applied sciences

MDPI

Article

An Experimental Study for Swelling Effect on Repairing of Cracks in Fine-Grained Clayey Soils

Mahdi Nikbakht [1], Fariba Behrooz Sarand [1], Arash Esmatkhah Irani [1], Masoud Hajialilue Bonab [2,*], Mohammad Azarafza [2] and Reza Derakhshani [3,*]

[1] Department of Civil Engineering, Islamic Azad University, Tabriz Branch, Tabriz 5157944533, Iran
[2] Department of Civil Engineering, University of Tabriz, Tabriz 5166616471, Iran
[3] Department of Earth Sciences, Utrecht University, 3584 CS Utrecht, The Netherlands
* Correspondence: hajialilue@tabrizu.ac.ir (M.H.B.); r.derakhshani@uu.nl (R.D.)

Abstract: Earth-dam failure starts with cracking in the clay core, and this cracking is not easy to detect and prevent. Therefore, swellable clay is a feasible solution, which helps to close the cracks automatically based on the self-healing process. The presented study utilizes experimental procedures to analyze the swelling behavior of fine-grained clayey soils to prevent structural failure regarding crack generations. In this regard, the clayey materials were modified using Kaolin and Bentonite mixed with various weight percentages (2.5, 5.0, 7.5, 10.0, and 12.5%) and extracted the geotechnical characteristics of the studied soils, which included 90 specimens and 85 tests, such as physical properties, consolidation, particle-size analysis, hydrometry, Atterberg limits, compaction, odometer, and pinhole. The experimental results revealed that the swelling of the Bentonite is more than Kaolin satisfied for self-healing features in clayey soils. Regarding the numerous swelling tests, Bentonite provides optimum results (attained 10%) compared to Kaolin. As a verification procedure, the pinhole test was performed on samples, which revealed that Bentonite was dominant in controlling the water flow through the samples.

Keywords: geotechnical characteristics; cracks; swelling effect; self-healing process; clayey soils

check for updates

Citation: Nikbakht, M.; Sarand, F.B.; Esmatkhah Irani, A.; Hajialilue Bonab, M.; Azarafza, M.; Derakhshani, R. An Experimental Study for Swelling Effect on Repairing of Cracks in Fine-Grained Clayey Soils. *Appl. Sci.* **2022**, *12*, 8596. https://doi.org/10.3390/app12178596

Academic Editor: Roohollah Kalatehjari

Received: 7 August 2022
Accepted: 25 August 2022
Published: 27 August 2022

1. Introduction

Cracking is a basic phenomenon in fine-grained soil with varying amounts of clay content, which frequently occurs in earth-fill dams, clay-liners of landfills, concrete-faced rockfill dams, etc. The generation and propagation of cracks can lead to structural failures in clayey soils, especially when appearing around the cores of earth-fill dams, where they appear almost vertically and occur in the water-destabilized sections [1–3]. The crack generation is caused by a stress field related to the temperature, structure, water pressure, and drying shrinkage [4], which can be propagated in the presence of water [5]. Nevertheless, the appearance of the crack in geo-structures like earth-fill dams, especially the dam's core, can be considered the first step in the structural failure and destruction of the entire dam [6]. In this regard, correcting actions are required to control the local or general instabilities in the dam [7]. The results of the experimental studies concerning the reasons for earth-dam failures mainly indicate the fact that the appearance of the initial cracks in the dam's core, unawareness of them and not executing the preventive measures, and subsequently, internal erosion and dispersion, are the most hazardous phenomena in soil dam failures [8]. In addition, the information presented regarding the incidents demonstrates that the first year after the construction of the dams accounts for approximately 60% of the earth-dam failures [9]. Various researchers conducted different protection procedures to prevent crack generation/propagation in earth-fill dams' cores, categorized in the laboratory and in-situ experiments [10]. Numerous laboratory studies are established on the drying shrinkage mechanism of fine-grained soil with different amounts of clay content to provide the self-stabilization-based self-healing process concerning the environmental conditions [7].

Regarding the fact that the initial stage of the appearance of the cracks inside the earth-fill dam's core with fine-grained clayey soil is not possible to recognize after finishing the construction, it is improbable to prevent the crack generation, propagation, or repair them [11]. In the meantime, applying self-healable materials like swellable clay can be useful to control the crack generation at the dam's core, which helps to close the cracks automatically based on the self-healing process [12]. Ashayeri and Yasrebi [13] mentioned that the swelling behavior of fine-grained soils can be used to control the dispersion of compacted clayey soils, which is potentially applied for earth-fill dam core stabilization. According to the results, the swelling is directly controlled by clay minerals type, plasticity ($10 \leq PI < 50$), clay particles, degree of compaction, and density of soil. Kakuturu and Reddi [14] provided experimental methods to understand the self-healing progressive erosion process of cracks in earth dams' cores. The results of the experiments indicate that the finest content of more than 85% (D_{15F}/d_e) should be less than 9. Gueddouda et al. [15] investigated the Bentonite impact on the sand-bentonite mixture's compaction characteristics and shear strength parameters. According to the results, the adequate bentonite percentage should be 12% to 15% until hydraulic conductivity is reduced to 10^{-6} cm/s and the shear strength is improved. Wang et al. [12] stated that using the clay particles for self-healing in a five-layer embankment dam can prevent the critical flow rate for crack propagation in the dam's core. In their experiments, the results indicate that the crack's self-healing is induced under 300 kPa of water pressure. The critical flow rate through the sample before the self-healing of the crack is different in the experiments, but it increases with the increase of the crack depth or/and the D_{15}/d_{85} value. Soltani et al. [16] used the drying shrinkage relationship with pore moisture and mechanical properties to understand the swelling potential and soil activity under different percentages of bentonite. Based on the results, it shows that using 50 gr/lit NaCl to 250 gr/lit CaCl can improve the uniaxial strength of swellable soils up to 10 kPa. Xu et al. [17] used the swellable clays to control the crack generation and propagation on concrete-faced rockfill dams (CFRDs). The analysis indicated that the wet swelling of concrete significantly impacted the increase in tensile stress distribution in the concrete slab around the water surface. Mohammadi and Choobbasti [6] investigated the nano-montmorillonite impact on self-healing on clayey soil concerning the geotechnical characteristics of the fine-grained soil. According to their results, the geotechnical properties of clayey soils were modified by treatments. Data was collected from uniaxial tests and scanning of electron microscope images, which indicated that the maximum amount of self-healing occurred in the 5% nano-clay samples on the 60th day after the initial crack. Han et al. [18] established the experimental task of applying expanded clay for self-healing concrete. The clay particles crystallized the cracks and sealed the crack fracture in the face of the water. Roushangar et al. [10] mentioned that the piping from the existence of cracks in the dam core is one of the major reasons for the failure of earth dams. The article used different empirical approaches based on Bentonite clay (10%) to estimate the capability of Bentonite to heal the Vanyar dam borrow pit. Tabassum and Bheemasetti [19] used the swellable effect of the polydimethylsiloxane (PDMS) polymer and plate-like nano-montmorillonite (MMT) to investigate the healing efficiency in the Kaolinite-rich soil of Western South Dakota. The results indicated that the additives led to substantial changes in crack formation, propagation, and increased the healing efficiency. Roushangar et al. [20] performed an experiment assessment to analyze the swellable clay for self-healing in Vanyar earth-fill dams. According to the results, the sample with 20% bentonite and 2% moisture content less than the optimum showed the most reduction in the outflow (38%) when compared with the natural soil sample. So, it can be concluded that a PI between 7% and 26% can cause non-dispersive clay and increase the self-healing ability. The research conducted various geotechnical tests on basic materials of the dam's core to evaluate the swelling effects on crack control. Andalib et al. [11] utilized the experimental procedure to investigate the clay's crack self-healing phenomenon in compacted clay layers using the pinhole test. The authors provide the empirical relationship between Bentonite and moisture content in soils.

Referring to the mentioned literatures, the main shortcomings of previous research considered in this article and used to modify the analysis can be classified as the lack of knowledge regarding bentonite or other clay materials usage limits, the divergence property of bentonite soils in threshold uses, and the deviation of PI with an increasing percentage of bentonite in the self-healing process. The study aims to reconstruct the dam's clay core conditions and the possibility of improving the invisible cracks in the core using a self-healing process. This event is with respect to the limits of swelling pressure, which itself is the main factor in the dam core's failures. As the objective of the study, it can be stated as the assessment of an alternative task to investigate the self-healing behavior of clayey materials that are useable in a dam's core to prevent core failure and the destruction of a dam. In addition, using self-healing clays reduces the environmental impacts, provides fast stabilizations, and reduces renovation costs. In this regard, the presented article focuses on the self-healing behavior assessment of fine-grained clayey soil (Kaolin and Bentonite) concerning the geotechnical properties of clayey soil, which is mainly used for crack closing in earth-fill dams' cores. The physiomechanical soil properties are investigated to obtain the geotechnical characteristics, which are concluded through various soil index experiments such as sieve analyses, hydrometers, Atterberg limits, proctors, and pinhole tests. Entire experiments were conducted in ASTM instructions with repetition tests that were done to reduce the calculations error. To obtain the increased self-healing in compacted clays, Kaolin and Bentonite admixtures with various weight percentages (2.5, 5.0, 7.5, 10.0, and 12.5%) were used.

2. Materials and Methods

The presented article provides a comprehensive study to draw a geo-engineering framework on fine-grained clayey soil self-healing behavior assessment, which is considered a vital element in an earth dam's clay core design. The study contains experimental analysis on compacted clayey soils taken from KalganChay Dam with clay with low plasticity (CL) class and some clay with high plasticity (CH) based on the Unified Soil Classification System (USCS). The dam site was located about 70 km from Tabriz, near Bostanabad, upstream of the Jighar village. A comprehensive sampling was conducted during the field survey. The samples concluded that 90 specimens were prepared for 85 geotechnical tests. All tests were repeated to reduce the test error and evaluate the average values of measurements. In order to determine the soil index properties and geotechnical characteristics of clayey soil, the specimens are prepared, and different soil mechanical tests have been carried out according to the American Society for Testing and Materials (ASTM) standards. The soil index tests concluded that screen-sieve analysis, hydrometry, Atterberg limits, and compaction were used to determine the soil's physiomechanical properties. Swelling potential tests like odometer and consolidation were performed to analyze the studied soil's swelling potential and activity number. All tests were performed on additional samples with 2.5% to 12.5% Bentonite and Kaolin weight percentages. The kaolin used in this study was obtained from the Zonouz Mine, located 20 km northeast of Marand. The product is marketed as SZWMK1. The Bentonite used in the experiments was a product of the Barit Falat Iran Company. In addition, the pinhole test was used to evaluate the self-healing characteristics of clayey soil. This test can be considered a direct approach to the dispersion and colloidal erosion ability of fine-grained clayey soil. The pinhole test is established on distilled water flowing horizontally under a hydraulic head of 50 mm through a 1 mm diameter fracture on the soil specimen.

3. Results and Discussion

To assess the self-healing property of clay soils, several experimental stages were conducted to estimate the soil's index properties and swelling requirements. The experimental results are described as follows.

3.1. Geo-Engineering Characteristics

The geo-engineering characteristics of the soils are represented by the physiomechanical properties description of materials that can cover several features such as gradation, clay content, porosity, density, plasticity, water content, etc. [21–23]. ASTM provides extensive instruction for conducting geotechnical experiments that are used to estimate such parameters. Experiments such as particle-size distribution [24] and hydrometer [25] can be mentioned. Figure 1 illustrates the particle-size distribution results for the studied clayey soil samples. As is shown in the figure, adding Kaolin and Bentonite causes an increase in the fine-grained portion of the clayey soil and moves the base soil granulation curve towards the fine-grained part. This is more noticeable in the case of adding Bentonite due to its finer grains. Obviously, by adding Bentonite to the mixture, its fine-grained nature causes the fine particles to stay within the clay particles. In addition, when water flows into the mixture, Bentonite particles become hydrated and reduce porosity, increase cohesion, and decrease the permeability in clayey soils [26,27]. Several relations have been presented in technical sources to predict the permeability coefficient, the most important of which is the Hazen relation. There is a direct relationship between the permeability coefficient and the effective grain diameter ($K = CD_{10}^2$). According to Figure 1, adding 10% Bentonite to the clay in the sample changes the effective grain size from 0.002 mm to 0.0023 mm, which does not appear to have a significant effect on the permeability. This variation prevents the clayey soil from draining, resulting in hydraulic failure. Therefore, the addition of 10% Kaolin and Bentonite cannot have a negative impact on the drainage of the studied soils.

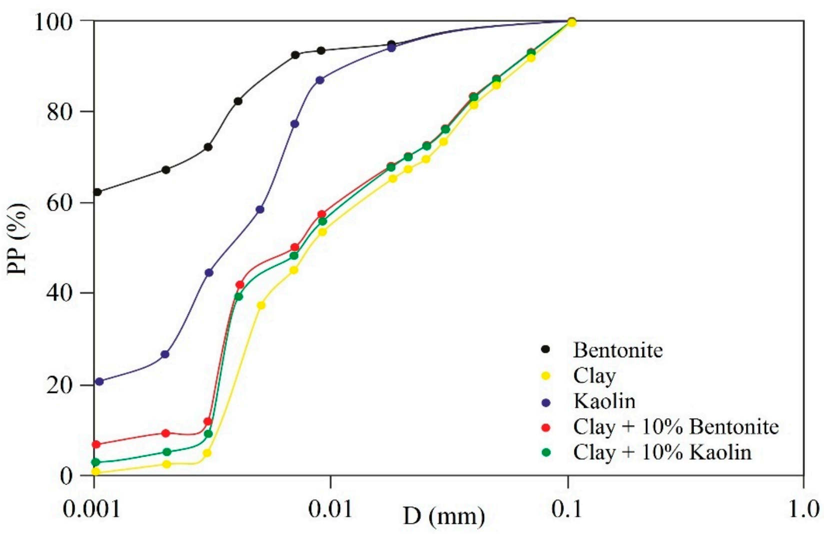

Figure 1. Results of the particle-size distribution for the studied soils from the hydrometer test.

The physiomechanical properties of clayey soil used in this research are presented in Table 1. These index properties are estimated according to the ASTM [24–26,28]. This table shows the physical and mechanical characteristics obtained from the soil samples. Table 2 provides the relevant information about the plasticity and Atterberg limits of the studied soil. Atterberg limits tests were performed under ASTM D4318 [29] regulations. The table demonstrates the plasticity indexes, clay mineral majority, clay activity number, and swelling index, which establish the proper understanding of the geo-engineering characteristics of soils. Compared to the results of the Atterberg limits, it is demonstrated that the increase in Bentonite and Kaolin results in an increase in water content, liquid limit (LL), and, therefore, the increase in plasticity index (PI). Based on the obtained results, the PI of pure Kaolin is 19 and the PI of pure Bentonite is 355.

Table 1. The physiomechanical properties of the studied clayey soil.

Soil Type	USCS	Particle-Size Distribution (%)			Dry Density (g/cm^3)	Water Content (%)	C_C
		D_{10}	D_{30}	D_{60}			
Bentonite	CH	94	100	100	1.01	28.5	1.06
Clay	CL	58	94	100	1.46	11.7	1.52
Kaolin	CL	88	99	100	1.31	10.9	1.11
Clay + 10% Bentonite	CL	60	94	100	1.48	15.9	1.47
Clay + 10% Kaolin	CL	60	94	100	1.39	15.1	1.47

Table 2. Results of the geo-engineering description ofthe studied clayey soil.

Soil Type	USCS	Atterberg Limits (%)			Activity Number	Swelling Potential (%) [30]	
		LL	PL	PI			
Bentonite	CH	415	60	355	5.7	4812	Very high
Clay	CL	40	25	15	3075	0.1	Low
Kaolin	CL	46	27	19	0.42	0.004	Low
Clay + 10% Bentonite	CL	51	28	23	4.5	0.38	Medium
Clay + 10% Kaolin	CL	42	25	17	3.8	1.9	Low

Given that the PI of a clayey soil is 15, it is evident that mixing Kaolin with clay will not have much influence on raising the PI of the clay sample, which is observed in the test results presented in Table 2, which shows that the combination of 10% Kaolin with the clayey soil has changed the plastic index by two units. However, the combination of clay with Bentonite due to the high PI of Bentonite has caused a noticeable change and a significant increase in the PI. Increases in the PI result in absorbing further moisture and soil swelling, which can considerably help seal the created cracks. On the other hand, higher rates of water absorption and the increase in soil volume during shrinkage time due to the dryness in hot and arid seasons of the year cause cracking of the soil. Therefore, the rate of PI has been limited. Based on the recommendations found in technical texts, the rate of the clay plasticity index (PI) applied in soil dam cores has been limited to 25. PI for the clay with 12.5% Bentonite mixture is evaluated as 27%. The range of PI in the clay-Bentonite mixtures is shown in Figure 2. Regarding this figure, it can be inferred that a combination of clay and 10% bentonite is a suitable percentage because it does not exceed the dam core plastic index (PI = 25).

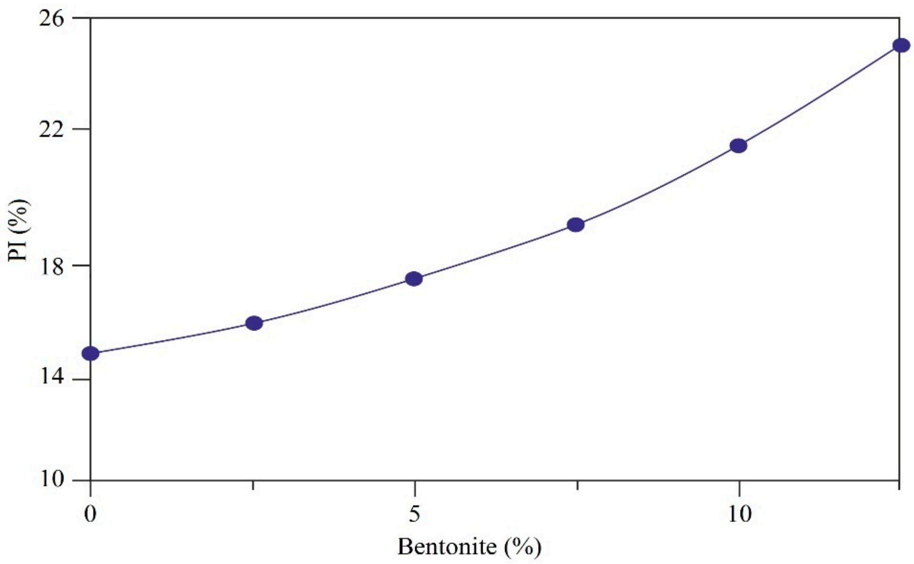

Figure 2. Effect of Bentonite additive on PI index in clayey soil.

Compatibility is another geo-engineering parameter that has an impact on fine-grained clayey soils. Compaction occurs when the air in the soil is driven out and causes the grains to move closer to each other and become attached, increasing the shear strength and decreasing the soil settlement. Compaction activity plays an important part in the clay soil swelling potential by reducing the porous spacing to a minimum. The sample's moisture rate and dry density are among the parameters determining compaction, providing the optimal condition for the best condition of consolidation in soils. Nevertheless, the presented study uses the test to monitor the Bentonite and Kaolin admixture on clay behavior. The results show that mixing Kaolin with clay could not cause much change in the dry density and optimum moisture. The mixture of clay with 10% Kaolin caused only an 11% increase in the optimum moisture and a 2% decrease in the dry density of the sample. Figure 3 provides the Bentonite variation on clayey soil, which has a considerable impact on the soil's compatibility.

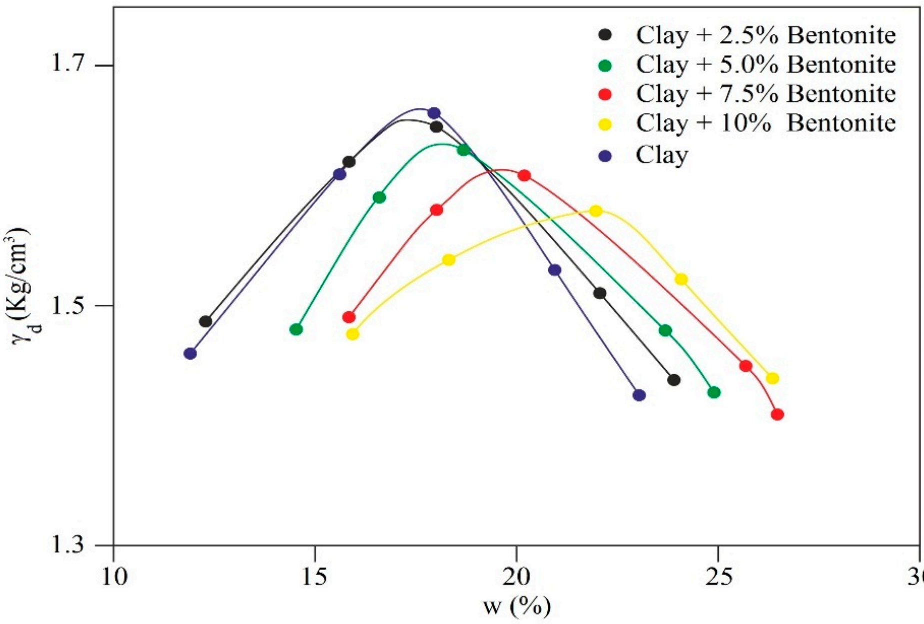

Figure 3. Effect of the Bentonite additive on the compaction behavior in clayey soil.

3.2. Swelling and Swell-Ability

Swelling is one of the fine-grained clayey soil features that can have both positive and negative effects on geotechnical projects. The swelling potential directly depends on clay particles. Of course, the type of clay mineral affects the degree of swelling but is generally reduced by increasing the coarse particles. For example, Bentonite is much more swellable than Kaolin. In this regard, the Bentonite additive content in clayey soil was used to obtain the swelling potential and activity number. The swelling evaluation is illustrated in Table 2 and Figure 4.

Regarding this figure, the 12.5% Bentonite admixture to clay causes about a 6-fold increase in the soil's swelling potential and 1.2-fold increase in activity. Using the consolidation test [31], the rate of swelling variation for the studied soil is evaluated. The consolidation test used Terzaghi's one-dimensional consolidation theory to estimate the consolidation characteristics of soils, swelling potential, and swelling pressure of the clayey soils. A simple one-dimensional consolidation model consists of a rectilinear element of soil subject to vertical changes in loading and through which vertical (only) seepage flow is taking place. Whereasa fully swollen sample is compressed back under vertical compressive stress, the vertical swelling pressure (σ_{vs}) is determined from the e-log σ_v curve as the pressure corresponding to the initial void ratio (e_0). Figure 5 provides the results of the free swelling and swelling pressure for pure and additive Kaolin and Bentonite samples. According to this figure, the free swelling of Kaolin and Bentonite is 0.5

and 6.42 (mm), respectively, and their swelling pressures are about 0.1 and 6.5 (kg/cm^2), respectively. Figure 6 provides the consolidation coefficient and swelling coefficient due to the increase in Bentonite percentage, which indicates that Bentonite values increase the coefficients. In addition, a swelling pressure index was obtained for all specimens with various amounts of Bentonite, as illustrated in Figure 7. As indicated by the results in this figure, it can be mentioned that the Bentonite additive increased the swelling pressure. On the other hand, Kaolin has an insignificant effect on clayey soil; therefore, the Kaolin additive is discarded to estimate the swelling pressure index. However, in clayey soil, the Bentonite additive plays a significant role in the swelling pressure. Based on these findings, it appears that Bentonite has a higher swelling degree than Kaolin. The reasons for this occurrence were related to the nature and high affinities of water, which distribute themselves evenly throughout water, swell when wet and reverse when dry, and have electrically active surfaces and high specific charges (charge/mass). Bentonite expands up to 10–12 times its dry size and has excellent swell characteristics. Kaolin has a low rate of activity.

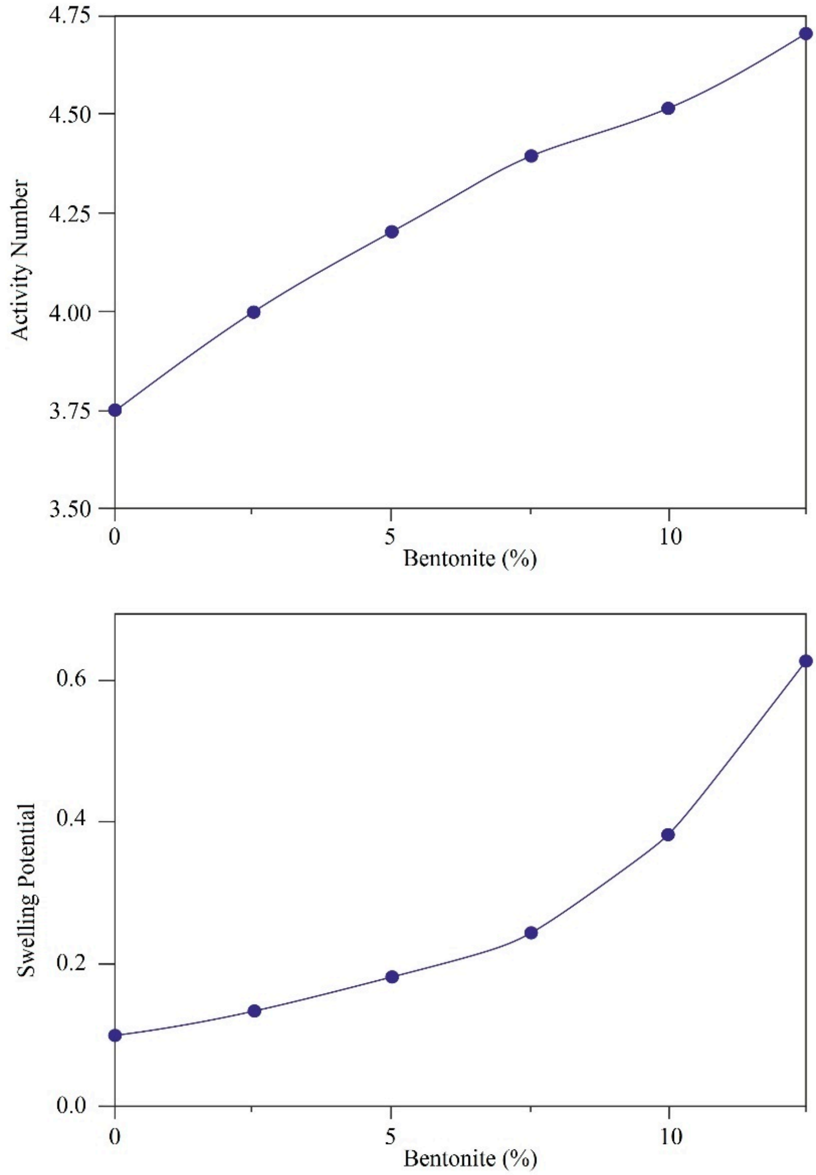

Figure 4. Effect of the Bentonite additive on swelling and activity variation in clayey soil.

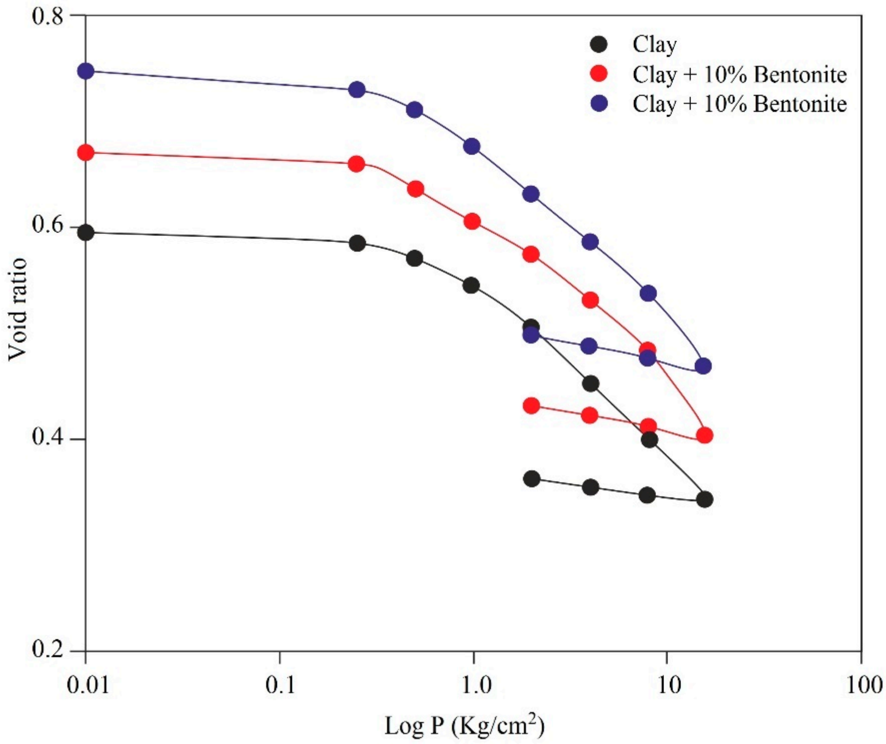

Figure 5. Diagram of the swelling and consolidation status for different samples.

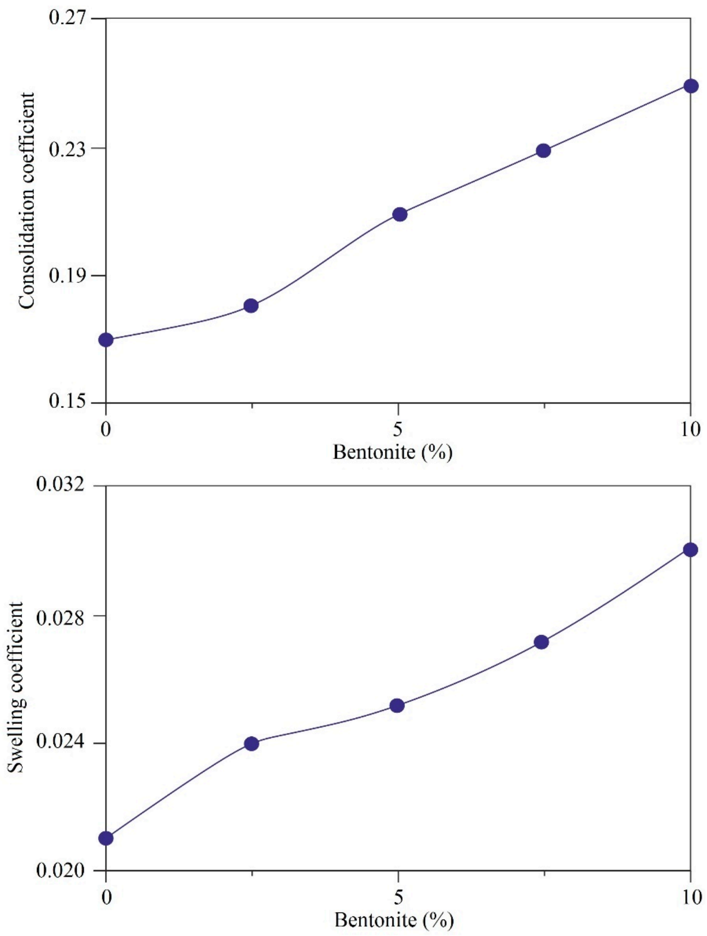

Figure 6. Effect of the Bentonite percentage on consolidation and swelling coefficients.

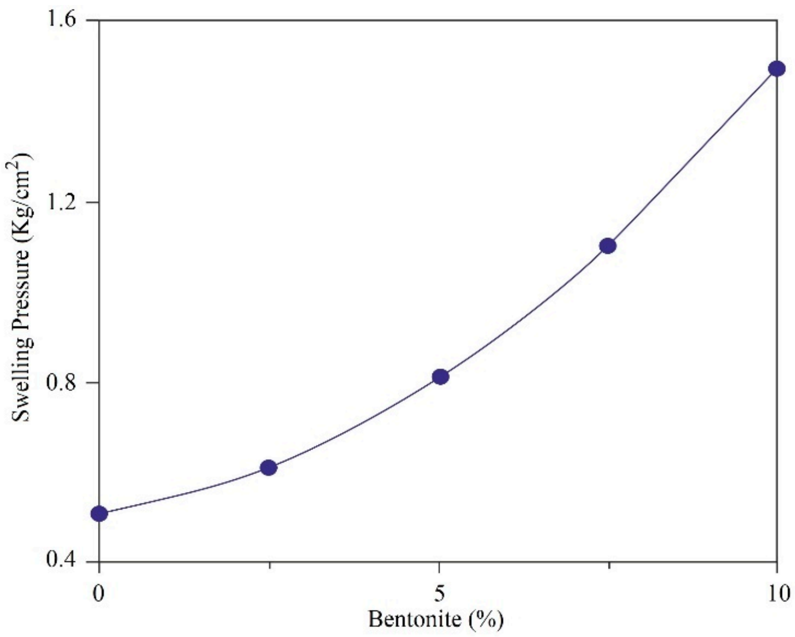

Figure 7. Effect of the Bentonite percentage on the swelling pressure.

3.3. Self-Healing Process

The pinhole test [32] was used to categorize the fine-grained clayey soil into the dispersion and self-healing groups described in Table 3. The dispersion classification based on the pinhole test is categorized into various groups that contain non-dispersive (ND) to highly dispersive (D1). Each class has a specific size of hole opening and flow rate after the test, which is illustrated in Table 3. Figure 8 presents the classification system [33] that is used in the pinhole tests. The pinhole test is a model of water-flow performance along the crack created in the clayey soil, which is applied to measure the colloidal divergence and erosion potential by passing through a tiny 1 mm hole created in the middle of a cylindrical sample. A pinhole test can be used to predict the self-healing capability in clayey soil by controlling the artificial crack divergence. Figures 9 and 10 show the diagrams of water-flow variation vs. time for the samples. The figures indicated that by increasing the water head by 50 and 180 mm, the water flow did not reach the necessary standard level for specifying the sample's type. However, the water flow at the head increased by 380 and reached 2.67 mL/s (from 1.8 to 3.2). In addition, the water flow-out of the clayey soil did not show a noticeable variation in the diameter of the hole. So, the clayey soil is considered a low divergence soil (ND3).

Table 3. The self-healing classification based on the pinhole test [34,35].

Dispersive Classification	Head (mm)	Cloudiness of Flow at the End of Test		Hole Size after Test (mm)
		from Side	from Top	
D1	50	Dark	Very dark	≥2.0
D2	50	Moderately dark	Dark	>1.5
ND4	50	Slightly dark	Moderately dark	≤1.5
ND3	180	Barely visible	Slightly dark	≥1.5
	380	Barely visible	Slightly dark	≥1.5
ND2	1020	Clear	Barely visible	<1.5
ND1	1020	Perfectly clear	Perfectly clear	1.0

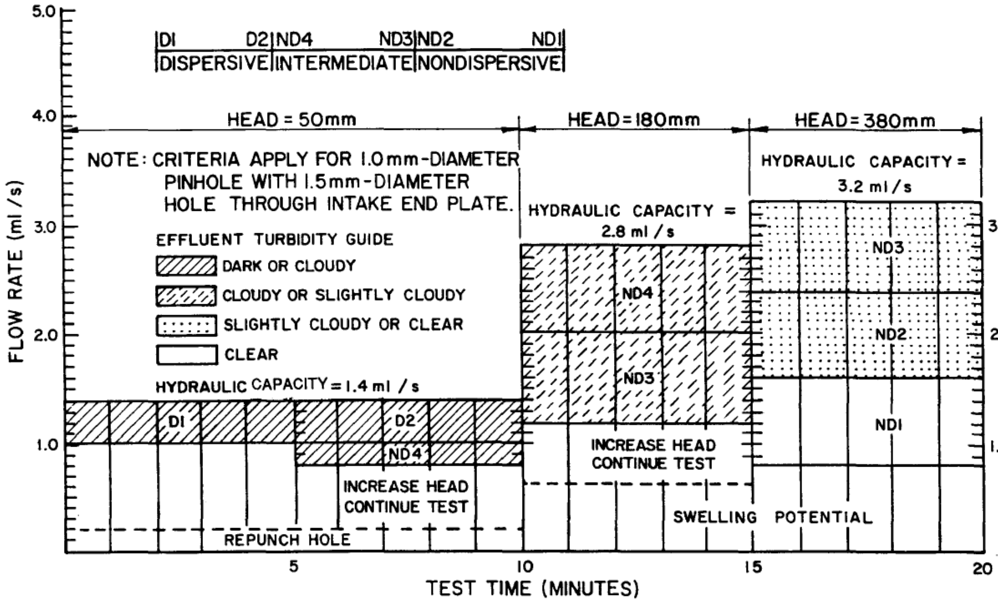

Figure 8. The pinhole test-based dispersion classification for clayey soils [33].

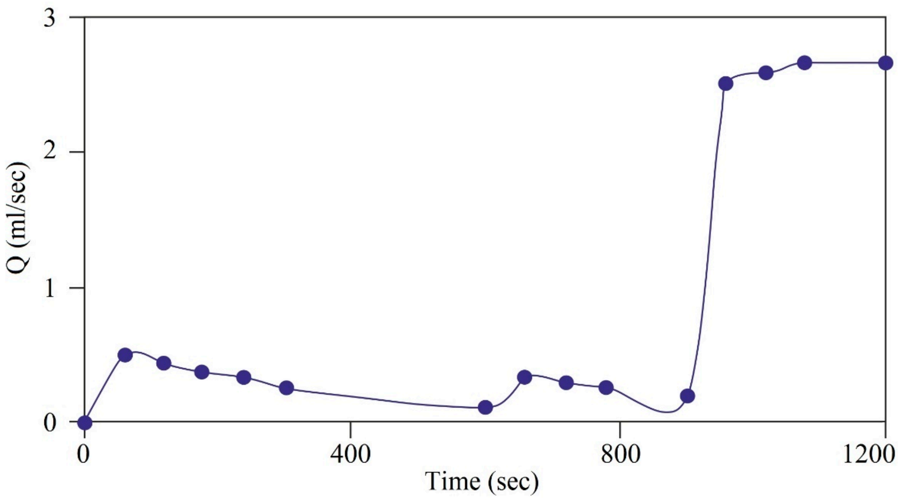

Figure 9. Variation of water flow in a clayey soil sample without additives.

Although the pinhole test's results indicate that Bentonite with the specified weight percentage used did not negatively affect the clayey soil, the double-hydrometric test detected divergence in admixture (clay + 10% Bentonite). The experiment variation graph is presented in Figure 11. Based on the results, the percentage of grains smaller than 5 microns for the solution without a separating agent and with its presence is about 11% (which is less than 30%) and is considered non-divergent. Figure 12 shows a view of the samples at the pinhole test's end. As seen in this figure, the hole created in the pure clay sample did not show any variation at the end of the test. In the clay sample mixed with 10% Kaolin, there is a little change in the hole size toward becoming smaller, which indicates that the hole has been slightly repaired. However, in the clay sample in combination with 10% Bentonite, the hole has completely been closed, and on account of the given reasons for the effect of swelling, the mixture of clay with 10% Bentonite has led to the complete repair of the created hole or crack.

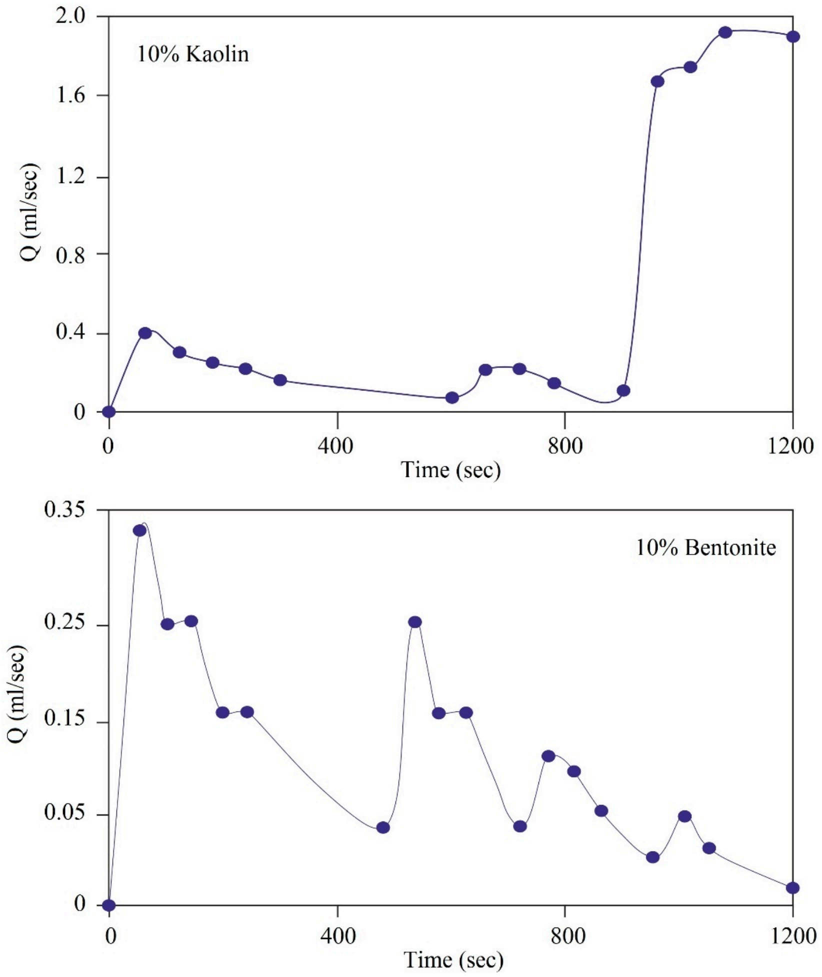

Figure 10. Variation of water flow in a clayey soil sample with additives.

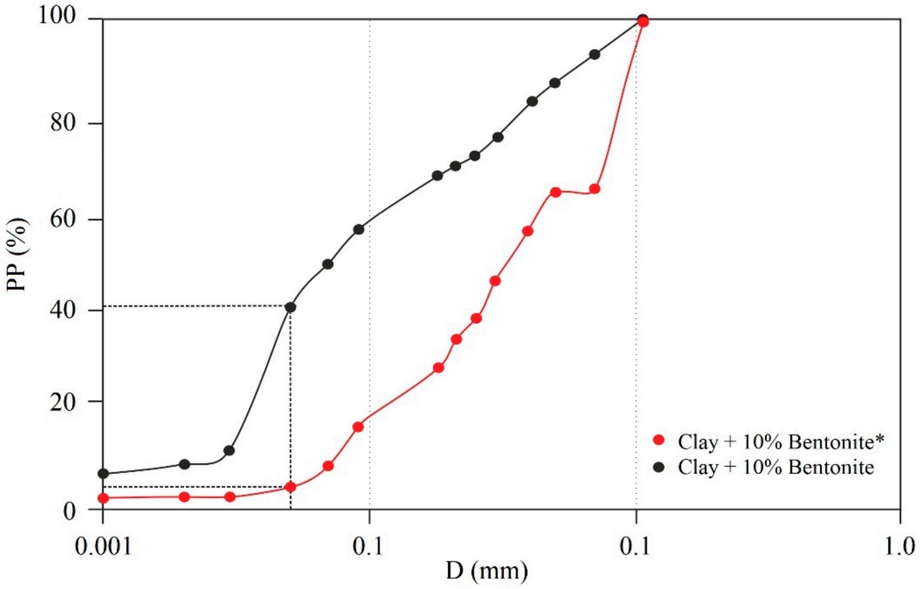

Figure 11. Result of the double hydrometer test on clayey soil with 10% Bentonite (Note: Bentonite* is the value of Bentonite without Sodium hexametaphosphate).

Figure 12. Repairing of the sample holes in the pinhole test.

4. Conclusions

The presented study is based on an experimental assessment to understand the self-healing process in cracked fine-grained clayey soil modification. A self-healing process is a well-known event for an earth-fill dam's core to reinforce against structural failure. The study aimed to investigate the self-healing capability in the Kalgan Chay Dam's core clay near Tabriz, northwest Iran. The following categories can be applied to the findings of this study:

- By adding the weight percent of Bentonite to the clay soil, the water content liquid limit and plasticity index are increased, and the increase in plasticity index leads to further soil cohesion and further hydration and swelling of the soil, which in turn greatly contributes to the sealing of the created cracks. However, since the increase in the plasticity index causes cracks in the drying period, the increase in the weight percentage cannot exceed the standard limit. Based on the current recommendations, the plasticity index, in this case, should not exceed 25. Therefore, according to the obtained results, it is impossible to use 12.5% Bentonite in the mixture with clay soil;
- Regarding Bentonite's swelling potential and expansion property, the soil's swelling potential is increased by adding a percentage of Bentonite to the clay soil, which has a key role in repairing the soil dam core cracks. By adding 12.5% Bentonite to the clay soil, the swelling potential of the mixture increases more than six times, from 0.1 to 0.63;
- By adding 10% Bentonite to the clay soil, the swelling pressure of the clay soil is increased by three times, which leads to an increase in the repairing power of the samples;
- Regarding the previous points, in the present research, the best combination of Bentonite with core clay repairs the cracks and is applicable in clay dam cores with a mixture of clay with 10% Bentonites;
- In this research, in order to verify and objectively observe the repairing of cracks, the researchers used a pinhole test. By comparing the test on the core clay sample, using a combination of clay with 10% Kaolin and a combination of clay with 10% Bentonite, it was noted that only in the sample of clay combined with 10% Bentonite did the flow of water gradually decrease during the test, so that even at the end of the test, despite the increase in the head, the speed of water outflow was diminished and almost stopped, which indicated the closing of the hole and repairing of the cracks.

Author Contributions: M.N. and A.E.I.: writing—original draft preparation, methodology, investigation, resources; M.A.: conceptualization, validation, visualization, formal analysis, methodology; F.B.S. and M.H.B.: supervision, writing—review and editing; R.D.: supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Acknowledgments: The authors wish to thank the Department of Civil Engineering, University of Tabriz for providing permission to conduct the geotechnical investigations. In addition, the authors would like to thank the anonymous reviewers for providing invaluable review comments and recommendations for improving the scientific level of the article.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Fell, R.; Wan, C.F.; Cyganiewicz, J.; Foster, M. Time for development of internal erosion and piping in embankment dams. *J. Geotech. Geoenviron. Eng.* **2003**, *129*, 307–314. [CrossRef]
2. Angin, Z.; İkizler, S.B. Assessment of swelling pressure of stabilized Bentonite. *Geomech. Eng.* **2018**, *15*, 1219–1225. [CrossRef]
3. Karalar, M.; Cavusli, M. Three dimensional seismic deformation-shear strain-swelling performance of America-California Oroville Earth-Fill Dam. *Geomech. Eng.* **2021**, *24*, 443–456. [CrossRef]
4. Wang, Z.; Liu, S.; Vallejo, L.; Wang, L. Numerical analysis of the causes of face slab cracks in Gongboxia rockfill dam. *Eng. Geol.* **2014**, *181*, 224–232. [CrossRef]
5. Chen, N. Analysis on causes of cracks in concrete face slabs in water variation section of Gongboxia concrete face rockfill dam. *Northwest Hydropower* **2015**, *2015*, 23–27.
6. Mohammadi, M.; Choobbasti, A.J. The effect of self-healing process on the strength increase in clay. *J. Adhes. Sci. Technol.* **2018**, *32*, 1750–1772. [CrossRef]
7. Julina, M.; Thyagaraj, T. Combined effects of wet-dry cycles and interacting fluid on desiccation cracks and hydraulic conductivity of compacted clay. *Eng. Geol.* **2020**, *267*, 105505. [CrossRef]
8. Valizadeh, M.; Choobbasti, A.J. Evaluation of nano-graphene effect on mechanical behavior of clayey sand with microstructural and self-healing approach. *J. Adhes. Sci. Technol.* **2020**, *34*, 299–318. [CrossRef]
9. Baziar, M.H.; Saeidaskari, J.; Alibolandi, M. Effects of nanoclay on the treatment of core material in earth dams. *J. Mater. Civ. Eng.* **2018**, *30*, 04018250. [CrossRef]
10. Roushangar, K.; Alami, M.T.; Houshyar, Y. Experimental Investigation of Self-healing Phenomenon of Clay in Earth Dams and its Influencing Factors. *J. Water Soil Sci.* **2019**, *29*, 15–25.
11. Andalib, G.; Houshyar, Y.; Roushangar, K. Evaluation of Influencing Factors in Outflow Control and Self-healing Property of Clay Core (case study: Vanyar dam–Iran). *Adv. Res. Civ. Eng.* **2021**, *3*, 55–71. [CrossRef]
12. Wang, J.J.; Zhang, H.P.; Zhang, L.; Liang, Y. Experimental study on self-healing of crack in clay seepage barrier. *Eng. Geol.* **2013**, *159*, 31–35. [CrossRef]
13. Ashayeri, I.; Yasrebi, S.S. Investigation of free swelling potential of compacted clayey soils. *Modarres Civ. Eng. J.* **2006**, *25*, 19–28. (In Persian)
14. Kakuturu, S.; Reddi, L.N. Evaluation of the Parameters Influencing Self-Healing in Earth Dams. *J. Geotech. Geoenviron. Eng.* **2006**, *132*, 879–889. [CrossRef]
15. Gueddouda, M.K.; Goual, I.; Lamara, M.; Aboubaker, N. Hydraulic conductivity and shear strength of compacted dune sand-bentonite mixtures. In Proceeding of the 16th International Conference on Construction and Building Technology, Kuala Lumpur, Malaysia, 20 June 2008.
16. Soltani, A.; Raeesi, A.; Abdollahi, J. Effect of chemical quality of initial moisture on mechanical properties of swelling soil in wetting and drying cycles. *Iran. J. Water Soil Res.* **2014**, *46*, 71–79. (In Persian)
17. Xu, W.; Li, Q.; Hu, Y.; Li, S. Wet swelling effect on crack performance of facing concrete for rockfill dams. *Mag. Concr. Res.* **2017**, *69*, 1055–1066. [CrossRef]
18. Han, S.; Choi, E.K.; Park, W.; Yi, C.; Chung, N. Effectiveness of expanded clay as a bacteria carrier for self-healing concrete. *Appl. Biol. Chem.* **2019**, *62*, 19. [CrossRef]
19. Tabassum, T.; Bheemasetti, T.V. Self-Healing and Desiccation Crack Behavior of Kaolinite-Rich Clay Soil. In Proceedings of the Geo-Congress 2020, Minneapolis, MN, USA, 25–28 February 2020; pp. 582–591.
20. Roushangar, K.; Alami, M.T.; Houshyar, Y. Experimental investigation of bentonite impact on self-healing of clay soils. *Arab. J. Geosci.* **2020**, *13*, 1122. [CrossRef]
21. Azarafza, M.; Akgün, H.; Asghari-Kaljahi, E. Assessment of rock slope stability by slope mass rating (SMR): A case study for the gas flare site in Assalouyeh, South of Iran. *Geomech. Eng.* **2017**, *13*, 571–584. [CrossRef]
22. Azarafza, M.; Ghazifard, A.; Akgun, H.; Asghari-Kaljahi, E. Geotechnical characteristics and empirical geo-engineering relations of the South Pars Zone marls, Iran. *Geomech. Eng.* **2019**, *19*, 393–405. [CrossRef]
23. Azarafza, M.; Hajialilue Bonab, M.; Akgün, H. Numerical analysis and stability assessment of complex secondary toppling failures: A case study for the south pars special zone. *Geomech. Eng.* **2021**, *27*, 481–495. [CrossRef]
24. *ASTM D422*; Standard Test Method for Particle-Size Analysis of Soils. ASTM International: West Conshohocken, PA, USA, 2007.

25. *ASTM D7928*; Standard Test Method for Particle-Size Distribution (Gradation) of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. ASTM International: West Conshohocken, PA, USA, 2021.
26. Zhu, X.; Zhang, Q.; Zang, W.; Shao, J.; Wang, Z.; Wu, X. Experimental Study on the Basic Properties of a Green New Coal Mine Grouting Reinforcement Material. *ACS Omega* **2020**, *5*, 16722–16732. [CrossRef] [PubMed]
27. Wang, Z.; Zhang, Q.; Shao, J.; Zhang, W.; Wu, X.; Zhu, X. New Type of Similar Material for Simulating the Processes of Water Inrush from Roof Bed Separation. *ACS Omega* **2020**, *5*, 30405–30415. [CrossRef] [PubMed]
28. *ASTM D7263*; Standard Test Methods for Laboratory Determination of Density and Unit Weight of Soil Specimens. ASTM International: West Conshohocken, PA, USA, 2021.
29. *ASTM D4318*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International: West Conshohocken, PA, USA, 2017.
30. Seed, H.B.; Woodward, R.J.; Lundgren, R. Prediction of swelling potential for compacted clays. *J. Soil Mech. Found. Div.* **1962**, *88*, 53–87. [CrossRef]
31. *ASTM D2435*; Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. ASTM International: West Conshohocken, PA, USA, 2020.
32. *ASTM D4647*; Standard Test Methods for Identification and Classification of Dispersive Clay Soils by the Pinhole Test. ASTM International: West Conshohocken, PA, USA, 2020.
33. U.S. Department of the Interior—Bureau of Reclamation. *Characteristics of Dispersive and Problems Clay Soils*; Research and Laboratory Services Division Materials Engineering Branch: Denver, CO, USA, 1991.
34. Sherard, J.L.; Decker, R.S.; Ryker, N.L. Piping in earth dams of dispersive clay. In Proceedings of the Specialty Conference on Performance of Earth and Earth-Supported Structures, West Lafayette, IN, USA, 11–14 June 1972; pp. 584–626.
35. El-Zein, A.; Airey, D.; Yu, B.; Esgandani, G.A.; Proust, G.; Dias-da-Costa, D.; Chen, S. Self-repair of cracks and defects in clay: A review of evidence, mechanisms, theories and nomenclature. *Acta Geotech.* **2021**, *16*, 3741–3760. [CrossRef]