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Evaluation of Influencing Factors in Outflow Control and Self-healing Property of Clay Core (case study: Vanyar dam- Iran)

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ABSTRACT

Compacted clay layers are the most common impermeable layers of earth dams. Due to the specific nature of clay and its unique geotechnical properties, these layers are damaged over time by cracking. The crack healing property of clay is its ability to close up its external cracks and reduce the outflow rate. Hence, in this study, a new method is presented to assess the self-healing phenomenon of clays using pinhole test. In this regard, three soil samples from Vanyar dam (Iran) were treated to obtain the Plasticity Index (PI) between 7 to 26. Different percent of bentonite was added to samples (i.e. 5%, 10%, 15%, 20%) and the impact of bentonite percentage increasing was investigated on self-healing property and outflow rate of clay soil. The obtained results showed that soil dispersion reduced and it became non-dispersive when bentonite was added to the soil samples with the optimum water content and 2% below it. Self-healing phenomenon was visible and predictable with the increase of bentonite in natural soil. For the sample with 20% bentonite, this phenomenon was observed from an early age due to high PI and the potential for high inflation. The sample with 20% bentonite and a moisture content of 2% less than the optimum showed the most reduction in outflow (38%) when compared with the natural soil sample. Therefore, it can be concluded that the PI increment for mixed bentonite-clay soil (between 7 to 26) can increase the self-healing ability.

Keywords:

Bentonite, Clay, Core, Pinhole Test, Outflow, Self-Healing

1. Introduction

In most of the failed earth dams, piping was the primary cause of the failure. Piping is the internal erosion of soil mass which causes seepage and water discharge through a hole that appears in the downstream of the embankment (Moffat et al., 2011) [1]. Foster et al. (2000a & 2000b) [2-3] noted that this failure can occur in just six to twelve hours. Therefore, this fact should be carefully taken into consideration for the safety of the hydraulic soil structures, as piping can be a dangerous phenomenon which causes failures in soil embankments and earth dams (Fell et al., 2003) [4]. Dispersive clays and soil dispersion are some of the piping factors. In all states of Australia, (Aitchison & Wood, 1965) [5], USA (Sherard et al., 1972) [6] and other regions in the world as well as Iran, piping failures caused by the dispersive feature of clays in small earth dams were widely reported. Sherard et al., (1977) [7] believed that dispersive clay particles are a type of soil that is most subjected to piping. they further stated that dispersive soils cannot be separated from those soils that are naturally resistant to erosion by ordinary engineering specifications; i.e. piping failures occurred in some soil embankments which have the same engineering properties as those that did not even experience any sign of failure. Dispersive clay soils can cause problems for many practices or structures. Their appearance is like normal clays that are stable and somewhat resistant to erosion, but actually, they can be highly erosive and appropriate to severe damage or failure. It is important to understand the essence of these soils and identify them so that they can be treated or avoided. Dispersive clays are specific kinds of soil material, where the clay fraction grind down in the existence of water through a de-flocculation process. When the inter-particle forces of repulsion go beyond those in attraction, this de-flocculation happens so that the clay particles get suspended, and in case of the flowing water, the detached particles will be carried away and piping will occur similar to the case of a crack in an earth embankment. Consequently, recently, special attention have been paid to the characteristics of clay, especially its self-healing property. Honjo and Veneziano (1989) [8] studied the ability of filters to hold cohesionless base soils through combining a physical soil particle transport model using statistical analysis of experimental results. It is indicated that the most single significant predictor of filter performance is the DF15/DB85 ratio, the factor utilized in Terzaghi's criterion. A pure physical explanation of this factor is extracted. A second significant factor, DB95/DB75, is also obtained. This factor is associated with the ability of the base soil to shape self-healing layers. About self-healing, Eigenbrod (2003) [9] investigated temporal variations in the interaction between the macropores and the soil matrix and the size and shape of the macropores, since these parameters will influence in the hydraulic conductivity of a fractured soil. He found out that for the fractures closure in the fine-grained soils, three main causes could be identified including (i) incremented effective stress above the undrained shear strength level of the undamaged soil; (ii) clogging the fractures caused by particles eroded from the fracture surfaces during penetration for non- or low-plastic soils; and (iii) swelling the clay particles near the fracture surfaces in high-swelling clay. Bendahmane et al. (2008) [10] examined the impact of three crucial factors on clay and sand erosion mechanisms. In low hydraulic gradient, it was found that the clay fraction erosion of the structure was caused by the stain. Increasing the hydraulic gradient, it was understood that the initiation of sand fraction erosion was as a result of the regressive erosion. The erosion extent was reliant on the clay content. The study underlined the complication of the confinement stress effects on both erosion phenomena. Vekli et al. (2016) [11] investigated the effects of iron and chrome slag on the index compaction and strength parameters of clayey soils. To comprehend the self-healing or progressive erosion of core cracks in earth dams, Kakuturu and Reddi (2006a) [12] developed experimental methods. Intense seepages through two kinds of core cracks are simulated in flow cells of diverse configurations experimentally. The results show that the current experiential filter criterion for base soils with fines contents of more than 85% requiring DF15/DB85 of less than 9, is conservative. On the other hand, the experimental results analysis indicates that the D15F/d85B ratio cannot show the rate of progressive erosion or self-healing. Kakuturu and Reddi (2006b) [13] described a mechanistic model to clarify the self-healing mechanism of two kinds of cracks in impermeable cores of earth dams; in type A core cracks prolonging from the interior of the core to the downstream filter, and in type B core cracks extending from the upstream face of the core to the downstream filter. The following points are concluded:

- Erosion of the base soil raises self-healing to the degree to which it supports the creation of a plug layer beforehand the filter; as a result of the entrapment of eroded base soil, it also decreases the filter permeability. These processes, consecutively, lead to the reduction in the leakage rate and soil erosion, consequently, resulting in self-healing.
- In assessing the self-healing rate; greater mean sizes of eroded soil particles increase the self-healing, assessment and reflection of the mean size of eroded base soil particles are essential.
- The filter critical seepage velocity (Vcr) is a critical factor governing self-healing. In such a manner that the seepage velocity in the filter is always less than Vcr, the hydraulic head, the filter permeability, and the filter length should be combined.
- The eroded base soil mass is controlled by the width of the core, thus, it leads to the different rates of self-healing.

Chinn and Pillai (2008) [14] developed an analytical experimental technique, explicitly for vertisols, to associate soil inherent features with the simplicity by which they undertake structure reparation (or increase their structure) following wet/dry phases and plant growth. To rank compacted vertisols regarding their capability to self-repair, such a relationship can be used. This study indicated that an experimental index, RT(1), in terms of the compressive strength of compacted soil cores beforehand and afterward a single wet/dry cycle, included the best potential to rank Vertisols from generally measured soil properties and predict self-repair capacity. The existence of fine sand along with clay content, instead of clay content on its own, indicated a better relation with RT(1). Wang et al. (2013) [15] concentrated on the parameters influencing the self-healing of cracks in clay seepage barrier. These parameters are the grain size of base soils, crack depth, and grain size of filter soils. The experimental results show that during testing with the underwater pressure of 300 kPa, the self-healing of cracks in the base soil layer of the sample is prompted. Cracks may not be fractured once more after self-healing, while the water pressure is incremented from 300 kPa to 400 kPa and then to 500 kPa. In the critical flow rate, the cracks self-healing initiates increasing with the increment of the crack depth or/and the value of D15/d85. Chai et al. (2016) [16] investigated the self-healing ratio of geosynthetic clay liner (GCL) with a destruction hole. Experimental leakage rate/self-healing capacity examinations of GCLs with destruction hole were carried out and the findings indicated that the amounts of bentonite entering the damaged hole and its water content are a function of the used liquid type, the damage hole diameter and overload pressure on the GCL sample. Rowe and Li (2016) [17] examined the self-healing of slits in GCLs upon hydration with deionized water under a confining stress of 2 kPa.

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They showed that full self-healing was observed when there was a 20 mm-wide strip of undamaged GCL between the slits. However full self-healing did not occur when the widths of this strip of bentonite between slits were reduced to 10 mm and 5 mm. Also, other studies were presented in communicating with the self-healing of GCLs (Egloffstein, 2001 [18]; Li & Rowe, 2017 [19]). Self-healing property of clay soils has a high importance as it is critical in huge structures like earth dams. Therefore, the focus of this paper is on presenting a new applicable method to elevate self-healing behavior of clays. For assessing the ability and reliability of this new method soil index (Physical Properties) and pinhole tests were conducted. Also, physical and identification tests (e.g. Sieve analyses, Hydrometer, Atterberg limits, and Proctor tests) were performed to correlate with the results of the pinhole test. To obtain the increased self-healing in clays, different soil types (with 0%, 5%, 10%, 15%, and 20% bentonite) were investigated via this method.

2. Methods and Materials

In this study, an excavated sample from the Vanyar dam was obtained as a low plasticity clay in terms of the Unified Soil Classification System (USCS). The Vanyar Reservoir Dam has been designed to provide agricultural water to Tabriz's plain from the Aji Chay River, the largest river of East Azerbaijan, located on 5 km northeast of Tabriz, in the downstream of the village of the Vanyar (Figure 1a). In this study, a sample of the secondary borrow dikes of the Vanyar dam has been prepared, including clay soils with low PI based on USCS classification. In order to determine the physical properties of the examined soils, the physical and chemical tests have been carried out according to ASTM standards. In this research, gradation, hydrometer and Atterberg limits have been used to determine the plasticity limit, clay percentage, activity number, and swelling soils potential. Soil samples of this research were created by adding 5% to 20% bentonite to clay soil with plastic properties around $7 < PI < 26$. The samples were provided in five modes (0%, 5%, 10%, 15% and 20% bentonite) with optimum moisture and 2% below optimum moisture (see Figure 1b). Also, for compaction test, the samples were exposed to air after drying and then, they were crushed; afterward, they were used for standard compaction test ASTM D698, and for determination of compaction optimum moisture and dry density (D 698, 2000). In this study, the pinhole test was used to evaluate the self-healing characteristic of clays. This test is a direct method for measuring the dispersion ability and colloidal erosion of clays which is caused by the movement of water through small holes in the sample hole. This test begins with distilled water flowing horizontally under the hydraulic head of 50 mm through a drilled hole with a diameter of 1 mm in a soil sample.

Naturally, sample particles exit from the dispersion and non-dispersion clays under hydraulic head by dissolving. The results of testing of samples can be investigated and classified based on the number of particles dissolved out of the sample, flow velocity, outflow rate, ultimate size of sample hole and observation (Table 1).

In the pinhole test classification of soil samples in the dispersion category is as follows:

2.1. Method A

D1, D2: dispersive clays failing quickly under 50 mm head; ND4, ND3: slightly to temperately dispersive clays eroding gradually under 50 mm or 180 mm head; ND2, ND1: non-dispersive clay with very slight to no colloidal erosion under 380 mm or 1020 mm head.

2.2. Method B

D: dispersive clays that erode fast under 50 mm head; SD: slightly dispersive clays that erode gradually under 180 mm head; ND: non-dispersive clays that show very slight or no colloidal erosion under 380 mm head.

2.3. Method C

D1, D2: dispersive clays failing fast under 50 mm head; ND4, ND3: dispersive clays eroding gradually under 50 mm, 180 mm, or 380 mm head; ND2, ND1: non-dispersive clay with very slight to no colloidal erosion under 380 mm head (Figure 2).

Table 1. Criteria for evaluating pinhole test results (ASTM D4647-93, 98).

Dispersive Classification	**Head,**	**Test time for given head,**	**Final flow rate through specimen,**	**Cloudiness of flow at end of test**		**Hole size after test,**
	mm	**min**	**ml/s**	**from side**	**from top**	**mm**
D1	50	5	1-1.4	dark	very dark	≥2
D2	50	10	1-1.4	moderately dark	dark	>1.5
ND4	50	10	0.8-1	slightly dark	moderately dark	≤1.5
ND3	180	5	1.4-2.7	barely visible	slightly dark	≥1.5
	380	5	1.8-3.2			
ND2	1020	5	>3	clear	barely	<1.5
ND1	1020	5	3≥	perfectly clear	perfectly clear	1
Method B						
D	50	10	-	slightly dark to dark	very dark to moderately dark	≥1.5
SD	180-380	5	-	barely visible	slightly dark	≥1.5
ND	380	5	-	clear	barely visible to clear	<1.5

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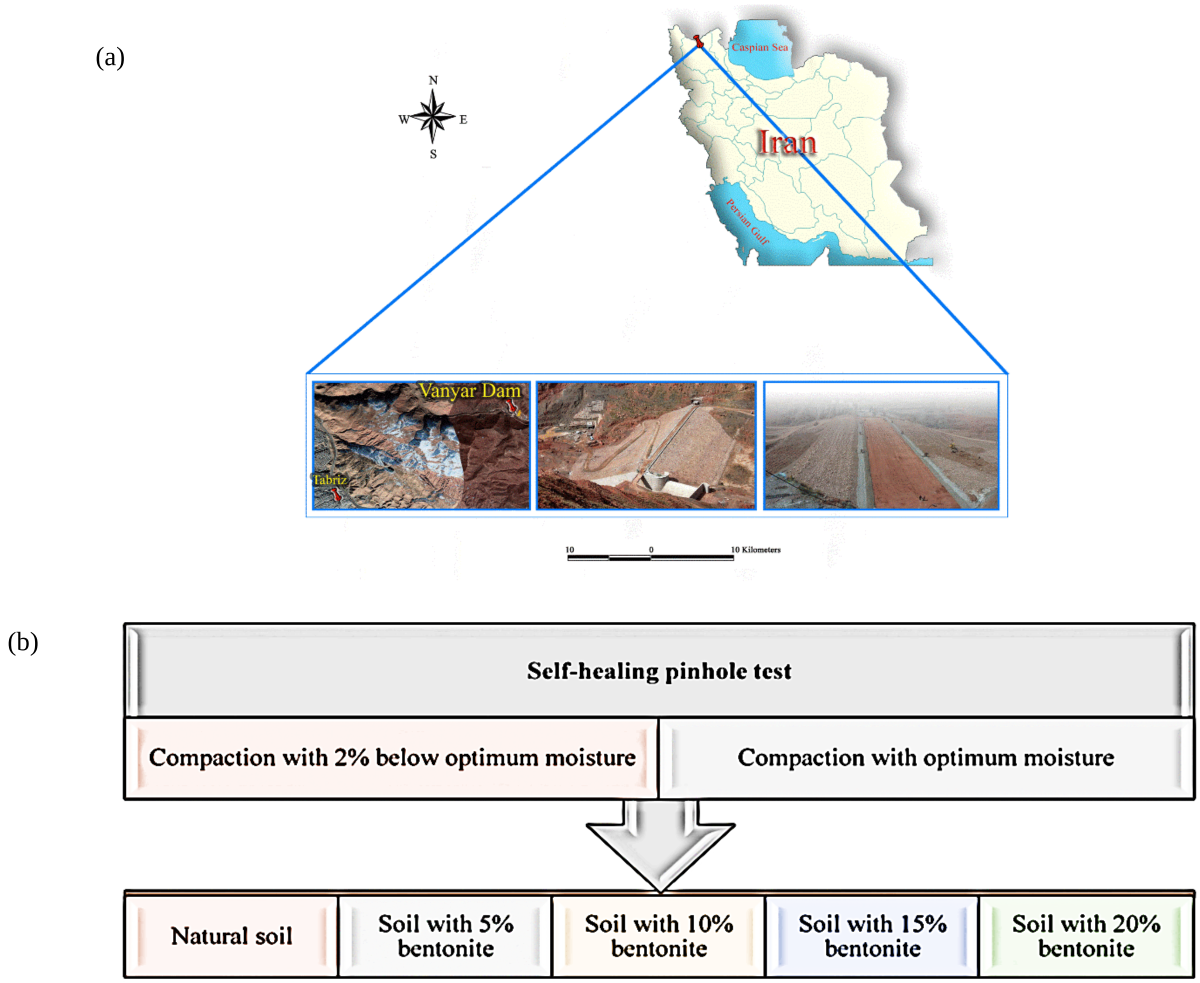

Figure 1. (a): Location of the Vanyar dam and (b): flowchart of the samples and moisture contents.

Figure 2. Pinhole test steps.

3. Result and Discussion

Fine soil formation is one of the effective factors in the subject of soil swelling. Based on this fact, the swelling potential of fine soil samples is reduced due to the increase in the percentage of coarse particles. Increasing the percentage of these particles by more than 10% leads to a significant decrease in the swelling potential for inflation. The Hydrometer analysis has been used for particle size distribution and fine grain size percentage. A sample of the graphs has been shown in Figure 3. Based on the results, almost all samples have a diameter of more than 90% of their particles less than 0.075 mm. The swelling of clay soils is due to the increased thickness of the distributed ion after increasing the water. Seed et al. (1962) [20] provided an exact relationship between the potential of swelling, activity numbers and percentage of clay soil.

$$S = (3.6\times10^{-5})(A)^{2.44}\times C^{3.44} \tag{1}$$

Where A is Activity Number and C is percentage of passive from sieve # 200. Table 2 and Figure 4 show the relationship between these parameters with percentage of bentonite. It can be seen that by increasing the percentage of bentonite, the swelling potential and activity number have been increased. Also, Figure 4 shows that the increase of the PI and the clay particles less than 2 mm in the samples cause an increment in amount of the activity number and swelling potential.

Table 2. The obtained results for activity numbers and swelling potential of clay soil with different percent of bentonite.

Type of Soil	(PI)	Percentage of Clay (2μ >)	Activity number (A)	Swelling potential (S)
Natural Soil	0.03	0.77	9%	7%
Soil with 5% betonies	0.31	1	14%	14%
Soil with 10% betonies	0.966	1.11	18%	20%
Soil with 15% betonies	1.759	1.142	21%	24%
Soil with 20% betonies	2.24	1.181	22%	26%

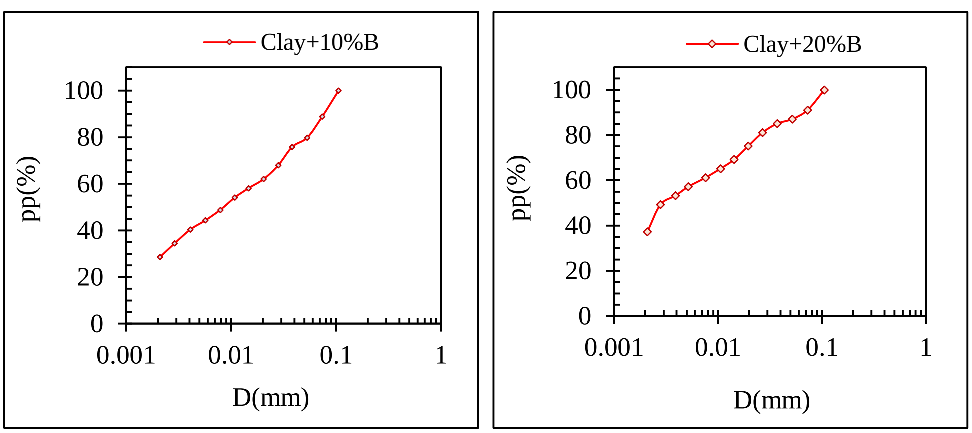

Figure 3. Hydrometric test of the sample with 10 and 20% bentonite**.**

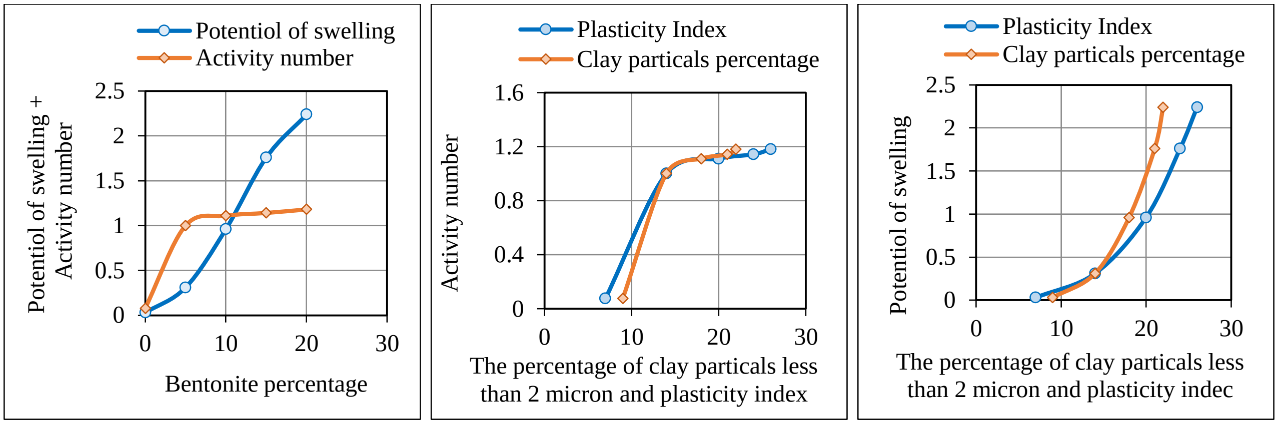

Figure 4. The relationship between the potential of swelling, activity numbers and percentage of clay soil with percentage of bentonite.

Figure 5 shows geotechnical properties of the samples against the optimum moisture content. For the five modes (samples with 5%, 10%, 15%, 20% bentonite; and the last one without bentonite), it is implied from Fig. 5 that the optimum moisture content of compacted soils increases linearly with the increment of LL and PL and it increases non-linearly with the increment of PI. According to Table 3, for fixed fine-grained content, wide variations were induced in the dry density and optimum moisture by changing clay minerals. Also, it could be stated that the existence of montmorillonite minerals increases the swelling potential of clays in different situations.

Table 3. Results of gradation, hydrometer and Atterberg limits tests.

Soil	Liquid Limit	Plasticity Limit	Plasticity Index	Passing a No. 200 sieve (%)	Particles smaller than 2 microns in size (%)	A	S	Moisture content	Dry density
	LL%	PL%	PI%					(%)	(gr/cm^3)
Natural soil	28	21	7	80.8	9	0.77	0.03	17	1.8
Soil with 5% bentonite	38	24	14	81	14	1	0.31	17.5	1.78
Soil with 10% bentonite	46	26	20	81.2	18	1.11	0.96	18	1.725
Soil with 15% bentonite	53	27	24	81.3	22	1.42	1.75	19.5	1.69
Soil with 20% bentonite	58	32	26	81.4	26	1.18	2.24	21	1.65

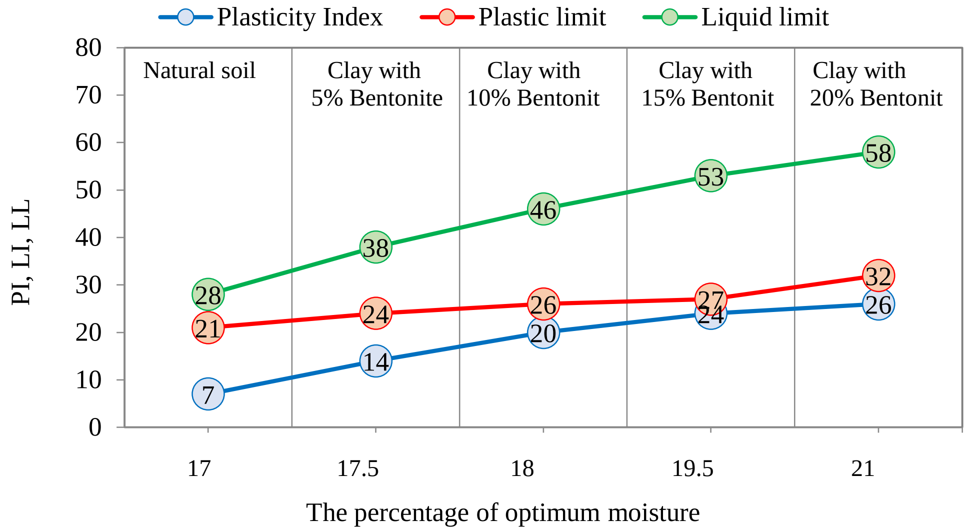

Figure 5. Optimum moisture content versus PI, PL, and LL.

Classification of soil samples into dispersion and self-healing, based on the observation of pinhole test, is presented in Table 4. Samples were tested for 25 minutes under the hydraulic 50-900 mm head. Investigation of the results presented in Table 4 and observation of tests that include increasing or decreasing the diameter of the holes created in the sample, the color and rate of outlet discharge, grain size, time and different hydraulic heads show that samples with 10% and 20% bentonite are non-dispersive in all situations and, for natural soil, dispersivity has not occurred only for optimum moisture 17%. For samples with 10% and 20% bentonite, self-healing is observed for all situations. The results in Table 4 show that for samples with 20% bentonite, self-healing begins from early ages which is due to high plasticity index. Also, for the sample with 10% bentonite, self-healing is activated in a short time in optimum moisture 18%. At the same compaction and moisture rates, samples with higher PL show more self-healing rates in short time; hence, high PI with an optimum moisture content of compaction activates the self-healing mechanism in a short time. Therefore, the direct effect of characteristics of plasticity and its related factors are observable in the potential rate of inflation. Whereas, the sample with 20% bentonite has the highest potential rate of inflation, it shows observable and predictable self-healing in all investigated moisture content. Moreover, in this sample, reduction of the diameter of the hole was evident in different moisture contents from the beginning and the rate of decline increased with time, whereby after about 2 months, it seemed that the hole was completely healed. Among the samples with a moisture content of 2% below the optimum one, self-healing and diameter reduction were more desirable. In the samples with a moisture content of 2% below the optimum (19%), self-healing and diameter reduction were more noticeable.

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Table 4. Results of classification and self-healing of samples.

Self-healing	Classification	Cloudiness of flow	Test time (*min*)	Hydraulic head (mm)	Sample age (day)	Sample's moisture (%)
Sample with 20% bentonite						
Self-healing is predictable	(*ND2*)	Dark clear	20	380	3	21
Self-healing is predictable	(*ND2*)	Dark clear	21	900	13	21
Self-healing is observable	(*ND2*)	Dark clear	20	380	20	21
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	9	19
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	13	19
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	20	19
Sample with 15% bentonite						
Self-healing is predictable	(*ND2*)	Dark clear	20	900	3	19.5
Self-healing is predictable	(*ND2*)	Dark clear	21	900	14	19.5
Self-healing is observable	(*ND2*)	Dark clear	20	900	20	19.5
Self-healing is predictable	(*ND1*)	Dark clear	20	900	9	17.5
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	13	17.5
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	20	17.5
Sample with 10% bentonite						
-	(*ND1*)	perfectly clear	21	900	3	18
Self-healing is observable	(ND1)	perfectly clear	21	900	10	18
Self-healing is observable	(*ND2*)	perfectly clear	21	900	20	18
-	(*ND1*)	perfectly clear	21	380	5	16
Self-healing is predictable	(*ND1*)	perfectly clear	18	380	15	16
Sample with 5% bentonite						
-	(*ND2*)	Dark clear	20	900	3	17.5
Self-healing is predictable	(*ND2*)	Dark clear	21	900	14	17.5
Self-healing is observable	(*ND2*)	Dark clear	20	900	20	17.5
-	(*ND1*)	Dark clear	20	900	3	15.5
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	14	15.5
Self-healing is predictable	(*ND1*)	perfectly clear	21	900	20	15.5
Natural soil sample						
-	(*ND1*)	perfectly clear	20	380	3	15
predictable	(*ND3*)	perfectly clear	20	380	14	15
predictable	(*ND2*)	perfectly clear	20	380	20	15
-	(*ND2*)	perfectly clear	20	380	10	17
predictable	(*ND2*)	perfectly clear	20	380	20	17

Figure 6(a) shows average outflow from the sample with 20% bentonite at different ages and moisture contents and Figure 6(b) shows outflow at 10, 15, 20 and 25 minutes at different ages. It could be seen that the average outflow decreased as the time elapsed. Additionally, at all ages, the outflow of the sample with a moisture content of 2% under the optimum moisture was lower than that of the sample with the optimum moisture content. Figure 6(c) shows outflow rate of the sample with 20% bentonite for different moisture contents at the age of 20 days. The output flow rate for both samples is very close together in the last five minutes of testing. In the last five minutes of the test, the outflow rate for the sample with 19% moisture content was lower than that for the sample with 21% moisture content.

(a) (b) (c)

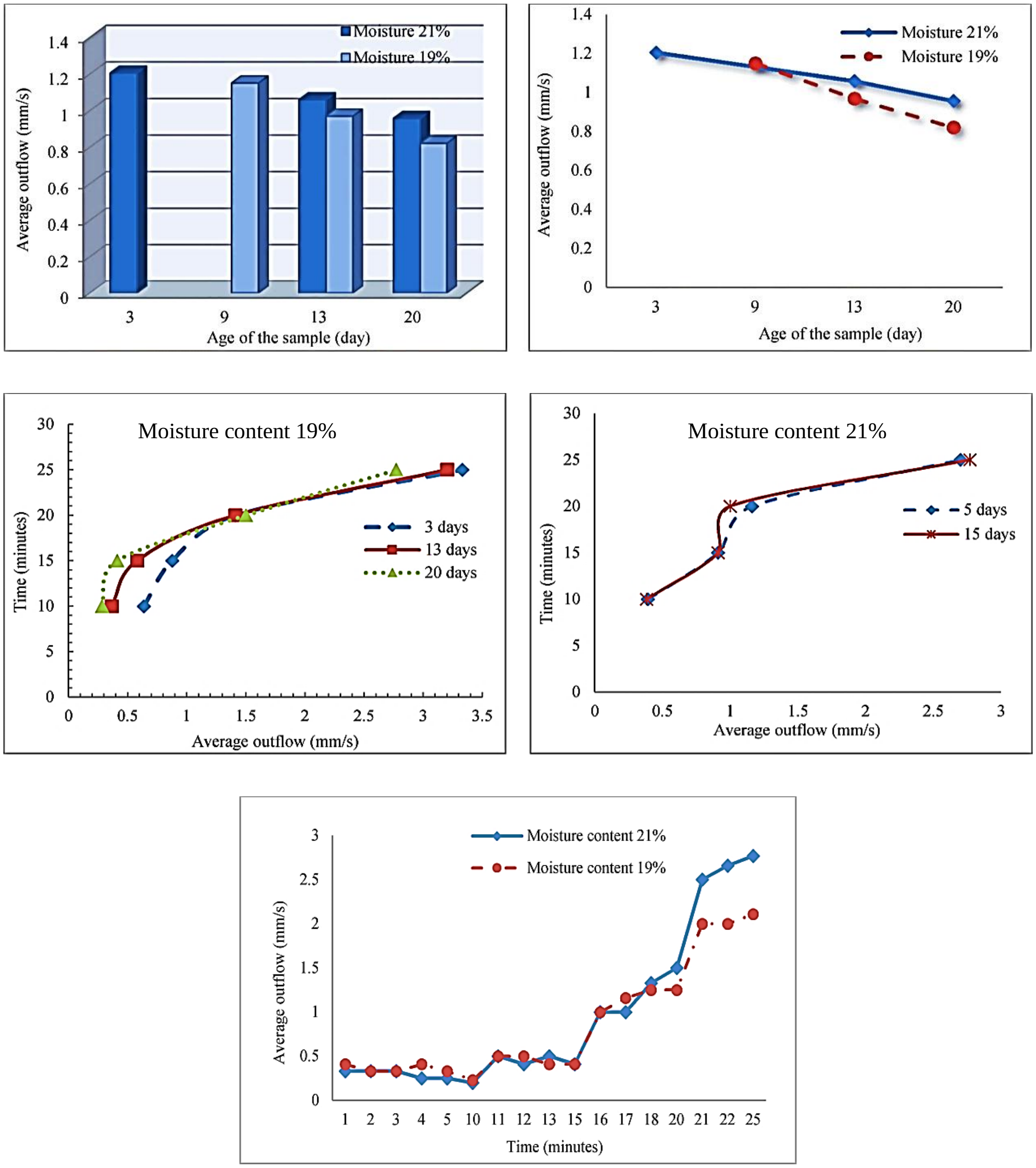

Figure 6. (a): average outflow from the samples with 20% bentonite in different ages, (b): average outflow in testing time for the sample with 20% bentonite, and (c): outflow rate for the sample with 20% bentonite at the age of 20 day.

For the 10% bentonite sample, with optimum moisture content and a moisture content of 2% below the optimum, it is observed that the average outflow decreases with time (Figure 7(a, b)). However, self-healing happens practically over time. As can be seen in Figure 7(c), self-healing emerges in the low hydraulic head and becomes dispersive as the head increases and hence the outflow increases, too. This is more than the outflow at the optimum water content. But, this trend decreases with time and the self-healing process occurs completely. Though the sample with 10% bentonite does not show remarkable and uniform self-healing by the increment of hydraulic head and age, it should be noted that in compared with the sample with optimum moisture content, the sample with a moisture content of 2% below the optimum moisture has shown favorable reduction in diameter of the hole and increased outflow (Figure 7 (a, b)).

(a)

(b)

(c)

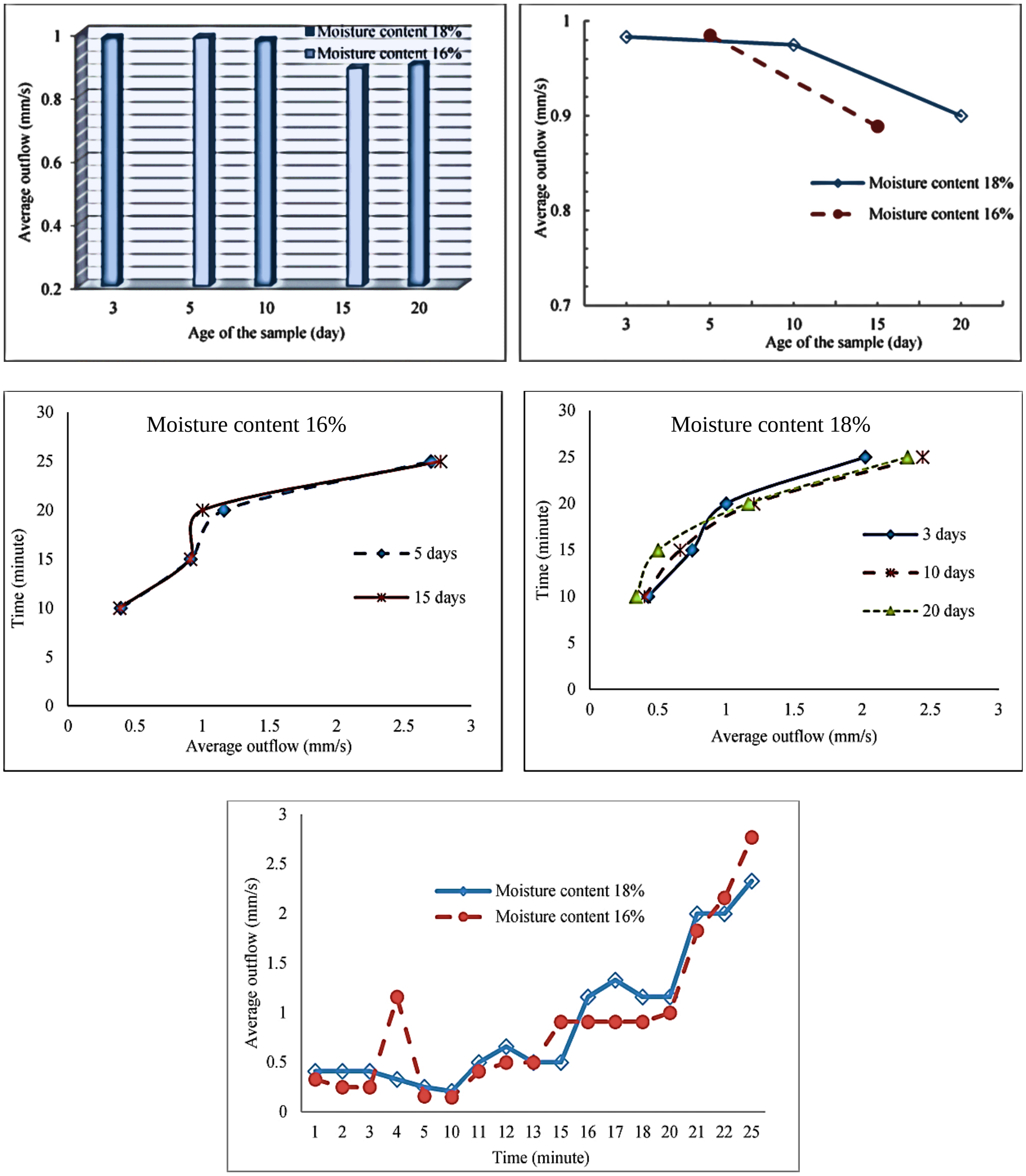

Figure 7. (a): average outflow from the samples with 10% bentonite in different ages, (b): average outflow in testing time for the sample with 10% bentonite, and (c): outflow rate for the sample with 10% bentonite at the age of 15 and 20 day.

The natural sample soil (i.e. samples without bentonite) shows favorable self-healing in optimum moisture content over time. Although it is not visible in the form of reduced diameter, the outflow reflects this fact. This trend is inverse in the samples with a moisture content of 2% below the optimum moisture and the sample goes on to dispersion mode (Figure 8 (a, b, c)).

(a)

(b)

(c)

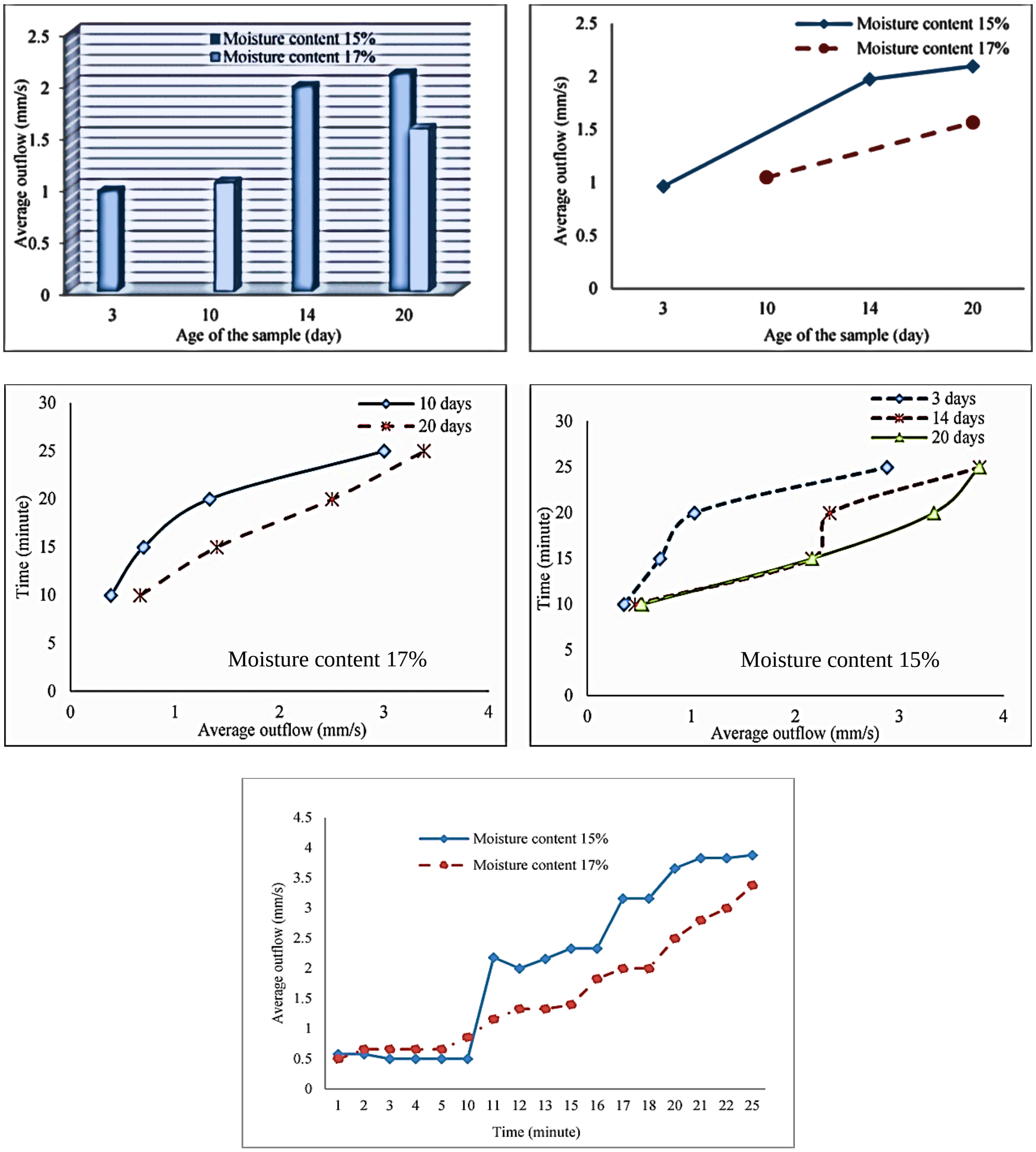

Figure 8. (a): average outflow from the natural soil samples in different ages, (b): average outflow in testing time for the natural soil samples, (c): outflow rate for the natural soil samples at the age of 20 day.

In Table 5, the discharge rates have been presented based on the percentage of bentonite and optimal moisture content and 2% below the optimum moisture content. Results indicate that by increasing the sample age in different conditions for different moisture contents, the mean flow rate decreases which shows the improvement of self-healing status over time, that shows the better results in case with 2% below optimum moisture content. It is also observed that with increasing bentonite rate, the soil self-healing process has an increasing trend, which is best for the sample with 20% bentonite and 2% below optimum moisture content, which has been completely shown in Fig. 9. For compaction with optimum moisture content and 2% moisture content below optimum moisture and for the different bentonite percentages, it has been observed that the average outflow decreases with increasing percentage of bentonite, which indicate an increase in self-healing process. Figure 10 shows the maximum outflow from the samples with different bentonite contents. It is concluded that in optimum moisture content, the rates of outflow for the samples with 10% bentonite and 20% bentonite are respectively 31% and 18% less than the natural soil sample. In the samples with a moisture content of 2% below the optimum moisture, the rates of the outflow for the samples with 10% bentonite and 20% bentonite are respectively 33% and 38% less than the natural soil sample. Therefore, it is concluded that the highest reduction in outflow rate is for the sample with 20% bentonite and with a moisture content of 2% below the optimum moisture. Furthermore, it is derivable that reduction in outflow can be achieved by adding bentonite.

Table 5. The discharge rates based on the percentage of bentonite and optimal moisture content and 2% below the optimum moisture content.

Type of Soil / Age of the Sample	Natural Soil		Soil with 5% betonies		Soil with 10% betonies		Soil with 15% betonies		Soil with 20% betonies	
	Optimum moisture	2% below optimum moisture	Optimum moisture	2% below optimum moisture	Optimum moisture	2% below optimum moisture	Optimum moisture	2% below optimum moisture	Optimum moisture	2% below optimum moisture
	%17	%15	%17.5	%15.5	18%	%16	%19.5	%17.5	%21	%19
Day	Average outflow									
3	1.25	1.2	1.25	1.12	1.15	1.05	1.07	1.01	1.02	0.98
14	1.4	1.97	1.22	1.1	1.12	1.01	1.02	0.93	0.95	0.88
20	1.57	2.06	1.2	1	1.05	0.89	0.93	0.84	0.90	0.8

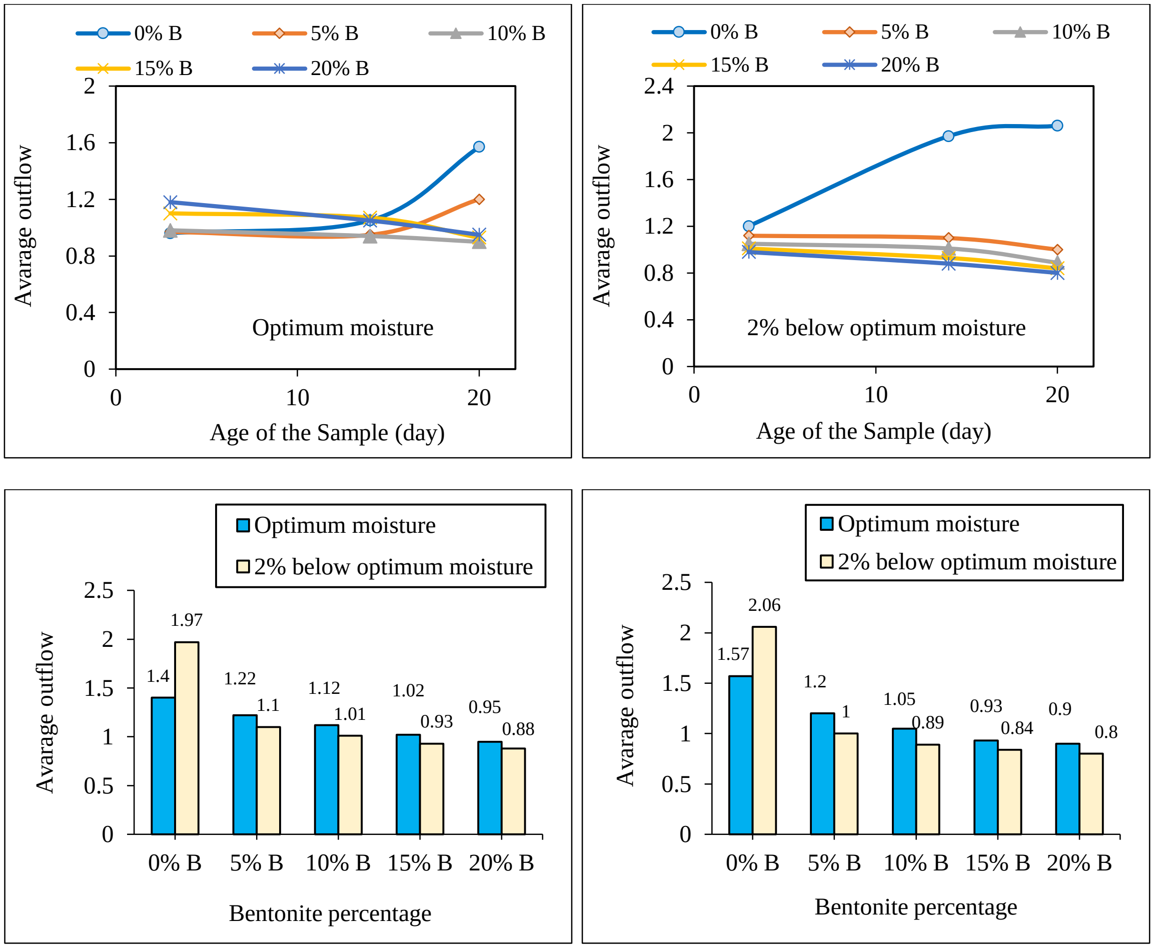

Figure 9. The impact of Bentonite percentage on self-healing process.

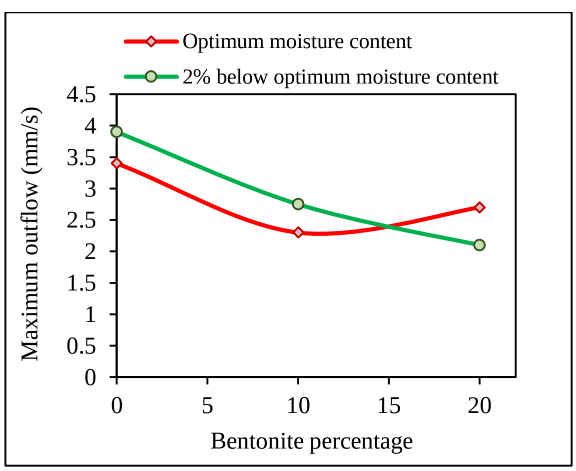

Figure 10. Maximum outflow from the samples at ending ages for optimum moister content and 2% below with different bentonite contents.

4. Conclusion

This study was concentrated on the experimental investigations of the self-healing of cracked clay core of the Vanyar earth dam. Several samples in five modes (samples with 0%, 5%, 10%, 15%, 20% bentonite) were prepared and investigated by pinhole test. For determining physical characteristics of the samples, physical and chemical tests were conducted based on ASTM standards. The results are concluded as follows:

Type of clay and its properties showed significant effects on characteristics of compacted clay soils so that the self-healing process changed based on properties of clays. The existence of montmorillonite minerals increased self-healing potential of clays in different situations. Both samples with 10% and 20% bentonite were non-dispersive for both optimum moisture content and 2% below it, while the sample without bentonite was non-dispersive only in optimum moisture content (17%).

In the tested samples, self-healing was observed by an increase in PI. This process for the sample with 20% bentonite started from early ages, that means the samples with higher PL show more self-healing in short time, at the same compaction and moisture state. By adding bentonite to natural soil, decrease in outflow was observed at about the minimum of 18% and a maximum of 38%. The maximum reduction of outflow belonged to the sample with 20% bentonite with a moisture content of 2% below the optimum moisture. Thus, it could be concluded that by increasing PI, the maximum outflow reduced in samples with the moisture contents below the optimum. The samples with higher PL shows more self-healing at a short time, at the same compaction and moisture state. Therefore, for the sample with 20% bentonite which had the highest PI (PI=26), a maximum reduction in diameter and outflow obseved.

Impermeability of layers of clay varies by different moisture content, compaction, and constitutive minerals. If there are cracks in the impermeable layer, they will be healed over time and impermeability will decrease. This is observed in soils with high inflation potential. In the tested samples, the best mode was observed in the soil with 20% bentonite with the moisture content of 2% below the optimum moisture and in the standard compaction with the highest inflation potential (S=2.06) when the self-healing process continues for a long time and existing cracks heal. Therefore, due to inflation characteristics of each soil, self-healing effect is different. Ultimately, it was concluded that the admixture of bentonite with the clay soils in a logical ratio leads to justifying PI in a suitable range which tends to elevate self-healing property of clays.

5. References

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