soil against the PLS and compare it with that measured in the laboratory (Figure 6). This comparison is demonstrated in Figure 8. As shown in Figure 6, there is a good agreement between theoretical and laboratory outcomes. It can be, thus, concluded that in order to determine the permeability coefficient of the gravelly drainage layer of a heap leaching structure against PLS, the theoretical Equation (9) and Figure 7 can be used instead of direct tests which are mostly time-consuming and costly.

6. Case study (Taft heap leaching structure, Yazd, Iran)

Laboratory permeability coefficient of the gravelly drainage layer of heap leaching structures plays an important role in the design of the drainage system of such structures. As mentioned before, permeability coefficient against the PLS is less than that against pure water. Also, due to the exothermal reaction between the acidic solution and the copper oxide soil, the temperature of the PLS is more than that of the dripping acidic solution. Therefore, the required tests have to be carried out at appropriate temperatures, so that a proper drainage system can be designed for the structure. Under conditions where there is no possibility of doing the tests with the PLS due to safety issues, time and costs, it is suggested that the tests be carried out with pure water and the results be modified using Equation (9) and Figure 7. To verify the results found in this research, a case history (Taft heap leaching structure, Yazd, Iran) was studied and its gravelly drainage layer was designed based on the results of the present research.

6.1. Description of the case-study

Taft heap leaching structure was designed and constructed for leaching and extracting copper from 32 million m^3 copper ore of Aliabad and Darreh Zereshk mines in an area of about 330,000 m^2 (Figure 9). Taft and Sarcheshmeh are close, and their ores and climates are similar. It is, therefore, possible to use the data of Sarcheshmeh heap No.1 (Figures 3, 6, 7) in the design of the drainage system of Taft heap leaching structure. Figure 10 shows the succession of layers used in the bed of Taft heap. The heap's drainage system consists of a network of perforated polyethylene pipes and gravelly layers. In this system, the PLS is initially drained through the gravelly layer in the bed, then directed toward the perforated pipes network, and finally drained off the leaching heap through the network. Therefore, the heap bed gravelly layer is only responsible for transferring the pregnant solution from the heap bed to the drainage pipes.

6.2. Design of the thickness of gravelly drainage layer of Taft heap leaching structure

Considering topographic map of the heap bed (Figure 9), the SX-EW plant production procedure and Figures 3, 6 and 7, the parameters needed to design the thickness of gravelly drainage layer were identified (Table 2). The gravelly drainage thickness required for the heap in question was calculated according to Equation (1) under the following three states:

- K_{la} is measured with the PLS at a temperature of 25°C;
- K_{la} is measured with pure water at a temperature of 25 degrees Celsius and the result modified for the PLS according to Equation (9) and Figure 7; and
- K_{la} is measured with pure water at a temperature of 25°C and the test result used directly in the design.

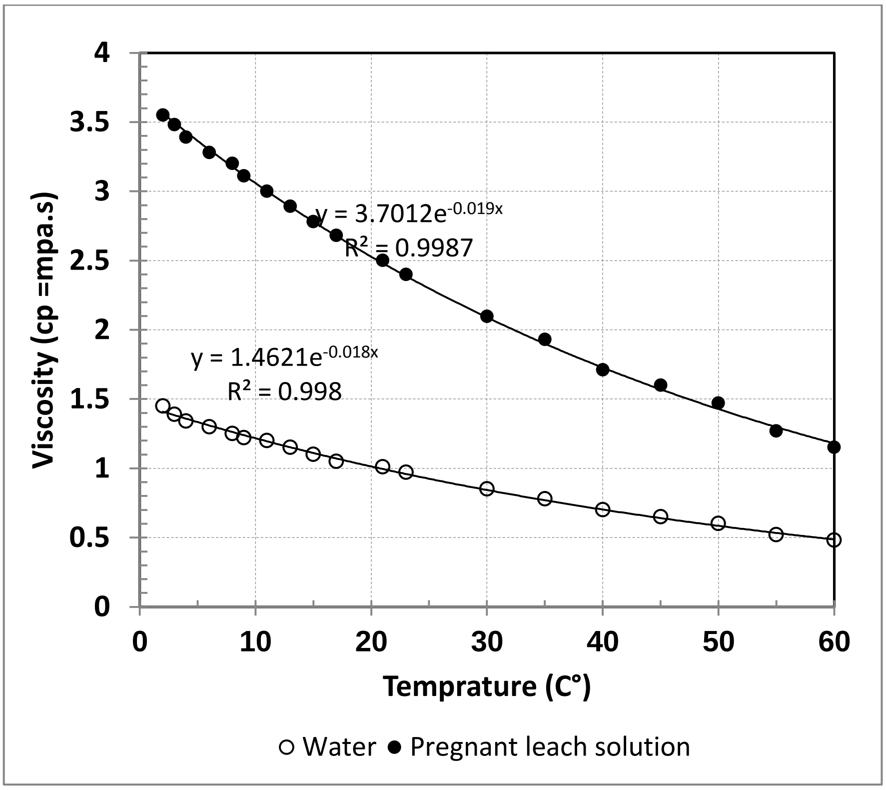


Figure 7. PLS and pure water viscosity variations with respect to temperature.

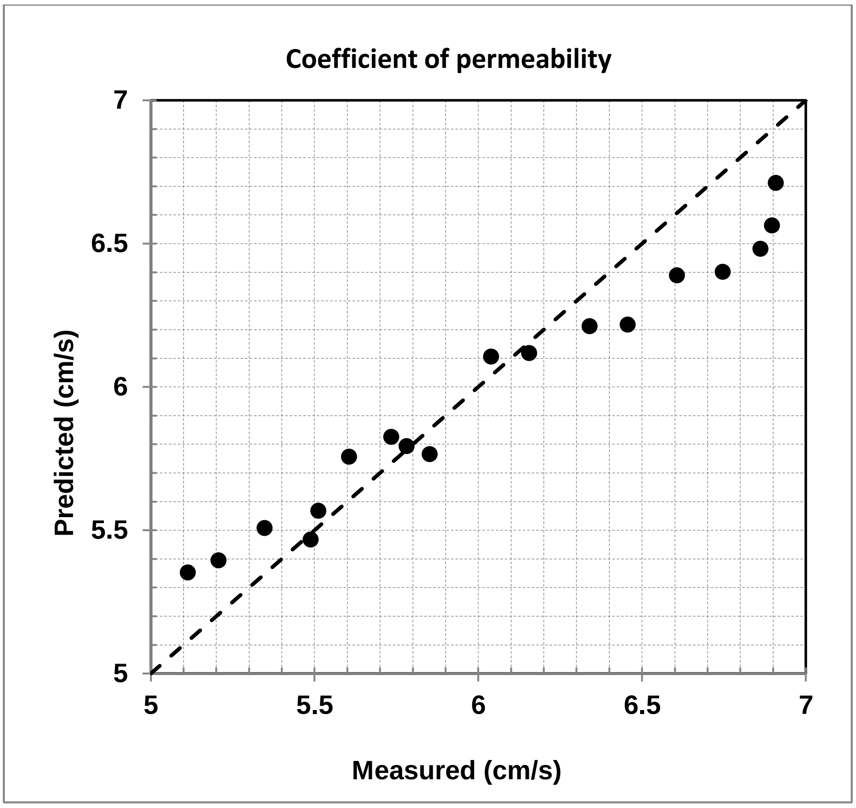
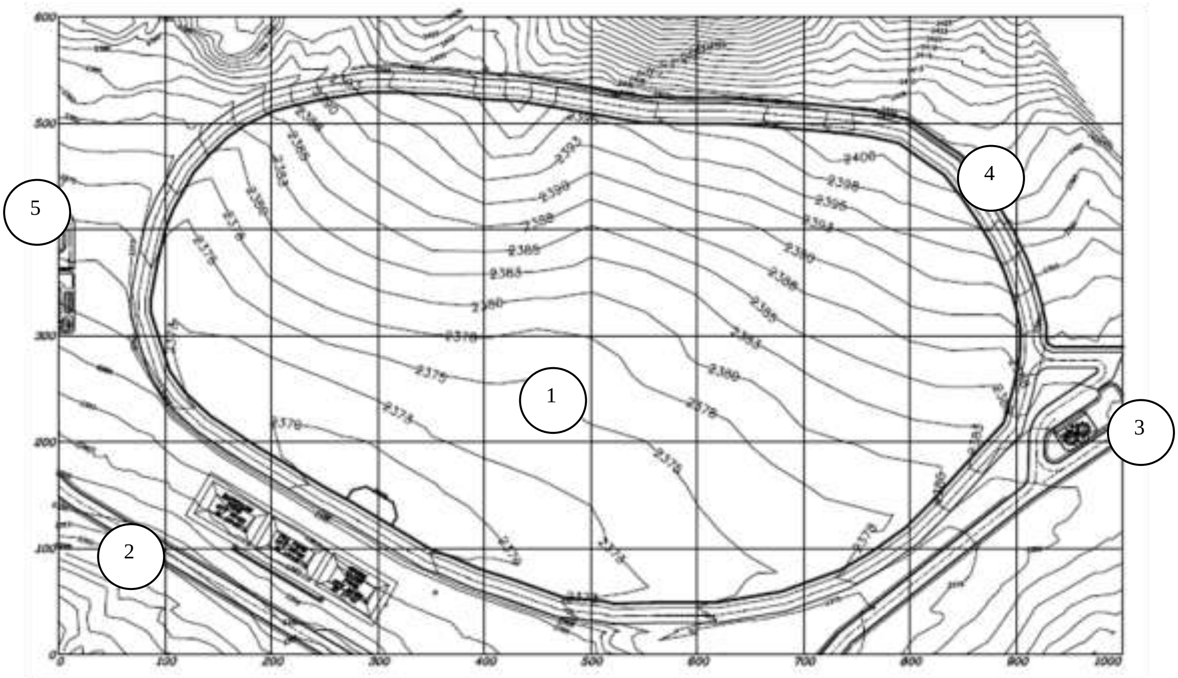


Figure 8. Comparison of the theoretical and laboratory results of the permeability coefficient of the gravelly drainage layer of heap leaching structures against PLS.



1. Heap area, 2. Ponds, 3. Crusher area, 4. Ring Road, 5.SX-EW plant

Figure 9. Topography of the bed of Taft heap leaching structure.

Table 2. Parameters required for thickness design of the gravelly drainage layer of Taft heap leaching structure.

Par. / Solution	RF_{PC}	RF_{CC}	RF_{BC}	K_{la} (cmS^{-1})	L (m)	β (Deg)	F_S	q_l $(m^3S^{-1}m^{-2})$	H (cm)
PLS (Measured)	2	1.5	1.5	6.23	100	5	2	2 *10-6	31
PLS (Predicted)	2	1.5	1.5	5.33	100	5	2	2 *10-6	36
Water	2	1.5	1.5	12.5	100	5	2	2 *10-6	15

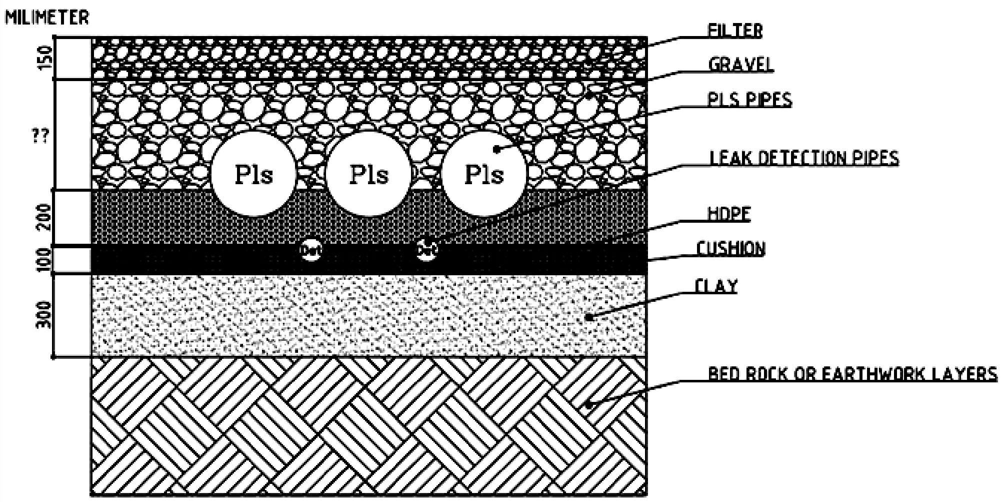


Figure 10. Succession of the layers of the bed of Taft heap.

The results are presented in the last column of Table 2. As provided in Table 2, if the drainage system is designed on the basis of the results of permeability tests with the PLS, it will be required to place 31 cm of gravelly soil over the whole bed, but if the permeability tests are carried out with water, the results modified (using Equation (7)) and the designed heap drainage system, the need for the same soil will be 36 cm. Since the latter case is 5 cm thicker, the gravelly layer of the heap bed can transfer the whole acidic solution entering the heap to the drainage pipes, preventing the PLS level from increasing. However, if the drainage system is designed based on the result of the permeability test with pure water, the gravelly drainage thickness will be 15 cm. This can drain only part of the acidic solution entering the heap and the rest will remain in the heap. Over time, the remaining solution causes an increase in the PLS level in the ore heap, which may result in great problems in the hydrometallurgical process as follows:

- an increase in the hydro-static pressure of the acid solution at the interfacing layer between heap structure and the floor which causes a reduction in the stability and increases the heap-slide potential;
- an increase in the contact time between the acid and minerals in the copper oxide waste rock, thus increasing the impurity due to the dissolution of unwanted minerals in the acid;
- an increase in the amount of acid absorbed by the environment which, in

turn, increases the risks of both soil and groundwater pollution; and
- an increase in the liquefaction potential due to earthquake and mine blasting activities [16].

7. Conclusions

In this research, following experimental and theoretical approaches, the permeability coefficients of gravelly drainage layer of heap leaching structures against PLS and pure water were determined at different temperatures.

The results can be summarized as follows:

- The temperature of the PLS leaving the heap is higher than that of the dripping acidic solution. Over a one-year period, the mean temperatures of the PLS of Darezar bio-heap, Sarcheshmeh heap No. 1 and Sarcheshmeh site environment are 45°C, 25°C and 14°C , respectively. Therefore, due to bacterial activities, bioleaching process increases the solution temperature more than the ordinary leaching process does;
- Comparing the results of the tests shows that the permeability coefficient of the gravelly drainage layer against pure water is higher than that against the PLS, because the latter is more viscous than the former and it passess through the drainage system with more difficult;
- If the temperature of the PLS varies between 3°c and 60°c, the permeability coefficient of the gravelly drainage layer will show an increase of about 40%, which greatly affects the design of the thickness of the drainage system of heap leaching structures;
- In this research, the samples of the gravelly drainage layer and the PLS were selected from a real case (Sarcheshmeh heap leaching structure No. 1), though the results could be generalized to other cases as the most important parameters in this design are coefficient permeability of gravel and viscosity of PLS which are approximately constant; and
- The thickness of the gravelly drainage layer of Taft leaching structure was designed using the results of this research. If the drainage system is designed based on the result of the permeability test with pure water, the gravelly drainage thickness will be 15 cm. However, if the drainage system is designed on the basis of the results of permeability tests with the PLS, it will be required to place 31 cm of gravelly soil over the whole bed.

Acknowledgments

This research was sponsored by "Cany-Mess Technical and Engineering Services" and "Zamin-Sakht-Azma Geotechnical Engineers" companies. The authors hereby express their gratitude and feel greatly indebted for their invaluable cooperation and help.

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