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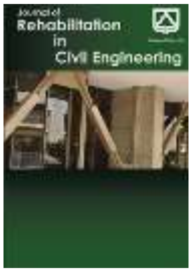

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Experimentally Investigation of Nano Clay Effects on Leaching and Self-healing Process of Cracked Clayey Soils

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ABSTRACT

Compacted clay layers are known as one of the common low impermeable layers used in geotechnical structures. Due to geotechnical properties, these layers damaged through cracks in their lifespan. This research has attempted to improve the workability by using self-healing features of clays. By conducting numerous experimental tests, it has been shown that, by increasing the plasticity index of clays, the pace of crack healing process will be enhanced. Experiments have shown that percentages of Montmorillonite Nano Clay (MNC) are quite effective and reduce the flow rate in the samples, which is a sign of self-healing of the cracks by an NC additive. On this basis, NC can be perfectly used to repairing cracks in clayey soils. The results of this study show that in the sample with 1 mm crack, about 500 milliliters of water pass through the crack in 60 minutes under no pressuring conditions. While, if the sample contains 2 and 5 percent NC, the amount of water passing through the cracks within 60 minutes, will be 40 and 5 ml, respectively. This dramatic reduction for passing water reflects the positive effect of Nano sized grains on the closure of the created cracks. Therefore, it can be concluded that the self-healing process occurs earlier in smaller cracks, because the NC and soil particles can easily touch each other after swelling. Five percent of MNC can insure the cracks closure at 100% density. In the samples with a density below 100%, there is a large gap between the soil particles, and the swelling of the NC from absorbed water dedicated to fill these voids.

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1. Introduction

Clayey soils often have problems such as high compressibility and low shear strength. Different methods are proposed and used depending on the type of the project to provide suitable resistance and stability to such soils. Clay stabilization by using additives [1, 2], fly ash, Nano materials [3], etc. has been the focus of research interests. Clay, on the other hand, has a positive characteristic that reduces and heals the cracks in it. This feature is called self-healing. Crack healing means closing the cracks created in the sample. Factors affecting clay self-healing, especially the properties of soils under different compressive-consolidation and moisture conditions, lead to specific clay-related behaviors. Cracking is the cause of discontinuity in clayey soils. The advent of cracks due to desiccation is a common feature in clays. Because of this process, the hydraulic properties of the soil can no longer be assumed constant. Permeability changes due to the history of soil watering and dewatering cycles. This issue has been a major problem in understanding the hydraulic behavior of clayey soils and has attracted the attention of many researchers. The effective parameters in the cracking are known qualitatively, but the geometric properties of the cracking pattern, such as shape, distance, and depth of these cracks, are not clearly predictable. Cracking is caused by the evaporation of water and shrinkage of soil. Cracks are formed when the tensile forces inside the soil and its cavities exceed the tensile strength of the soil. The shrinkage-expansion behavior of clay soils, especially dispersive soils, is responsible for the formation of cracks due to drying. Cracks due to clay drying and shrinkage are affected by properties such as shear strength, tensile strength, Poisson coefficient, and a compressive modulus. In a classification according to nature of the cracks, the cracks can be divided into four types: *Shrinkage* cracks due to drying and loss of soil moisture. *Thermal* cracks caused by temperature changes. *Tensile* cracks develop mainly due to overhead pressure and sometimes develop in interaction with other cracks. *Fracture* cracks caused by loading [4]. According to the main cause of the breakdown, the cracks can be divided into three major groups: Cracks due to soil effective stress reduction, cracks caused by water pressure, and cracks caused by material strength decline. The presence of cracks is one of the major causes of leaching in dispersive soils. Preventing this phenomenon is one of the important issues. The higher the unit weight of the dry soil, the less its compressibility and settlements. If the soil is compressed on the wet side of optimum water content, it will have more settlements and also have more flexibility and less cracking due to factors such as settlement. It should be noted, however, that in this case, if the time between the embankments of two successive layers is prolonged, the possibility of cracking is increased due to the decrease of soil moisture and shrinkage.

Clays from the smectite group are layered with cations in the interlayer space; this indicates that swelling properties of the clay are obtained by hydration of the cations in the interlayer space. Because clay swelling implies a particular viscosity called thixotropy. This characteristic has the effect of blocking the void against water-soluble ions in the soil [5]. Due to this property, this clay is used as a barrier or sealing material for radioactive waste disposal sites [4] and earth dam cores [6]. The result of clay self-healing is the closure of the external cracks created in it and the surface cracks are easier to repair than deep cracks [7]. These cracks, of course, do not return to their pre-cracking form and in any case, there are changes in the properties of the clay layer [4]. For example, the permeability of the clay layer will increase slightly. In general, factors affecting self-healing in clays include swelling, settlement, and creep [4]. Determining the precise hydraulic properties of low permeable and non-saturated materials such as clay is important because this type of soil plays an important role in preventing leakage in hydraulic structures and also in protecting the environment against the transmission and spreading of contaminants, especially hazardous ones [8]. Increase in soil specific surface area changes its characteristics such as plasticity properties, permeability coefficient, and the double layer water thickness around the clay [9]. Due to their high specific surface area, nanoparticles are much more reactive than soil particles, causing inter-particle interactions, locking, and clogging of soil particles, resulting in reduced soil permeability [10]. Richard Feynman introduced the idea of nanotechnology in 1959. What has led to the emergence of nanotechnology is the high surface-to-volume ratio of these materials. The factor that controls many of the properties of nanomaterials seems to be the behavior of surface atoms and their amount. Nanotechnology in the field of geotechnics is relatively new to other branches, and human findings are particularly limited in the laboratory field.

Yantrapalli et al. [11] studied the effects of heavy metals on cracks in clays. Iranpour and Haddad [12] investigated the effect of different NC samples on properties of clay soils. They found that soil moisture and its unit weight had a significant effect on the failure. Since NC has a higher specific surface area than nano-silica, it is more effective in reducing soil breakage potential. Zomorodian et al. [13] experimentally investigated the effect of kerosene on resisting behavior of clayey soils with low plasticity. In this study, the effect of NC and nano-silica additives on the behavior of clay soils with and without kerosene was investigated. They found that the presence of kerosene reduced the strength, but with the presence of nano-silica and NC, the strength of kerosene contaminated clays increased. One of the applications of nanomaterial in geotechnical engineering is their use in improving the cracks and erosion created in earth structures. The use of nanomaterial can also be very effective in improving soil seepage, which is referred to as self-healing. Kakuturu and Reddy [14] studied self-healing in cracks created in the earth dam. In their research, they considered two different types of cracking. One from the core to the downstream filter and the other from the core to the upstream filter. They also took into account several parameters including hydraulic conditions, soil, and filter parameters. Wang et al. [7] conducted 12 experiments to investigate factors affecting the self-healing of cracks in clay sealers. These factors include the depth of cracks, the size of the base soil grains, and the size of the filter grains. Four types of cracks with different depths, five base soils, and five filters with different grading curves were investigated. The test results indicate that the self-healing of cracks in the base soil layer of the sample occurred during the test under water pressure up to 500 kPa. Cracking after self-healing may not break again under water pressure. Kalhor et al. [15] investigated the impact of nanomaterials on soils exposed to thawing and frost. These researchers used nano-silica as an additive in their research. Changizi and Haddad [16] investigated the effects of nano-silica (0.5, 0.7, and 1% by weight) on geotechnical properties of cohesive soil. They found that an increase in nano-SiO_2 content resulted in an increase in the angle of internal friction, the cohesion, the unconfined compression strength, and the maximum dry unit weight of the clayey soil. Abbasi et al. [17] conducted a series of tests on dispersive clays stabilized using NC. They performed tests on soil samples with different amounts of NC including (0, 0.25, 0.5, 1, 2 and 4% by dry weight) with respect to curing ages of 1, 3 and 7 days. Based on the results obtained from their research, it was found that the addition of NC to dispersive clayey soils could decrease their dispersivity potential considerably.

In this study, the effect of NC on self-healing of cracks in clayey soil samples with different plasticity index investigated by creating a crack, using the data of compressing and Atterberg limits test on soil reinforced with MNC. Since crack-healing is not such that the soil returns to its original form and its permeability may be somewhat increased, investigation of cracks self-healing at different plasticity index and its effect with nano-additive percentage (2 and 5%) are the target of this research.

2. Materials Characteristics and Experimental Equipment

2.1. Clay Specifications

The clay soil used in this study was derived from Boroujerd, Iran. The soil sample grading was performed by sieve (ASTM D422-87) and the hydrometer method (ASTM D422-63), which is shown in Figure 1. According to ASTM D4318, ASTM D854-87, ASTM D698-12, and ASTM D2434-68 standards, Atterberg limits, specific density, compaction, and permeability tests were performed on soil sample, respectively (Table 1).

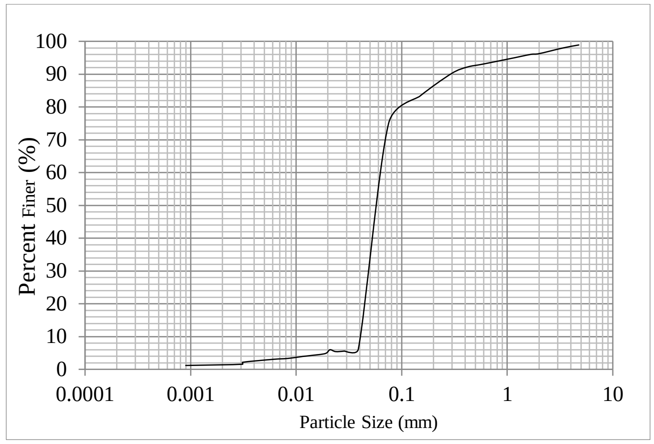


Fig. 1. Grain size distribution of soil sample

Table 1. Clay Sample Characteristics

Parameter	*Standard*	*Value*
G_S	(ASTM D854-87)	2.66
PL	(ASTM D4318-17)	18.00
LL	(ASTM D4318-17)	31.80
PI	(ASTM D4318-17)	13.80
$\gamma_{d\ max}$ (gr/cm^3)	(ASTM D698-12)	1.818
ω_{opt} (%)	(ASTM D698-12)	14.41
Permeability (cm^2/s)	(ASTM D2434-68)	7.34×10^{-7}

2.2. Montmorillonite Nano Caly (MNC)

The NC used in this study is K(10) – MNC. The specifications of which are presented in table 2, based on the manufacturer's company catalog.

Table 2. Physical and Chemical Characteristics of MNC

Clay Mineral	Montmorillonite
Density **(gr/m^3)**	0.5 - 0.7
Particle Size **(Nanometer)**	1 - 2
Specific Surface Area **(m^2/gr)**	220 - 270
Electric Exchange **(MV)**	250
Ion Exchange **(meg/100gr)**	480
Distance Between Particles **(A°)**	60
Moisture **(%)**	1 - 2
Color	Light Yellow

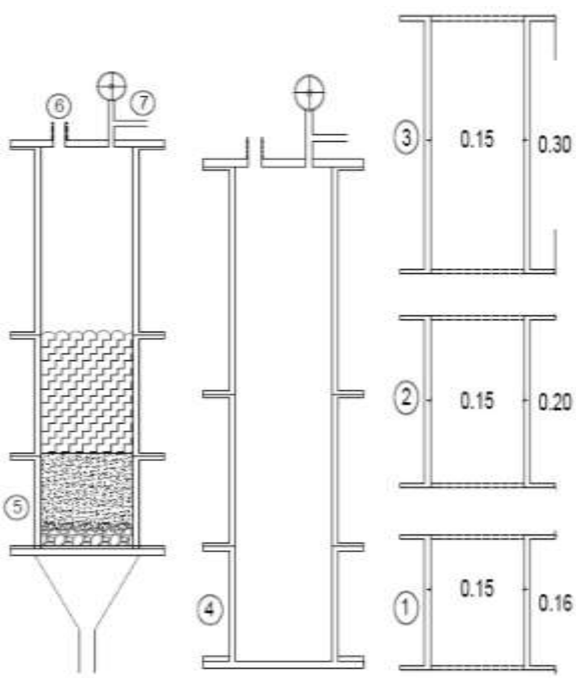
2.3. The Experimental Apparatus

A special template was used for this experiment. This mold is made of Russian stainless steel with a thickness of 3 mm and is resistant to water, moisture and pressure. The mold height is 15 cm with a diameter of 15 cm (Figure 2). After attaching the top of the mold, the total height of the template reaches 45 cm. At the top of the mold is an embedded faucet from which water is poured onto the sample, as well as a pressure gauge at the top of the mold, which can be used to control the pressure on the sample. The pressure applied by the air pump is connected to the inlet valve of the measuring gauge and its pressure level can be controlled. Below the mold, a funnel is attached to the mold that guides the outlet water centrally to the measuring vessel. One of the benefits of this mold is the dimensions of the device has been selected to provide a suitable working space when preparing the sample and, most importantly, to create a crack in the sample area without causing any damage to the original test. The outflow of water and pressure is such that it does not damage the sample in the early moments of the test. There is ample room for storing water and injecting it into the sample vertically (top to bottom) and the water outlet discharge can also be measured.

3. Sample Preparation and Experimental Tests

Sample reconstruction technique was used to perform the experiments. To obtain reproducible samples for all tests, the desired moisture content of each soil with optimum moisture content and maximum soil dry density was considered. In NC-stabilized experiments, firstly mix the nano-admixture with the soil performed in the dry state. Then divide the NC and water into 10 equal portions to obtain a homogeneous mixture of soil, stirring each portion separately for about 30 to 45 minutes, requiring mixing with a hand mixer. The amount of NC used in the samples is 2 and 5% of the total soil sample weight. Depending on the test conditions, a standard device on the specimen created a crack of 0.5 mm or 1 mm thickness. The procedure for the experiments is as follows. First, for non-pressurized samples for one hour, the outflow water is measured every minute, after one hour, the remaining water is drained out of the sample and into the mold, and the sample will be released into the mold for 24 hours, then repeat the same test procedure after 24 hours. For both 0.5- and 1-mm cracks, these series of tests performed.

In the next series of experiments, the pressure applied to the samples first examined the sample without NC in which cracks were created on the sample. For 5 minutes, pressures of 50, 100, 200, 300, 400, and 500 kPa were applied to the samples, and the output water was measured every minute; afterward the sample left in the mold for 24 hours. Then after 24 hours, the same test procedure was repeated and the water output was measured every minute. These series of experiments were performed for both 0.5- and 1-mm cracks. Figure 3 indicates crack geometry. Figure 4 shows how to create cracks in the specimens and the self-healing process of the cracks. How to prepare samples for tests is shown in Figure 5.



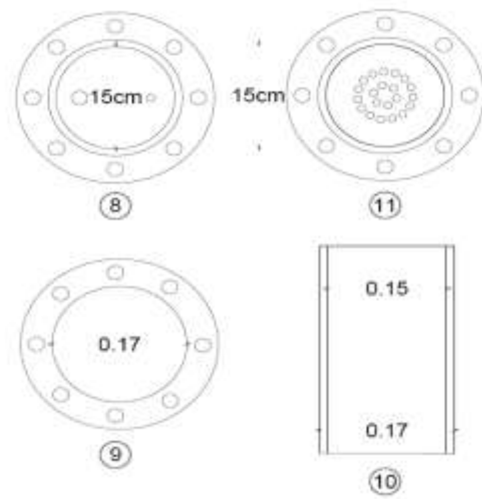


Fig 2. The mold used in experiments: 1) Soil sample reservoir. 2) Water reservoir for injection in the samples. 3) The pressure reservoir. 4) Connecting three reservoirs. 5) Funnel for soil samples. 6) Water input to reservoir. 7) Input and output of air pressure with dial gauge. 8) Upper cap. 9) Connecting rings. 10) Cylinder with 15cm diameter. 11) Bottom cap

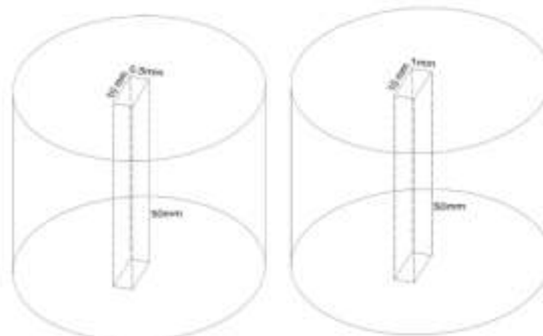


Fig. 3. Crack geometry in samples

Fig. 4. Crack creation (right) and self-healing process of cracks (left)

Fig. 5. Sample preparation for tests

3.1. Tests Performed on Samples without Pressure

In this section, the effect of cracks self-healing on specimens with 0.5 mm and 1 mm cracks, under conditions of without external pressure, is investigated. The results of the experiments are shown in Figures 6 to 9.

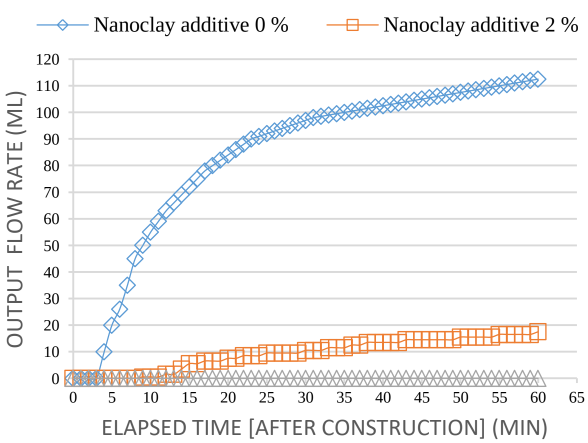


Fig. 6. Output flow rate of sample with 0.5 mm crack (After construction)

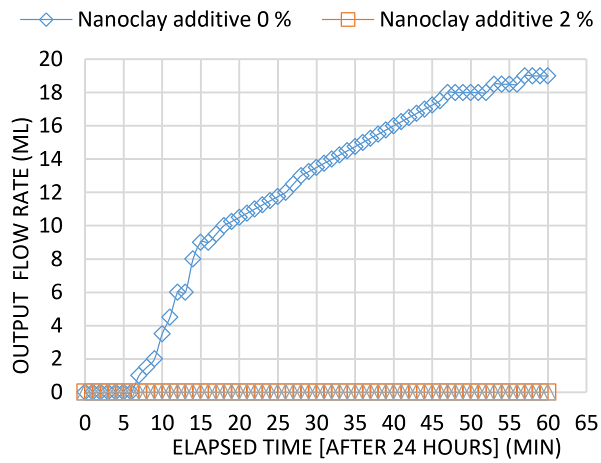


Fig. 7. Output flow rate of sample with 0.5 mm crack (After 24 hours)

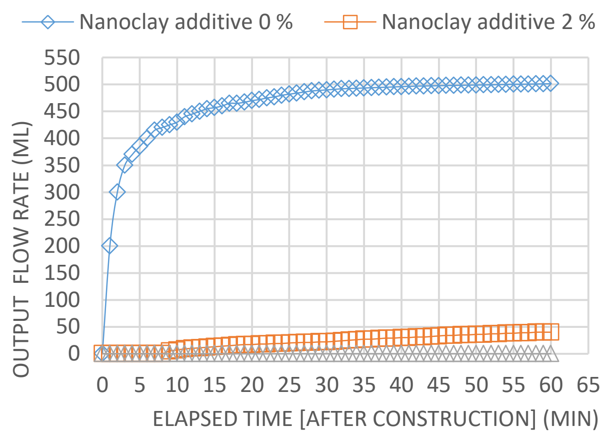


Fig. 8. Output flow rate of sample with 1 mm crack (After construction)

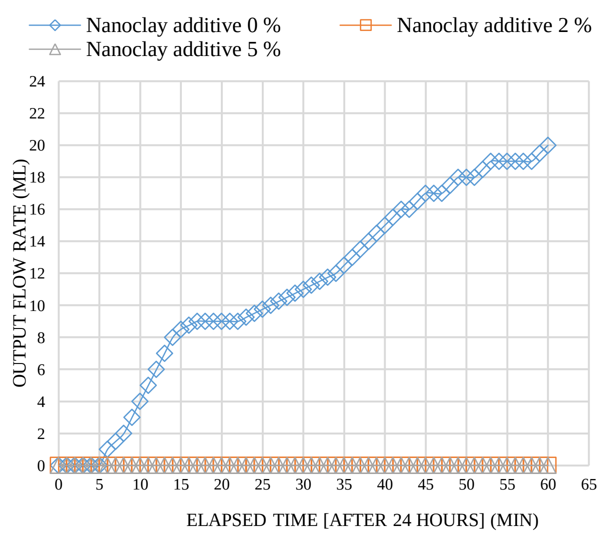


Fig. 9. Output flow rate of sample with 1 mm crack (After 24 hours)

3.2. Tests Performed on Samples with Pressure

In this part, the effects of self-healing cracks on specimens with 0.5- and 1-mm cracks with different pressures are investigated. The results of the experiments are shown in Figures 10 and 11.

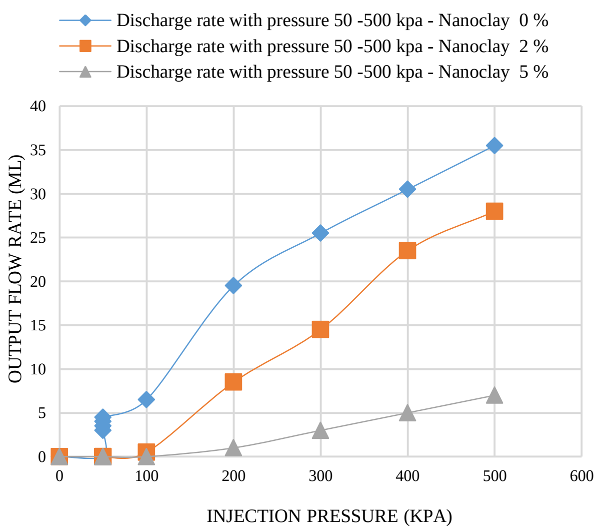


Fig. 10. Output flow rate of sample with 0.5 mm crack (After 24 hours)

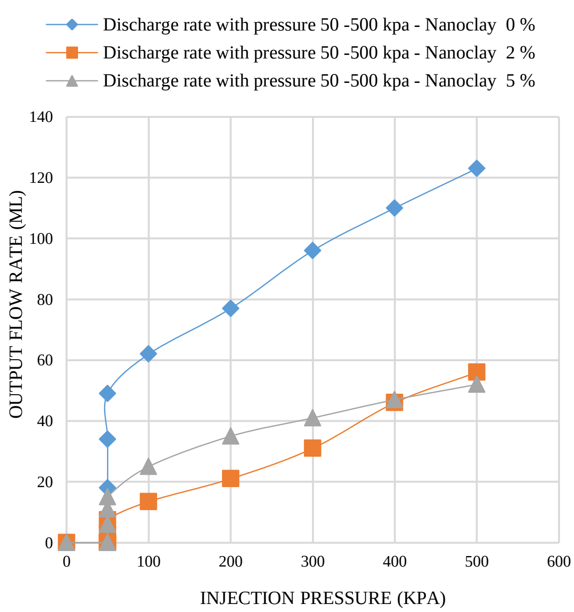


Fig. 11. Output flow rate of sample with 1 mm crack (After 24 hours).

3.3. Additional Experiments

To further investigate and better understand the cracks self-healing behavior of clays, more experiments were performed on two other clay samples (with different plasticity index), the results of which will be discussed below. Table 3 presents the specifications of the other two types of clays.

Table 3. Additional clay samples characteristics

Parameter	Standard	Sample A	Sample B
G_S	(ASTM D854-87)	2.55	2.51
PL	(ASTM D4318-17)	18.10	19.80
LL	(ASTM D4318-17)	26.40	38.35
PI	(ASTM D4318-17)	8.30	18.55
$\gamma_{d\ max}$ (gr/cm^3)	(ASTM D698-12)	1.778	1.776
ω_{opt} (%)	(ASTM D698-12)	16.67	18.13
Permeability (cm^2/s)	(ASTM D2434-68)	2.45×10^{-6}	1.95×10^{-6}

In the following, the changes in two soil samples are compared to investigate the influence of plasticity range on the outlet discharge process as well as the self-healing process. Initially, each experiment was compared individually in two-time steps, the initial stage of sample construction and after 24 hours (Figures 12 to 16).

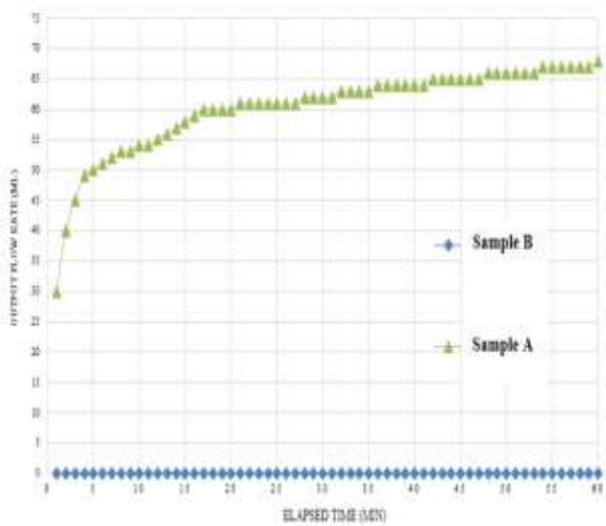


Fig. 12. Output flow rate of samples with 1 mm crack (After construction) [without NC & without pressure].

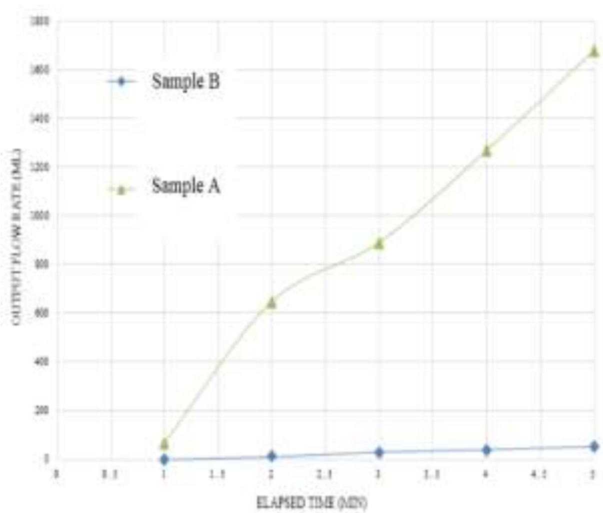


Fig. 13. Output flow rate of samples with 1 mm crack (After construction) [without NC & with pressure].

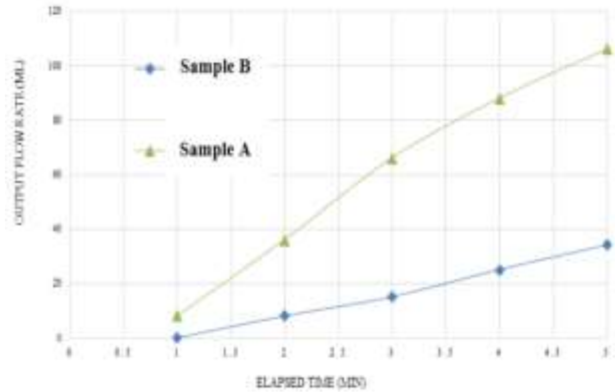


Fig. 14. Output flow rate of samples with 1 mm crack (After 24 hours) [without NC & with pressure].

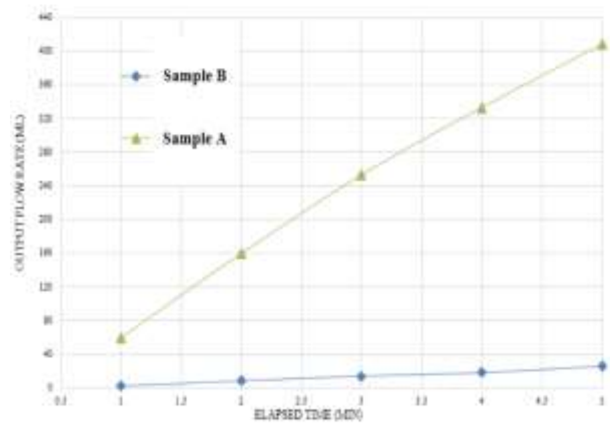


Fig. 15. Output flow rate of samples with 1 mm crack (After construction) [with 5% NC & with pressure].

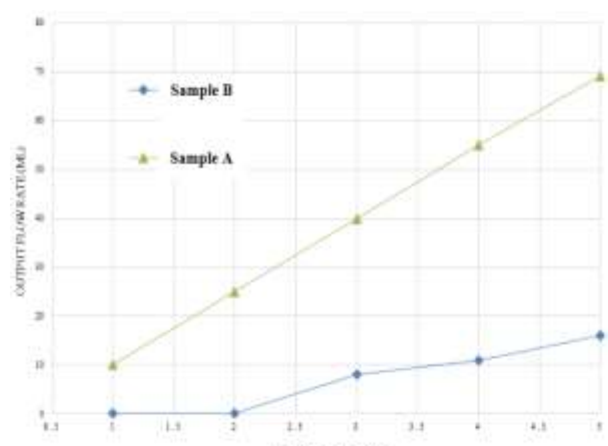


Fig. 16. Output flow rate of samples with 1 mm crack (After 24 hours) [with 5% NC & with pressure].

4. Discussion

As illustrated in Figures 6 to 9, the sample without additive and with 1 mm crack has the highest volume of water discharge. However, in two samples containing 2% and 5% MNC, the crack was largely repaired so that the sample with 2% MNC on the first day had discharge and after 24 hours (second day of experiment) discharge output reached zero. Nevertheless, for 5% of MNC, in the first day and after 24 hours the outflow rate is zero. The volume of outlet water from the 0.5 mm crack on the first day is less than 1 mm crack during the first 60 minutes and it is about one fifth. By comparing Figures 6 and 7, the effect of time on crack repair in the clay body can clearly observe. The 0.5 mm crack, which passed 100 ml of water for one hour within the first day, after 24 hours healed. This was accelerated by the presence of NC materials and samples with 2 and 5% MNC were able to fully recover 0.5 mm after 24 hours.

One of the important factors that can influence the flow rate of cracks passing through the clay is water pressure. For this purpose, specimens at different pressures were evaluated on the second day for cracks with diameters of 0.5 and 1 mm. For the sample in which the additive is not present and the crack diameter is 1 mm, until the pressure is less than 50 kPa, the volume of water passing is low but increasing pressure to 500 kPa causes 120 ml of water to pass through the crack. Figure 11 shows clearly that the sample containing 5% MNC reached outlet volume from 120 ml to 40 ml after 4 hours with a pressure of 500 kPa. This amount has also reached one-seventh for the 0.5 mm crack (reduction from 35 ml to 5 ml). In the supplementary experiments under conditions of 1 mm crack and in the non-pressurized phase without the NC additive, it is observed that the crack in soil sample *B* had no outflow and was initially closed, while for sample *A*, this amount was more than 65 ml (Figure 12). This Indicates that high cohesion between the grains due to the higher plasticity index causes the crack to close completely naturally. Similar conditions were observed for pressure conditions (Fig. 13). In this case, sample *B* outflow is approximately 60 ml, while for sample *A* the outflow is more than 1600 ml. The same issue demonstrates the significant importance of cohesion in the self-healing process. After 24 hours, as shown in Figure 14, the sample *B* outflow is approximately 30 ml, while for sample *A* the outflow is more than 110 ml. For sample *A*, a decrease of about 14 times is clearly visible, indicating the importance of plasticity domain in the closure of cracks and the self-healing process. According to Fig. 15 (adding 5% MNC to the samples and under pressure condition), it can be seen that the outflow rate for sample *A* was about 400 ml immediately after construction; i.e. in comparison to the same samples without additive, outflow rate became one fourth. For sample *B* in similar conditions, the outflow became half. As can be seen in Fig. 16, after 24 hours, the decrease in the outflow rate (self-healing process of cracks) is also evident. So that the output discharge of sample *A* has decreased by 1.4 times, while for sample *B* it has been reduced up to 2 times. Based on the figures outlined above, the role of MNC in reducing water leakage from cracks can be well understood. It is noteworthy that the effect of MNC on soil with higher plasticity is more dramatic.

Figures 17 and 18 illustrate the test specimens and their self-healing process.

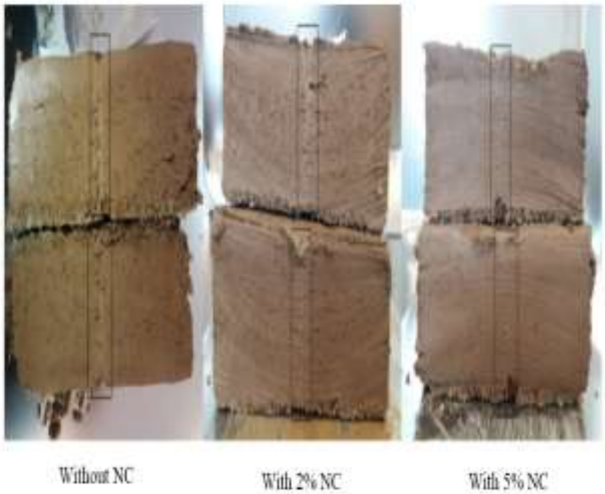


Fig. 17. Self-healing of samples with 0.5 mm crack [without pressure] (After construction)

Fig. 18. Self-healing of samples with 1 mm crack [without pressure] (After construction)

5. Conclusions

In this study, the criteria for evaluating the amount and process of self-healing of clayey soils in different plasticity range was determined at the time of sample preparation and at 24 hours afterward. For this purpose, first, the leaching and discharging rates in the non-additive state and then with the additive nano materials are shown. Then the leaching and discharge rate of each sample were calculated after 24 hours and the reactivity of the specimens in non-pressurized state for 60 minutes and with the overhead pressure up to 500 kPa for 5 minutes are considered as a self-healing process. The results are as follows:

1- From the experiments, it can be concluded that the plasticity index of the soil plays an important role in the self-healing process of the samples. The higher the plasticity of the soil sample, the greater the cohesion between the grain and the swelling of the fine particles. By adding NC materials, i.e. increase the specific surface area of the clayey soil samples, accelerating the self-healing process of the cracks.
2- From experiments without MNC, it can be understood that the self-healing process of cracks during the passage of water without additives, to some extent, occurred due to soil type. However, the effect of MNC in the experiments shows that the crack self-healing occurs much earlier and has a lower output discharge than that of the non-additive samples. The performance of this NC is due to its unique properties. One of the features that can be mentioned for the self-healing process of MNC is its extremely high surface area.
3- As it can be seen, the discharge rate of the cracks with 1 mm is higher than the cracks with 0.5 mm. Therefore, it can be concluded that the self-healing process occurs earlier in smaller cracks, because the NC and soil particles can easily touch each other after swelling.
4- In the experiments, time has had an important role in self-healing since soil particles, especially MNC particles, need sufficient time to

absorb water, or to achieve maximum swelling. Since the samples are not completely saturated, the initial phase of the experiment, and 24 hours' time gives the opportunity for clay particles, especially nanoparticles to absorb enough water. MNC is the best water absorber volumetrically, that can cause swelling and particles to reach each other in the crack and ultimately provide a self-healing process in clayey soils. On the other hand, it can be described that when water passes through the cracks, the NC particles absorb water, which keeps the water flowing in the cracks. This is why after the water absorption, initial swelling occurred, which the lowest output discharge had compared to the non-additive samples. In a clay sample with a 1 mm crack without the presence of MNC, 500 ml of water passes through the crack in 60 minutes. Nevertheless, if the sample contains 5% MNC, the water passage will be reduced to about 20 ml after 60 minutes. In a sample with 0.5 ml crack containing 5% MNC, the discharge reaches almost zero in 60 minutes. In the non-additive sample, with 1 mm crack when pressurized at 50 kPa for 5 minutes, 2000 ml of water passes through it, but when the sample is given 24 hours' time, tested with 50 kPa, the flow rate is reduced to 60 ml.

5- Experiments with high pressure had a higher flow rate, which is normal. Over time, by applying surface stress to the crack, the outflow discharge slowly decreased over the intended time. However, the effect of pressure on NC samples was better in self-healing. It can be understood that the pressure works much better with the participation of MNC samples. Another thing to note is that when the cracks are closed at lower pressures, they cannot withstand higher pressures, but the reverse is possible.

6- Five percent of MNC can insure the cracks closure at 100% density. In the samples with a density below 100%, there is a large gap between the soil particles, and the swelling of the NC from absorbed water dedicated to fill these voids. Where the soil experiment semi-liquefaction state and causes excessive erosion or leaching.

7- From the test images, it can be concluded that the crack with and without MNC are closed from the bottom to top. Since the effect of cracking after self-healing process is less evident at the bottom of the samples.

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