applied sciences

MDPI

Article

Influence of Five Additives on No Loading Swelling Potential of Red Clay

Bing Yue, Ziye Zhao and Zengzhen Qian *

School of Engineering and Technology, China University of Geosciences (Beijing), Beijing 100083, China; yue@email.cugb.edu.cn (B.Y.); ziye_zhao@cugb.edu.cn (Z.Z.)
* Correspondence: zzqian@cugb.edu.cn

Abstract: In this study, cement, zeolite powder and three industrial by-products (blast furnace slag, steel slag, and fly ash) were selected as additives to study their effects on the swelling potential of red clay with different curing ages and dosages. At the same time, the mechanism of additives reducing the swelling potential of red clay was analyzed by scanning electron microscope (SEM) and X-ray fluorescence (XRF) tests. The X-ray diffraction (XRD) test was used to detect the clay mineral content of the red clay specimens before and after the modification to determine the change in the clay mineral content of the specimens. The direct shear test was used to explore the influence of additives on the strength of red clay. The results show that with 9% cement content, the no loading swelling potential of specimens can be reduced by 82.5% under 28 days of curing, and the cohesion of the specimens can be greatly increased by 82%. However, the specimens with cement have an increase in no loading swelling potential under the condition of no curing. In contrast, when steel slag is used as an additive to modify the swelling properties of red clay, the swelling potential can be reduced without curing, but the addition of steel slag will reduce the cohesive strength of specimens. XRD testing shows that the clay mineral composition in cement-modified specimens and steel slag-modified specimens experienced a relative change, the relative content of montmorillonite and illite decreased, and the relative content of kaolinite increased. Combined with SEM and XRF test results, it is concluded that cement's reduction in the swelling potential of red clay depends on pozzolanic reaction products filling the pores in specimens and bonding clay particles, so as to reduce the permeability of red clay and increase the resistance during swelling. The addition of cement can also convert hydrophilic clay minerals into nonhydrophilic clay minerals. Compared with cement, the reduction in swelling potential caused by steel slag mainly depends on the adsorption of ions to reduce the adsorption of water molecules on the surface of clay slices.

Keywords: red clay; expansive soil; cement; steel slag; modification; swelling potential

Citation: Yue, B.; Zhao, Z.; Qian, Z. Influence of Five Additives on No Loading Swelling Potential of Red Clay. *Appl. Sci.* **2022**, *12*, 3455. https://doi.org/10.3390/app12073455

Academic Editor: Fernando Rocha

Received: 22 February 2022
Accepted: 22 March 2022
Published: 29 March 2022

1. Introduction

Red clay is widely distributed in southern China. It has good engineering mechanical properties under the condition of low water content, but the clay will expand and contract under the conditions of water absorption and loss. When red clay is used as a foundation, it will deform due to the dry–wet cycle, which will have an adverse impact on the upper pavement and other structures [1]. With the construction of infrastructure and the expansion of urban areas in recent years, engineering construction increasingly needs to be carried out in areas covered with red clay. Reducing the influence of red clay swelling and shrinkage has become a common problem in engineering construction. At present, the method of replacing foundation soil with other soil is often used to eliminate the influence of expansive soil. However, the replacement method not only has the problem of high cost, but also has the problem of environmental protection; that is, the excavated earthwork is difficult to dispose of. The use of additives to modify the engineering properties of soil can fully take advantage of the role of in situ soil as much as possible, reduce the excavation and disposal of soil, and achieve the dual benefits of reducing expenses and protecting the environment. The use of additives to modify the swelling properties of expansive soil mainly considers two aspects: one is to reduce the hydrophilicity of clay particles in soil by cation exchange, and the other is to bond soil particles by the pozzolanic reaction to increase the resistance of soil expansion. Lime is one of the most commonly used additives to modify expansive soil. Yongzhen Cheng et al. studied the modification effect of lime, pozzolana, and their combination on the expansibility of black cotton soil in Kenya using the liquid plastic limit test, California bearing ratio (CBR) test, and Unconfined Compressive Strength (UCS) test. Combined with the analysis of pH, electrical conductivity (EC), XRD, and transmission electron microscope (TEM) test results, lime was found to significantly modify the physical and mechanical properties of black cotton soil. Pozzolana was also found to modify the physical and mechanical properties of black cotton soil to a certain extent, but it is not as effective as lime. The combination of lime and pozzolan to modify the physical and mechanical properties of black cotton soil can achieve better results than adding one of them alone [2]. Muzahim al-Mukhtar et al. studied the treatment of bentonite by lime under high-temperature curing conditions and found that a certain amount of lime is used to destroy the silicate layer of bentonite and form different hydrates, whereas more than this quantity of lime results in a pozzolanic reaction to produce hydrated calcium aluminate (CAH) and hydrated calcium silicate (CSH), and a high temperature can greatly accelerate the rate of pozzolanic reaction [3]. Blast furnace slag (BFS) is a nonmetallic by-product obtained during the manufacturing process of cast iron. It consists primarily of silicates, aluminosilicates, and calcium aluminosilicates [4]. Different forms of slag products are manufactured depending on the method used to cool the molten slag. These products include air-cooled BFS, expanded or foamed slag, pelletized slag, and granulated blast furnace slag (GBFS). When crushed or ground into very fine particles, blast furnace slag has cementitious properties [5]. Mohammad Hamed Fasihnikoutala studied the unconfined compression strength of the olive–GGBS treated soil, and the experimental results showed that ground granulated blast furnace slag (GGBS) has soluble calcium, which can generate CSH gel to improve soil properties [6].

Cement is widely used in soil modification and solidification because of its large output, low cost, and small side effects on the environment. Cement has been used in improving the water stability of expansive soil, and the UCS tests and swelling potential tests show that the addition of cement can significantly improve the strength of soil and modify the swelling and shrinkage properties [7,8]. Steel slag is a common solid waste produced by steel-making, and its output accounts for 15–20% of the total crude steel production [9]. In 2020, Chinese crude steel production was 1053 million tons, accounting for 56.5% of global production [10]. Massive quantities of steel slag are discarded because it cannot be effectively utilized, which has a negative effect on the environment. The efficient utilization of steel slag has become an urgent problem to be solved. Previous studies have shown that steel slag has a similar chemical and mineral composition to that of Portland cement. In many cases, steel slag can be used as an additive for soil modification, so as to save resources and reduce carbon emission in cement production. Nicholas E. Malasavage conducted field experiments to study the engineering properties of a steel slag mixed soil embankment. The Cone Penetration Test (CPT) results of the studied embankment with different steel slag contents showed that the average tip resistance of the test embankment improved by steel slag was greatly improved, and there was no expansion and heavy metal leaching in the experiment [11]. Poh H. Y. found that the swelling properties and long-term strength of soil treated with basic oxygen steel slag were better than those treated with lime [12]. Akinwumi Isaac proposed that the cation exchange between soil and steel slag is the main factor affecting the modification of soil engineering properties by steel slag. The addition of steel slag reduces the diffusion water layer and agglomerates the clay particles in the soil–slag mixture, to improve the strength and plasticity of the soil [13]. Thermal power generation results in large quantities of coal ash. Fly ash, which is produced from the combustion of pulverized coal, has an important place among industrial by-products.

A large amount of fly ash cannot be used effectively, which results in environmental problems. B. A. Mir and A. Sridharan pointed out that the addition of fly ash to clayey soils significantly reduces their swelling due to the reduction in plastic fines of clay by non-plastic fines of fly ash. The swell potential decreases significantly as the percentage of fly ash increases [14,15]. K. Ramu and R. Dayakarbabu investigated the influence of fly ash on the free swell index of expansive soil. The differential free swell was reduced by 28.3% with 20% fly ash as a replacement in the expansive clay [16]. Zeolite and other pozzolanic materials may catalyze the occurrence of pozzolanic reactions due to their high SiO_2 and Al_2O_3 content. The addition of natural zeolite to cement kiln dust-stabilized expansive clayey soil has been proven to greatly improve the strength of the stabilized soil [17,18].

In the current study, paper, cement, zeolite powder, and three industrial by-products (blast furnace slag, steel slag, and fly ash) were selected as additives. The swelling potential of mixed specimens with different additive contents at different curing ages was tested through no loading swelling tests. The no loading swelling test measures the ratio of the unidirectional expansion in the height direction of the specimen after immersion in water to the original height value under the condition of no-load and side limit. This ratio is called the expansion rate and is expressed by a dial indicator. It is suitable for measuring the no loading swelling rate of undisturbed soil and compacted soil specimens, which can be used as a reference for evaluating the expansion potential energy of cohesive soil. Specimens with significantly reduced expansion potential were selected. Referring to the previous tests on soil modification, SEM tests and XRD tests were carried out on the red clay before and after modification to determine the changes in soil structure and mineral composition [19–21]. Direct shear tests are used to verify the effect of additives on soil strength [22]. XRD and SEM tests were carried out on these specimens to determine the changes in clay minerals in the specimens and observe the micromorphology of the specimens. Combined with the XRF test results, the modification mechanism of additives on the swelling potential of red clay was comprehensively analyzed. Then, the additives selected according to the above experiments to effectively decrease the swelling potential of red clay were used to make specimens for the direct shear test. The influence of additives on the shear strength of red clay was verified through the changes in cohesive force and internal friction angle. Through the experiments, it was verified that adding cement and steel slag to the red clay can effectively improve red clay's water stability. This paper proposes a means for the reuse of waste and provides a reference for reducing the impact on the environment in engineering construction.

2. Materials and Methods

2.1. Materials

The red clay used in this test was sourced from Honggutan District, Nanchang City, Jiangxi Province, China. Undisturbed red clay specimens were used for physical and mechanical property tests (the liquid limit and plastic limit were measured using a photoelectrical liquid plastic limit tester, and an electric strain-controlled direct shear apparatus was used for the direct shear test) and the XRF test (XRF-1800, Shimadzu, Kyoto City, Japan). The tests were conducted in accordance with the National Standard of the People's Republic of China [23] and American Society of Testing Materials standards [24,25]. The basic physical and mechanical properties of the red clay are shown in Table 1. The chemical composition was determined by the XRF test, and the results are shown in Table 2.

The five additives were ordered online from building material suppliers, and their XRF test results are shown in Table 2.

2.2. Specimen Preparation

The specimen used for the no loading swelling potential test was a cylinder with a diameter of 61.8 mm and a height of 20 mm. Before making the specimens, the red clay was crushed and dried naturally. The specimens were made from the clay passing through the 2 mm standard sieve. When making specimens, distilled water was added to the clay to ensure the clay had the best moisture content. The quantities of additives were calculated as follows: the mass of additives accounted for 3%, 6%, 9%, 12% and 15% of the dry weight of the clay and additives mixture. The dry density of each specimen was controlled at 1.6 g/cm^3. Three curing ages of 0, 7 and 28 days were taken for each dosage of different additives. The clay specimen was kept in shape in a stainless steel ring, sealed and wrapped with plastic film, and then cured in a sealed box at room temperature.

Table 1. Properties of the tested red clay.

Physical and Index Properties of the Red Clay	Quantity
Natural density (g/cm^3)	1.92
Dry density (g/cm^3)	1.64
Liquid limit (%)	63.30
Plastic limit (%)	11.31
Plasticity index (%)	51.99
Optimum moisture content (%)	9.55
Unified soil classification	CH
Free swelling ratio (%)	68.00
Total cohesion (kPa)	21.51
Total angle of internal friction (°)	30.90

Table 2. Chemical properties of the red clay, cement, gypsum, steel slag, blast furnace slag, fly ash and zeolite.

Chemical Composition	Red Clay (%)	Cement (%)	Steel Slag (%)	BFS (%)	Fly Ash (%)	Zeolite (%)
CaO	0.74	47.40	41.22	59.31	3.60	2.80
SiO_2	52.99	15.82	6.32	16.31	35.71	65.41
Al_2O_3	18.78	10.67	2.88	10.24	37.34	11.02
Fe_2O_3	13.48	4.96	22.44	1.46	9.86	2.53
MgO	1.04	4.49	5.68	5.63	0.46	0.89
SO_3	-	-	0.59	-	-	-
Na_2O	0.07	0.65	0.37	0.43	0.19	1.37
K_2O	5.06	0.96	0.33	0.57	1.66	6.85
P_2O_5	0.08	0.06	-	-	0.43	0.04
MnO	0.17	0.37	3.80	1.00	0.09	0.13
ZrO_2	0.52	0.32	0.14	0.45	1.49	0.14
Cl	-	1.24	0.06	0.06	-	0.08
S	0.02	1.78	-	1.22	-	0.02
SrO	0.06	0.67	0.17	0.67	1.63	0.11
Loss of ignition	4.97	8.20	12.77	-	2.05	7.86

2.3. Test Procedures

The no loading swelling ratio test refers to the National Standard of the People's Republic of China: GB/T 50123-2019 Standard for geotechnical testing method. The red clay specimen and schematic of the test setup used for the no loading swelling ratio test are shown in Figure 1.

Through the no loading swelling test of red clay, the height of the red clay specimen increased by 1.89 mm three hours after adding water. The swelling of red clay specimens tended to be stable six hours after adding water, and the subsequent height increase was less than 0.1 mm. Therefore, the swelling ratio of the specimen was calculated according to the reading at 12 h after adding water. Three parallel tests were carried out for each specimen with a specific dosage and age, and the average value was taken. The swelling ratio was defined as the height change in the specimen after swelling after water addition divided by the original height of the specimen, and the result was taken as a percentage. The size, manufacturing method, and curing method of the specimen for the direct shear test were the same as those for the no loading swelling ratio test. Four specimens were used for each set of direct shear tests. The vertical pressures applied during the test were

100, 200, 300 and 400 kPa. The cohesion and internal friction angle of the specimen were tested by the fast shear test. XRD tests used an X-ray diffractometer D8 Advance (Bruker, Rheinstetten, Germany) to analyze the relative content of clay. SEM tests used a JSM-IT300 (JEOL, Tokyo, Japan) scanning electron microscope working at 15.0 kV to observe the microstructure of the section after the direct shear test.

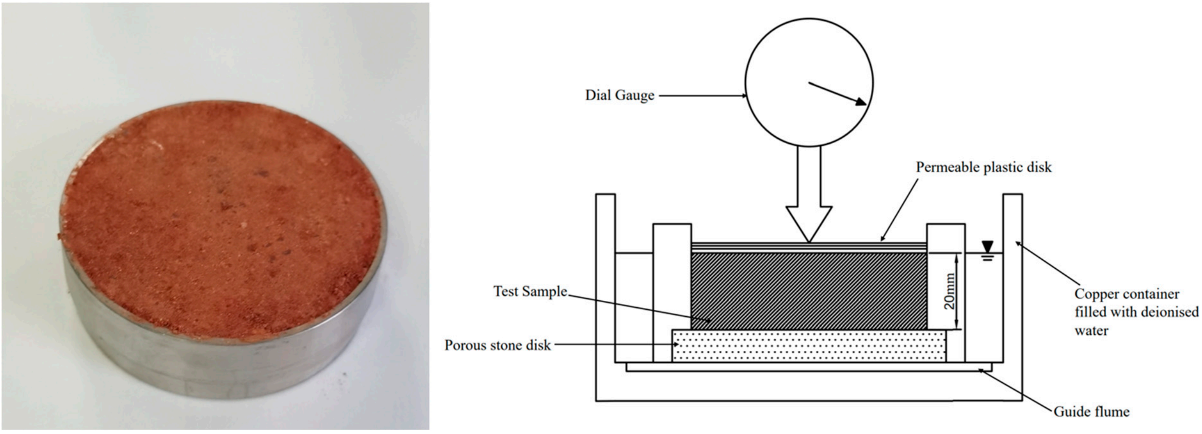


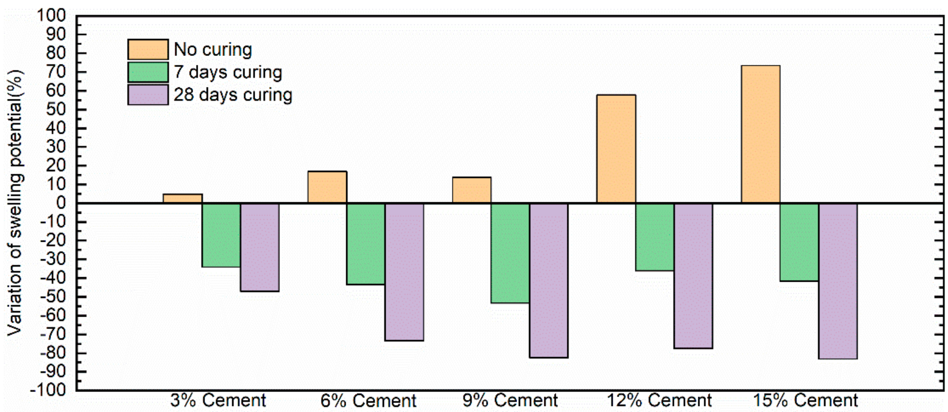
Figure 1. The specimen in the stainless steel ring (**left**) and schematic of the test setup used for the no loading swelling ratio test (**right**).

3. Results and Discussion

3.1. No Loading Swelling Ratio Test

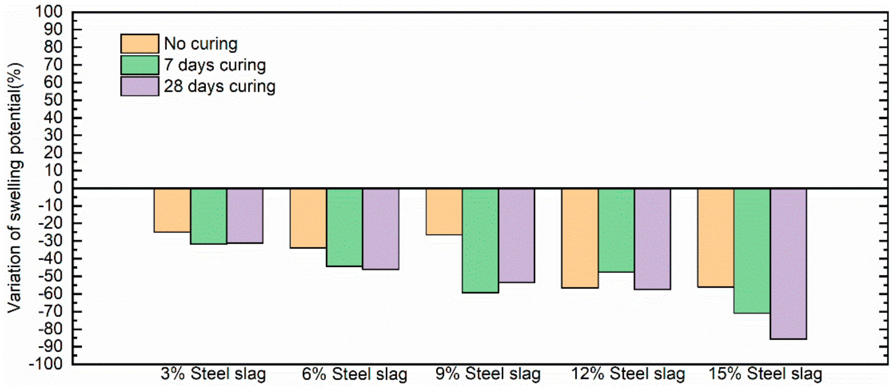
The variation in the swelling potential (the relative change in the no loading swelling ratio of specimens containing different additives compared with red clay specimens, taking a positive value when increasing and a negative value when decreasing) is shown in Figure 2.

Under three different curing conditions, the no loading swelling potential of steel slag-modified clay generally showed a more obvious decrease with the increase in steel slag content. Compared with the red clay without additives, the swelling potential of the fly ash-modified specimens and zeolite powder-modified specimens did not achieve the effect of reducing the swelling potential because of the lack of lime in the clay. The XRF test showed that the main components of zeolite and fly ash are SiO_2 and Al_2O_3. This indicates that their functions in pozzolanic reactions are similar. When zeolite powder and fly ash are used as additives, due to the lack of calcium ions, the pozzolanic reaction is not sufficient to produce CSH and CAH colloids, so it cannot effectively reduce the swelling potential of red clay. Because of the hygroscopicity of Al_2O_3, the soil expansion potential increased slightly after the addition of zeolite powder and fly ash. The no loading swelling potential of the blast furnace slag-modified specimen did not show a significant decline. Combined with the XRF test results, the blast furnace slag used in this test was alkaline slag with high CaO content, and its composition is similar to that of cement, but they have different effects on the swelling potential of red clay. This shows that the pozzolanic activity of blast furnace slag is far lower than that of cement. If blast furnace slag is used to improve the swelling potential of red clay, some methods need to be used to stimulate its reaction potential. It can be observed from the above figure that the cement can significantly inhibit the swelling potential of red clay under the curing times of 7 and 28 days, but cement-modified clay specimens without curing resulted in swelling potential that exceeded that of the no-additive clay specimens. Adding steel slag can greatly reduce the no loading swelling potential of specimens without curing. However, with the increase in curing age, the swelling potential of specimens to which steel slag was added did not decrease further. This shows that the mechanisms of cement and steel slag used as additives to reduce the swelling potential of red clay are different. The cement-modified specimens having a curing age of 28 days showed a further decrease in the swelling potential compared to the specimens with the same cement content with 7 days' curing. In other words, when cement is used as an additive, it needs a certain curing time to show the effect of reducing the swelling potential of red clay, and the longer the curing time, the better the effect. Without curing, or when the curing time is insufficient, a large number of unhydrated cement clinkers will no longer hydrate with the water distribution in the soil after immersion, but will directly absorb the outside water to form CSH and CAH colloids, which will promote the expansion of the clay. After curing the cement-modified specimens for a long enough period, sufficient parts of the clinker can react with the water in the clay. The hydration products are generated to fill the pores of the red clay, bond the red clay particles, reduce the water absorption of the red clay, and increase the resistance of the red clay expansion. When the cement content exceeded 9%, the swelling rate of specimens rose slightly, which indicates that the hydration reaction of cement is limited due to the limited water content in the soil. When the curing time was 28 days, the swelling ratio of specimens with 3% cement content was lower than that of specimens with 15% cement content and a curing age of 7 days, which indicates that prolonging the curing age is a better choice to improve the cement modification effect than increasing the cement content. If the curing time is not long enough to hydrate the cement clinker and water in the red clay, increasing the cement content will result in a waste of cement clinker. In addition, a portion of the cement does not produce CSH and CAH colloids, and this portion of the cement clinker will absorb water from the outside of the clay and continue to react when the clay meets water, which will result in negative effects on the water stability of the red clay. Under 28 days of curing, the change in the soil swelling ratio is no longer obvious when the cement content reaches 6%. Therefore, under the condition of long-term curing, if the water content of the soil is not sufficient, a large amount of cement is not required to modify red clay. The appropriate amount of cement can fully enable the reaction potential of water content in clay and reduce possible cement waste. Compared with the case in which the swelling ratio of specimens with cement increased under the condition of no curing, the swelling ratio of specimens with steel slag was lower than that of red clay specimens without additives under the condition of no curing. In addition, the swelling ratio of specimens with steel slag in all three curing ages showed an overall trend of decreasing with the increase in steel slag content. There was no situation in which the modification effect of the clay swelling potential was no longer obvious after the content of the additive reached 9% when the cement-modified specimens were cured for 7 and 28 days.

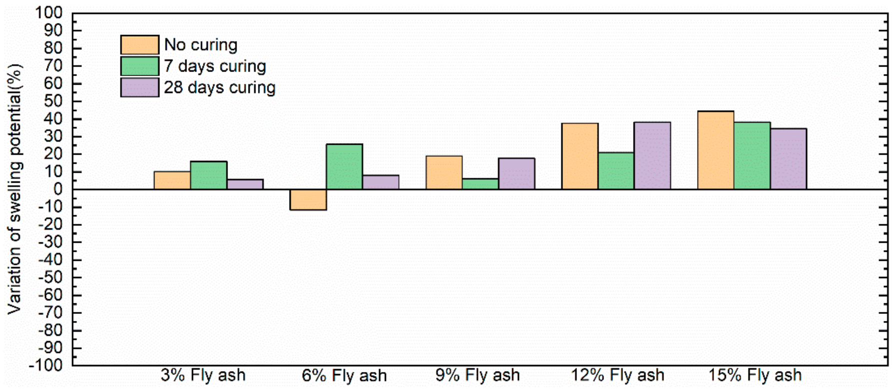


(**a**)

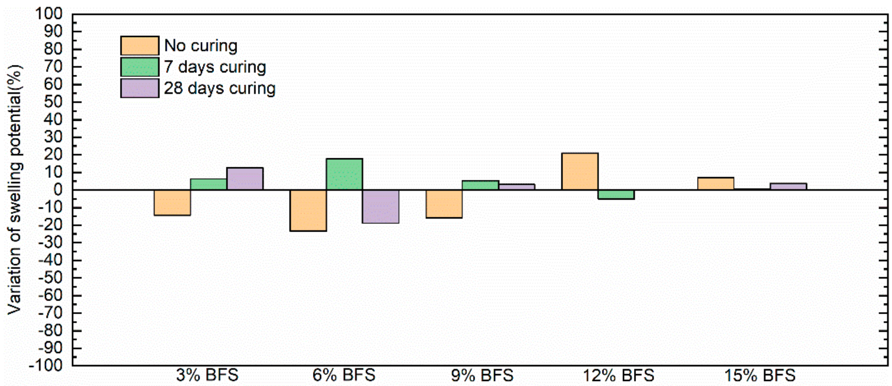
Figure 2. *Cont.*



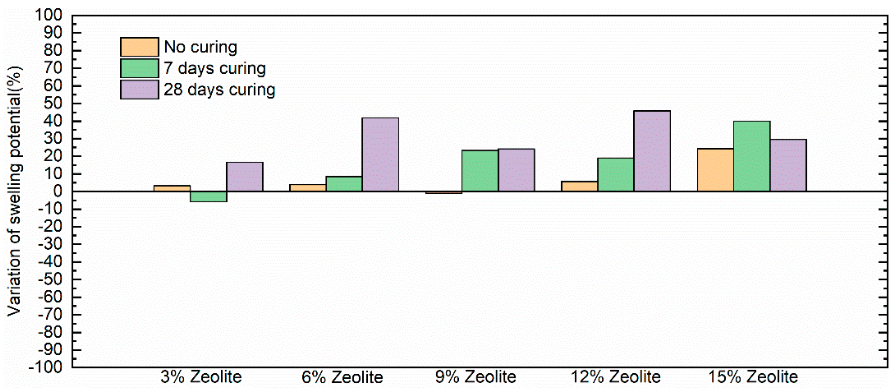
(**b**)



(**c**)



(**d**)



(**e**)

Figure 2. The change in the no loading swelling ratio of specimens with different additives relative to the red clay specimen: (**a**)-cement, (**b**)-steel slag, (**c**)-blast furnace slag, (**d**)-fly ash, (**e**)-zeolite.

The value of the change in the no loading swelling ratio of the cement and steel slag-modified specimens compared with the red clay specimen without additives was set as the dependent variable (the swelling ratio decreases to a positive value and increases to a negative value) in the binary linear regression equation between the improvement effect of the two additives, and the curing time and additive contents. The linear regression coefficient was calculated according to the following equations:

$$a_1 = -\frac{l_{1y}l_{22} - l_{2y}l_{12}}{l_{11}l_{22} - l_{12}^2} \tag{1}$$

$$a_2 = -\frac{l_{2y}l_{11} - l_{1y}l_{21}}{l_{11}l_{22} - l_{12}^2} \tag{2}$$

where:

$$l_{ij} = l_{ji} = \sum(x_i x_j) - (\sum x_i \sum x_j)/k$$
$$l_{iy} = l_{ji} = \sum(x_i y_i) - (\sum x_i \sum y_i)/k$$

and k is the number of test groups. After calculation using Equations (1) and (2), the values of a_1 and a_2 of cement-modified specimens were 3.26 and -1.05, respectively. The values of a_1 and a_2 of steel slag-modified specimens were 0.34 and 3.54, respectively.

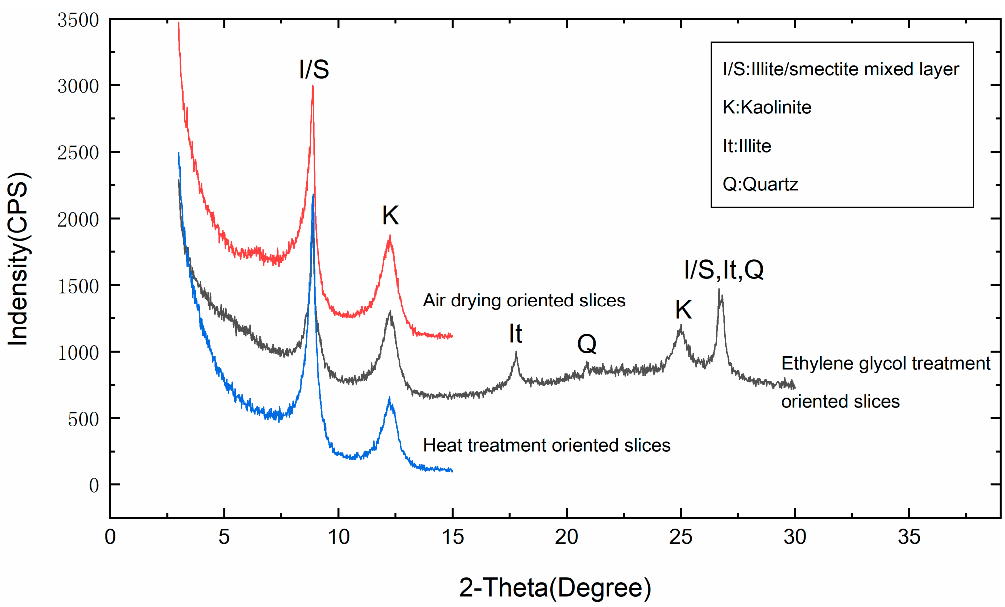
Through calculation, it was again verified that, when steel slag is used to modify red clay, the influence of the steel slag content is more significant than that of curing time, and for cement, the influence of curing time is more significant than that of the cement content. From the above results, it can be concluded that, when steel slag modifies the swelling potential of red clay, the main modification mechanism is not a hydration reaction like that in cement. Combined with the XRF test results, both cement and steel slag contain a large amount of the Ca element, and the contents of Si and Al in steel slag are lower than those in cement, but there are sufficient quantities of Si and Al in red clay. This shows that the relative lack of Al and Si in steel slag is not the main reason for its weak pozzolanic reaction. It can be considered that a portion of Ca in steel slag does not exist in the form of calcium oxide or calcium hydroxide, but in the form of calcium carbonate and other forms that are not prone to pozzolanic reaction. This situation should also exist in blast furnace slag. As a result, the ability of steel slag to produce CSH and CAH colloids in hydration reaction is less than that of cement. In addition, the Fe and Mn contents in steel slag are higher than those in cement. Therefore, it can be considered that a part of the ability of steel slag to modify red clay is related to the ions of Fe and Mn. According to the double layer theory of clays [26], shear displacement occurs between clay particles when the volume of clay changes. Because clay molecules contain a large number of oxygen atoms, the surface of clay particles has a fixed negative electric charge related to the crystal lattice. When the red clay encounters fresh water, a large number of water molecules are polarized, and a large number of hydrogen bonds are formed on the surface of the clay slices to adsorb water molecules on the surface of the clay slices. This leads to an increase in the volume of clay due to the filling of water [27–29]. For the steel slag modified clay, after the steel slag is mixed with clay, the Fe and Mn ions in the steel slag are adsorbed on the clay slices. This reduces the number of hydrogen bonds formed on the surface of the clay slices when the clay meets water, thus reducing the swelling of the clay caused by the filling of water molecules. Ion adsorption can be considered to occur instantaneously when red clay and steel slag are mixed, so the curing time does not affect the ion adsorption. With the increase in steel slag content, more cations are adsorbed on the surface of clay slices, so as to neutralize more negative charges on the surface of clay slices. This can further reduce the hydrogen bonds formed between the surface of clay slices and water molecules when clay meets water. Hence, when steel slag improves the swelling of red clay, the greater the steel slag content, the better the modification effect.

3.2. X-ray Diffraction Quantitative Analysis of Clay Minerals

After comprehensively considering the effect and economy of additives, a red clay specimen, a specimen having 15% steel slag content and 28 days curing, and a specimen having 9% cement content and 28 days curing, were selected to make air drying-oriented slices (the glass slides were coated with a clay suspension and dried naturally), ethylene glycol treatment-oriented slices (i.e., air drying-oriented slices after saturation treatment in a ethylene glycol steam), and heat treatment-oriented slices (obtained by natural cooling of ethylene glycol tablets after treatments at a high temperature and a constant temperature), respectively, for the XRD analysis of clay minerals. The XRD patterns of clay minerals in specimens are shown in Figure 3.

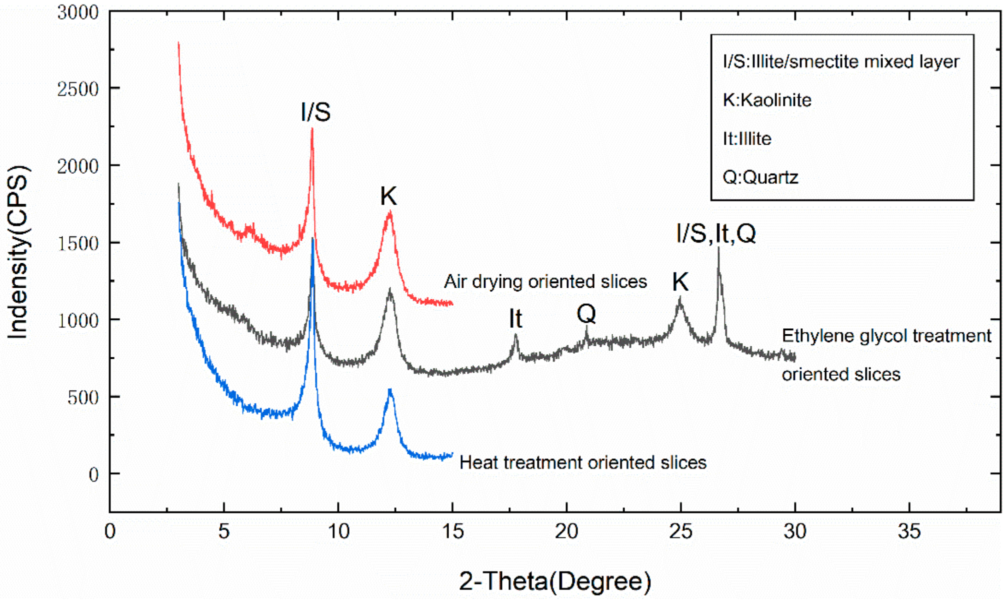
Comparing the relative intensity of each diffraction peak of the XRD pattern, the relative intensity of the theta angles of 12.27° and 25.00° in the XRD patterns of the red clay, steel slag-modified, and cement-modified specimens shows a gradually increasing trend. Therefore, it can be concluded that the relative content of kaolinite in the red clay specimen, the steel slag-modified specimen, and the cement-modified specimen increases gradually. The specific relative contents of clay minerals of the red clay, steel slag-modified, and cement-modified specimens are shown in Table 3.

The content of montmorillonite in the illite-montmorillonite mixed layer in specimen 1 is 10%. The content of montmorillonite in the illite-montmorillonite mixed layer in specimen 2 is 10%. Comparing the relative content of montmorillonite, that of specimen 1 is 5.9%, that of specimen 2 is 5.7%, and that of specimen 3 decreases to 2%. Comparing the relative content of illite, that of specimen 1 is 72.1%, that of specimen 2 is 67.3%, and that of specimen 3 is 48%. It can be seen that, under the condition of 28 days curing, the addition of cement can greatly reduce the content of montmorillonite and illite resulting in strong hydrophilicity, and increase the content of kaolinite resulting in poor hydrophilicity. The addition of steel slag to red clay can also reduce the relative content of montmorillonite and illite in clay minerals, and increase the relative content of kaolinite, but the effect is less than that of cement. From the analysis of XRD test results, it can be inferred that when cement is used to modify the swelling properties of red clay, it can change the relative content of clay minerals in the specimens. The relative content of hydrophilic clay minerals decreases, whereas the relative content of nonhydrophilic clay minerals increases, which reduces the water absorption of red clay.

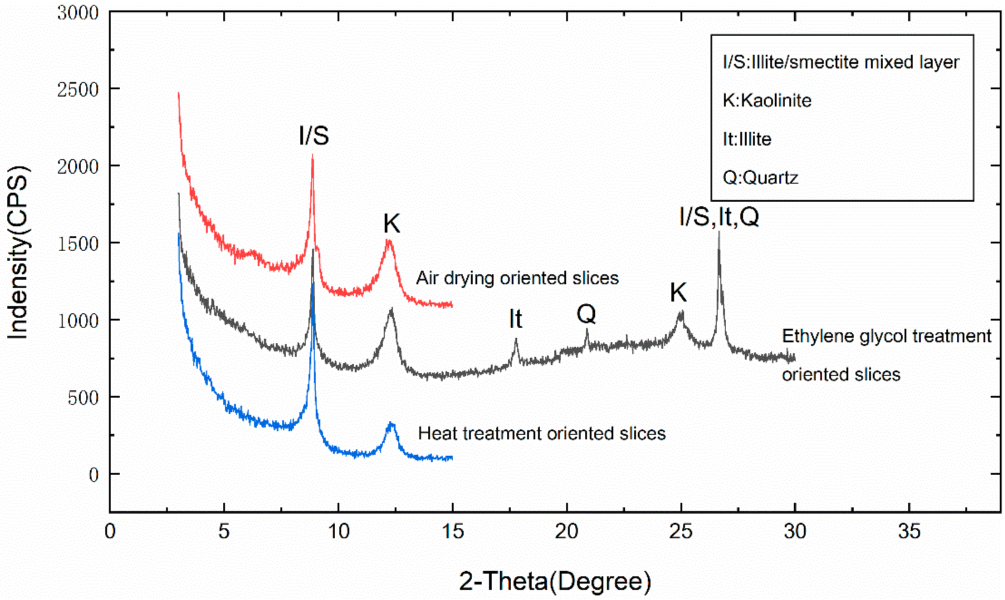


(**a**)

Figure 3. *Cont.*



(**b**)



(**c**)

Figure 3. XRD patterns of clay minerals (smectite, kaolinite, illite, and their mixed layer) in specimens at 28 days: (**a**) red clay; (**b**) 15% steel slag; (**c**) 9% cement.

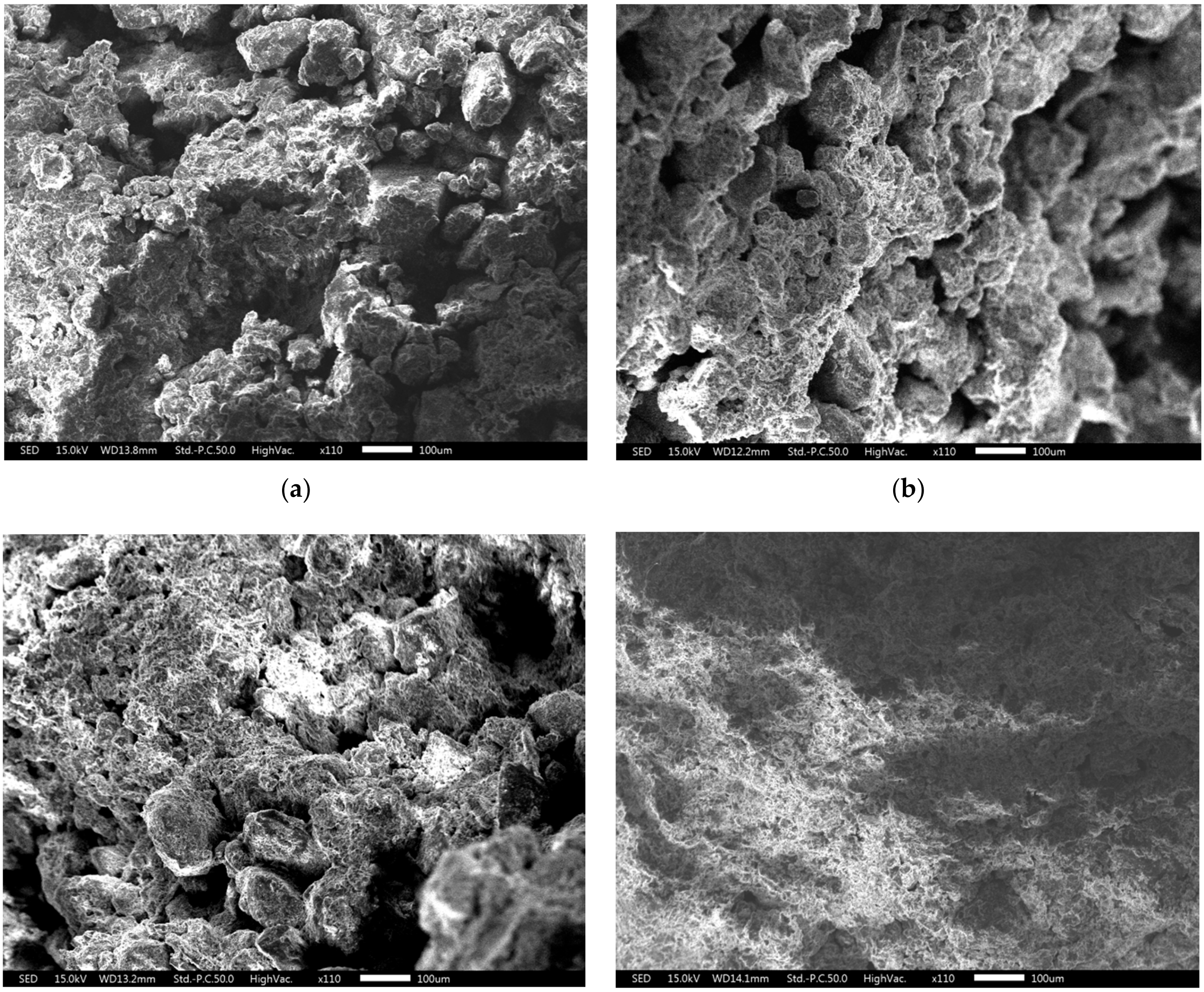
Table 3. The relative content of clay minerals in the red clay, steel slag-modified and cement-modified specimens.

Specimen Number	Additives	The Relative Content of Clay Minerals					
		S [1]	I/S [1]	It [1]	Kao [1]	C [1]	C/S [1]
1	-	1	49	28	22	-	-
2	15% Steel Slag	1	47	22	30	-	-
3	9% Cement	2	-	48	50	-	-

[1] S is montmorillonite, It is illite, Kao is kaolinite, C is chlorite, I/S is the illite montmorillonite mixed layer, and C/S is the chlorite montmorillonite mixed layer.

3.3. Scanning Electron Microscopy

Figure 4 shows the SEM images of sections of the red clay specimen, the steel slag-modified specimen with 15% steel slag content cured for 7 and 28 days, and the cement-modified specimen with 9% cement content cured for 28 days.



(**a**) (**b**)

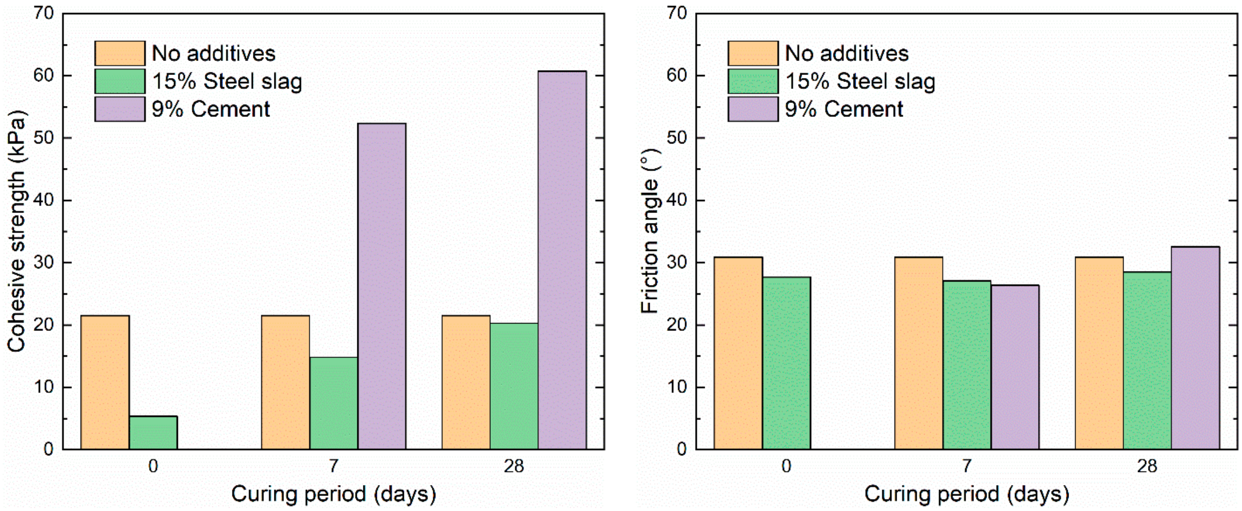
(**c**) (**d**)

Figure 4. SEM micrographs at 100 μm of (**a**)-red clay, (**b**)-15% steel slag-modified specimen at 7 days curing, (**c**)-15% steel slag-modified specimen at 28 days curing, (**d**)-9% cement-modified specimen at 28 days curing.

It can be seen from the image that there are many pores in the red clay. In the clay with steel slag, some smaller pores have been filled, but the pores with larger diameters are still not filled. In the red clay with cement, almost all pores are effectively filled. As a result, it is more difficult for the water to penetrate the interior of the cement-modified clay, and the number of pores in the clay that can hold water is greatly reduced.

3.4. Direct Shear Test

Through the above tests, it was found that, when cement or steel slag is used as a single additive, 9% cement content and 15% steel slag content are more suitable for reducing the swelling potential of red clay. Therefore, we selected the specimens with 9% cement content cured for 7 and 28 days, and the specimens with 15% steel slag content cured for 0, 7 and 28 days for the direct shear test. The obtained cohesive strength and internal friction angle were compared with those of the red clay specimen to verify the influence of the above treatment scheme, which can effectively reduce the swelling potential of red clay, on the strength of the specimens. By comparing the values of cohesive strength and internal friction angle obtained from the direct shear test given in Figure 5, it can be seen that the addition of steel slag leads to the loss of cohesion of the clay. When the specimen is not cured, the cohesive strength of the modified clay containing 15% steel slag is reduced to 5.37 kPa, which is 75% lower than that of red clay. After a period of curing, the cohesive strength of the steel slag modified clay is restored. When the curing time is 28 days, the cohesive strength of the steel slag modified clay can be restored to 94% of the cohesive strength of the red clay before adding steel slag. The cohesive strength of the cement-modified specimens can be greatly improved after a certain curing time. After curing for 7 days, the cohesive strength of the modified clay with 9% cement content is 43% higher than that of the red clay. After curing for 28 days, the cohesive strength of the modified clay with 9% cement content is 82% higher than that of the red clay. Regardless of whether the additive is cement or steel slag, and the curing age is long or short, no particularly significant effect on the internal friction angle φ can be observed. Based on the XRF test results and SEM images, the ability of steel slag hydration to generate CAH and CSH colloids is far lower than that of cement, so the cementation and filling effect of steel slag on red clay particles is not obvious because the quantity of reactants for the pozzolanic reaction in steel slag is less than that in cement. When steel slag is added to the red clay, most of the calcium oxide in steel slag first reacts with the water in the clay. Then, CSH and CAH colloids are gradually formed, which takes a period of time. The above reaction process leads to a significant reduction in the water content of the clay in a short period after the steel slag is added to the clay. The decrease in water content in red clay will result in two problems. The first is the decrease in water tension between clay particles. The second is that part of the cohesion of clay depends on the hydrogen bond, and the water plays the role of the connecting node between the two clay slices [21]. The decrease in water leads to the loss of the bond strength between the clay particles, which relies on the hydrogen bond. This effect is more obvious in illite and montmorillonite, which are more hydrophilic. Previous experiments show that the shear strength of illite and montmorillonite will decrease with the decrease in water content when the clay's water content is lower than a certain level [6]. At the same time, because there is not enough CSH colloid in the clay to provide cementation between particles, the cohesion of the clay will be lost to a large extent. Then, with the increase in curing time, the pozzolanic reaction in steel slag is carried out gradually, and a part of the newly generated CSH colloid provides the adhesive force between some soil particles, which shows that the cohesion of the clay modified by steel slag measured by the direct shear test is partially restored after a period of curing. The quantity of reactants of the volcanic ash reaction in cement-modified clay is much greater than that in steel slag-modified clay. After a certain period of curing, a large number of generated CAH and CSH colloids directly fill the internal pores of the specimens and cement the clay particles. After 28 days of curing, the soil has formed a compact structure of the combination of soil particles and hydration products. Particles in the clay are connected as a whole. The hardened CSH and CAH colloids that fill the pores play an integral role in bearing the external force with the clay particles. Hence, the cohesion of cement-modified clay obtained from direct shear tests is greatly enhanced.



(**a**) (**b**)

Figure 5. Cohesive strength and internal friction angle of red clay and cement/steel slag-modified specimens: (**a**) the cohesive strength of specimens; (**b**) internal friction angle of specimens.

4. Conclusions

In this study, the influences of different additives on the swelling potential of red clay were investigated. The following conclusions can be summarized from this paper:

1. For cement, zeolite powder, blast furnace slag, steel slag and fly ash were added separately to red clay. Cement and steel slag can significantly reduce the swelling potential of red clay compared with the other three additives. The modification effect of cement can be reflected after a certain period of curing, whereas the modification effect of steel slag depends more on the increase in steel slag content. When cement is added to red clay, the cement clinker reacts with the water in the red clay to form a large number of CSH and CAH colloids. These colloids fill the pores in the red clay and bond the soil particles as a whole, which greatly improves the compactness of the clay, reduces the water absorption capacity of the clay, and improves the resistance to inhibit the swelling of the clay.
2. Adding steel slag can reduce the swelling potential of red clay without curing. The main reason for this is that Fe and Mn ions are adsorbed on the surface of negatively charged clay slices, so as to reduce the number of water molecules adsorbed by hydrogen bonds formed on the surface of the clay slices. Because the adsorption of ions on the surface of clay slices can be considered to occur at the same time when steel slag is added to red clay, the steel slag can immediately modify the swelling properties of red clay. SEM images show that the pozzolanic reaction in steel slag-modified specimens is similar to that in cement-modified specimens. A certain quantity of CSH and CAH colloids are formed, but this quantity is far less than that of cement.
3. According to the position and intensity of diffraction peaks of clay minerals shown in XRD patterns, the diffraction peak relative intensity of kaolinite in steel slag-modified clay and cement-modified clay is higher than that in red clay. Therefore, the addition of steel slag and cement can change the relative content of clay minerals in red clay, reduce the relative content of hydrophilic clay minerals such as montmorillonite and illite, and increase the relative content of kaolinite. The content of nonhydrophilic clay minerals in red clay increases relatively, and the water stability of red clay is also improved. The above phenomenon is more obvious in cement-modified clay than in steel slag-modified clay.
4. When steel slag is added alone, it causes a decrease in the water content in the specimen, and then causes a large loss of cohesion in the short term. After a certain curing period, the cohesion of the steel slag-modified specimen can be restored due

to the bonding effect of CSH and CAH colloids caused by the pozzolanic reaction in the steel slag modified-specimen. The production of CSH and CAH colloids in the cement-modified specimen is much higher than that in the steel slag-modified specimen, so the cohesion of the cement-modified specimen can be greatly improved after a certain period of curing.

Author Contributions: Conceptualization, Z.Q. and B.Y.; methodology, B.Y.; validation, B.Y. and Z.Z.; formal analysis, B.Y.; investigation, B.Y. and Z.Z.; resources, Z.Q.; data curation, B.Y.; writing—original draft preparation, B.Y.; writing—review and editing, B.Y.; visualization, B.Y.; supervision, Z.Q.; project administration, Z.Q.; funding acquisition, Z.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: The study did not require ethical approval.

Informed Consent Statement: The study did not involve humans.

Data Availability Statement: Not applicable.

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

References

1. She, J.; Lu, Z.; Yao, H.; Fang, R.; Xian, S. Experimental Study on the Swelling Behavior of Expansive Soil at Different Depths under Unidirectional Seepage. *Appl. Sci.* **2019**, *9*, 1233. [CrossRef]
2. Cheng, Y.; Huang, X. Effect of Mineral Additives on the Behavior of an Expansive Soil for Use in Highway Subgrade Soils. *Appl. Sci.* **2019**, *9*, 30. [CrossRef]
3. Al-Mukhtar, M.; Lasledj, A.; Alcover, J.-F. Behaviour and mineralogy changes in lime-treated expansive soil at 50 °C. *Appl. Clay Sci.* **2010**, *50*, 199–203. [CrossRef]
4. TFHRC. Transportation and Federal Highways Research Council-U.S. Department of Transportation. Blast Furnace Slag, Material Description Guideline. 2004. Available online: http://www.tfhrc.gov/hnr20/recycle/waste/bfs1.html (accessed on 22 December 2021).
5. Cokca, E.; Yazici, V.; Ozaydin, V. Stabilization of Expansive Clays Using Granulated Blast Furnace Slag (GBFS) and GBFS-Cement. *Geotech. Geol. Eng.* **2009**, *27*, 489–499. [CrossRef]
6. Fasihnikoutalab, M.H.; Pourakbar, S.; Ball, R.; Unluer, C.; Cristelo, N. Sustainable soil stabilisation with ground granulated blast-furnace slag activated by olivine and sodium hydroxide. *Acta Geotech.* **2020**, *15*, 1981–1991. [CrossRef]
7. Chen, L.; Chen, X.; Wang, H.; Huang, X.; Song, Y. Mechanical Properties and Microstructure of Lime-Treated Red Clay. *KSCE J. Civ. Eng.* **2021**, *25*, 70–77. [CrossRef]
8. Wang, J.; Wang, S.; Hong, M.; Li, Y.; Wu, G.; Li, L.; Zhang, J. Correlation Analysis between Clay Mineral Composition and Shear Strength. *J. Southwest Jiaotong Univ.* **2018**, *53*, 1033–1038. [CrossRef]
9. Yu, H.M.; Wang, Q. *Steel Slag: Treatment and Resource Utilization*; Metallurgical Industry Press: Beijing, China, 2015.
10. Global Crude Steel Output Decreases by 0.9% in 2020. Available online: https://www.worldsteel.org/media-centre/press-releases/2021/Global-crude-steel-output-decreases-by-0.9--in-2020.html (accessed on 22 December 2021).
11. Malasavage, N.E.; Jagupilla, S.; Grubb, D.G.; Wazne, M.; Coon, W.P. Geotechnical Performance of Dredged Material—Steel Slag Fines Blends: Laboratory and Field Evaluation. *J. Geotech. Geoenviron. Eng.* **2012**, *138*, 981–991. [CrossRef]
12. Poh, H.Y.; Ghataora, G.S.; Ghazireh, N. Soil Stabilization Using Basic Oxygen Steel Slag Fines. *J. Mater. Civ. Eng.* **2006**, *18*, 229–240. [CrossRef]
13. Akinwumi, I. Soil Modification by the Application of Steel Slag. *Period. Polytech. Civ. Eng.* **2014**, *58*, 371–377. [CrossRef]
14. Mir, B.A.; Sridharan, A. Mechanical behaviour of fly ash-treated expansive soil. *Ground Improv. Proc. Inst. Civ. Eng.* **2019**, *172*, 12–24. [CrossRef]
15. Mir, B.A.; Sridharan, A. Volume change behavior of clayey soil–fly ash mixtures. *Int. J. Geotech. Eng.* **2014**, *8*, 72–83. [CrossRef]
16. Ramu, K.; DayakarBabu, R. A Laboratory Study on the Stabilized Expansive Soil with Partial Replacement of Fly Ash and Palm Oil Fuel Ash. *Lect. Notes Civ. Eng.* **2022**, *152*, 69–78. [CrossRef]
17. Sharo, A.A.; Shaqour, F.M.; Ayyad, J.M. Maximizing Strength of CKD—Stabilized Expansive Clayey Soil Using Natural Zeolite. *KSCE J. Civ. Eng.* **2021**, *25*, 1204–1213. [CrossRef]
18. Eyo, E.U.; Ng'Ambi, S.; Abbey, S.J. Performance of clay stabilized by cementitious materials and inclusion of zeolite/alkaline metals-based additive. *Transp. Geotech.* **2020**, *23*, 100330. [CrossRef]
19. Goodarzi, A.R.; Goodarzi, S.; Akbari, H.R. Assessing geo-mechanical and micro-structural performance of modified expansive clayey soil by silica fume as industrial waste. *Iran. J. Sci. Technol.-Trans. Civ. Eng.* **2015**, *39*, 333–350. [CrossRef]
20. Xu, B.; Yi, Y. Soft Clay Stabilization Using Three Industry Byproducts. *J. Mater. Civ. Eng.* **2021**, *33*, 06021002. [CrossRef]
21. Yang, Q.; Du, C.; Zhang, J.; Yang, G. Influence of Silica Fume and Additives on Unconfined Compressive Strength of Cement-Stabilized Marine Soft Clay. *J. Mater. Civ. Eng.* **2020**, *32*, 04019346. [CrossRef]

22. Huang, K.; Wan, J.-W.; Chen, G.; Zeng, Y. Testing study of relationship between water content and shear strength of unsaturated soils. *Rock Soil Mech.* **2012**, *33*, 2600.
23. *GB/T 50123-2019*; National Standard of the People's Republic of China. Standard for Geotechnical Testing Method. CSBTS & Ministry of Construction: Beijing, China, 2019.
24. *ASTM D2487*; Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International: West Conshohocken, PA, USA, 2017.
25. *ASTM D4318*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM International: West Conshohocken, PA, USA, 2017.
26. Sridharan, A.; Jayadeva, M.S. Double layer theory and compressibility of clays. *Geotechnique* **1982**, *32*, 133–144. [CrossRef]
27. Ikari, M.J.; Kopf, A.J. Cohesive strength of clay-rich sediment. *Geophys. Res. Lett.* **2011**, *38*, L16309. [CrossRef]
28. Komine, H. Simplified evaluation for swelling characteristics of bentonites. *Eng. Geol.* **2004**, *71*, 265–279. [CrossRef]
29. Zeng, Z.; Cui, Y.-J.; Conil, N.; Talandier, J. Experimental study on the aeolotropic swelling behaviour of compacted bentonite/claystone mixture with axial/radial technological voids. *Eng. Geol.* **2020**, *278*, 105846. [CrossRef]