1 Article

2 Effects of initial water content on microstructure and 3 mechanical properties of lean clay soil stabilized by 4 compound calcium-based stabilizer

5 Cheng-long Yin, Wei Zhang, Xun-li Jiang and Zhi-yi Huang*

6 College of Civil Engineering and Architecture, Zhejiang University, 866 Yuhangtang Road, Hangzhou
 7 310058, China: vinchenglong@ziu.edu.cn (C.L.Y.): zhangw8778@ziu.edu.cn (W.Z.): 221712088@ziu.edu.cr

- 310058, China; yinchenglong@zju.edu.cn (C.L.Y.); zhangw8778@zju.edu.cn (W.Z.); 221712088@zju.edu.cn
 (X.L.I)
- 8 (X.L.J) 9 * Corr
- * Correspondence: hzy@zju.edu.cn; Tel.: +86-0571-88208702
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11 Abstract: Initial water content significantly affects the efficiency of soil stabilization. In this study, 12 the effects of initial water content on the compressibility, strength, microstructure and composition 13 of a lean clay soil stabilized by compound calcium-based stabilizer were investigated by static 14 compaction test, unconfined compression test, optical microscope observations, environment 15 scanning electron microscopy, energy dispersive X-ray spectroscopy and X-ray diffraction 16 spectroscopy. The results indicate that as the initial water content increases in the range studied, 17 both the compaction energy and the maximum compaction force decrease linearly and there are less 18 soil aggregates or agglomerations, and smaller proportion of large pores in the compacted mixture 19 structure. In addition, for specimens cured with or without external water supply and under 20 different compaction degrees, the variation law of the unconfined compressive strength with initial 21 water content is different and the highest strength value is obtained at various initial water contents. 22 With the increase of initial water content, the percentage of oxygen element tends to increase in the 23 reaction products of the calcium-based stabilizer, whereas the crystalline mineral of the soil did not 24 change obviously.

Keywords: initial water content; lean clay soil; compound calcium-based stabilizer; compressibility; strength; microstructure and composition

27

28 1. Introduction

29 From a historical perspective, clayey soil, derived from rock weathering process of geological 30 cycle[1, 2], already exists long before humankind come up. When people decide to use this kind of 31 material, they were amazed at its volume changing property with seasonal moisture variation[3-7]. 32 In order to control or constrain the deflections and movement of clayey soils and enhance its 33 compressibility, strength, stiffness, the resistance to water and crack and other engineering 34 properties, a variety of inorganic, organic, and biological materials such as lime[8-11], Portland 35 cement[12-15], fly ash[16, 17], granulated blast furnace slag[18-20], cement kiln dust[21, 22], rice husk 36 ash[23, 24], polyacrylamide copolymers[25, 26], bioenergy coproduct[27, 28] and so on, in the form 37 of powder or liquid, was mixed with this problematic material with or without extra water before 38 compaction. This operation is usually referred as soil stabilization. Soil stabilization is traditional but 39 cost-effective technique in civil engineering, and finds its prevailing applications in pavement base, 40 subbase or embankment, canal or reservoir lining, shallow building foundations, stabilized rammed 41 earth constructions among others, especially for locations where relatively high-cost materials such 42 as gravel and crushed stone are unavailable or have a long transportation distance while the budget 43 of the construction project is probably limited[6, 29, 30].

Lime, Portland cement and fly ash are the most commonly used binding materials in soil stabilization and they all comprise of calcium element, which can compose two main kinds of binding

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gels in soil stabilization: calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), because of which they are called calcium-based stabilizer. These calcium-based stabilizers are usually in the form of grinded powder. During soil stabilization practice, they are combined with soil and a certain amount of water to form the soil-water-binder reaction system. It is the chemical and/or physico-chemical reactions in the system that essentially transform the properties of the soils.

51 There are many factors affecting the efficiency of soil stabilization. Terashi [31] has categorized 52 them into four groups: a) characteristics of soils (soil structure, clay minerals, particle size 53 distribution, plasticity index, cation exchange capacity, pH, contents of sulphate and organic matter, 54 and so on), b) characteristics of binders (binder types, dosage methodology, corresponding reaction 55 processes such as dissolution, diffusion and precipitation, products of chemical or physico-chemical 56 reactions and so on), c) mixing and compaction procedures (pulverization, mixing uniformity, initial 57 water content (IWC), dry density and the like) d) curing procedures (temperature, air moisture, 58 curing time and the like).

59 Among all the influential factors of soil stabilization, initial water content is of first-level 60 importance. Firstly, the reaction process of soil-water- stabilizer reaction system can be simplified as 61 dissolution-precipitation[32-34], in which calcium-based binding materials and reactive minerals of 62 soil first dissolve into water and then precipitate on the surfaces of soil particles to fill the soil pores 63 (macropores and micropores[35]). Therefore, without water the reaction in the soil-water-stabilizer 64 system will not occur. Secondly, water is a strong polar molecule and has a very strong affinity to soil 65 minerals. Once water goes into the soil structure, a diffused double-layer (DDL) microstructure[36, 66 37] is formed around soil particles and influences the pore size distribution, matric suction, 67 compressibility and shear strength of the soils.

68 Initial water content as the first-considered and quality-controlled factor in soil stabilization, has 69 been studied by other researchers. Most of the research focus on the effects of IWC on the strength 70 property of the soil treated by stabilizers, but different studies report different results and 71 conclusions. For example, Ramesh and Sivapullaia[38] compared the development of strength of a 72 black cotton soil stabilized by lime under different IWCs and found that the strength of lime-73 stabilized black cotton soil increases rapidly when the specimens are compacted at a water content 74 slightly lower than the optimum moisture content. However, Guo et al. [39] analyzed the influence 75 of IWC on the strength of lime-modified expansive soil, and considered that the optimum IWC in the 76 construction of lime-modified expansive soil should be about 3 percentage points higher than the 77 optimum water content. Consoli et al. [40] studied the effects of IWC on the strength of a lime-treated 78 sandy lean clay and draw the conclusion that at the same curing age, the strength was not affected 79 by the IWC. Besides, Consoli et al.[41] also investigated the effects of IWC on the strength of cement-80 stabilized clayey sand and found that the unconfined compressive strength (UCS) first increased then 81 followed by decrease with the increase of IWC. He speculated that this was attributed to the different 82 structure formed during compaction where IWC played a fundamental role. Arora and Aydilek[42] 83 investigated the relation between UCS and IWC of a cement-treated sandy soil- fly ash mixture and 84 concluded that after the same curing period, the increase of IWC generally resulted in the decrease 85 of the UCS. And they ascribed this to the cementitious reactions, in which higher water/cement ratio 86 impaired the strength development. As a result, these contradictory results could not lead to a 87 defined recognition on the determination of optimum IWC in soil stabilization and there was not 88 enough information in the existing research to explain the reason why the IWC affect the strength 89 evolution of the stabilized soils.

90 Herein, the objective of this study is to investigate the effects of IWC on the machinal properties 91 (compressibility and strength), microstructure and composition of a lean clay soil stabilized by 92 compound calcium-based stabilizer comprised of cement, lime and fly ash, and explain how the 93 microstructure and composition variation of the soil-stabilizer mixture with different IWCs affect the 94 mechanical properties. To achieve this objective, a series of static compaction test, unconfined 95 compression test, optical microscope observations, Environment Scanning Electron Microscope 96 (ESEM) scanning, Environment Scanning Electron Microscope combined with Energy Dispersive X-97 Ray (ESEM-EDAX) analysis and X-Ray Diffraction (XRD) spectra analysis were conducted.

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Hopefully, the results of this manuscript can help in the determination of optimum initial watercontent of soil stabilization practice.

- 100 2. Materials and Methods
- 101 2.1. Material Properties
- 102 2.1.1. Soil

The soil used in the tests is a natural yellowish-brown muddy soft soil taken from the bottom of a 1.5m deep borrow pit near Hangzhou, China, which does not contain large particles of sand or gravel. After drying in the oven at the temperature of 105 $^{\circ}$ C for 3 days, the soil is pulverized to pass No. 4 (4.75mm) sieve and deposited in a sealed plastic drum for the tests. The particle size distribution of the dried soil is shown in Figure 1. Table 1 shows the physical properties of the soil. According to the Unified Soil Classification System (ASTM D2487-2017[43]), the soil is classified as lean clay (CL) type. The XRD pattern shown in Figure 2 indicates that the soil mainly contains clay minerals of

110 clinochlore, montmorillonite, and illite; and other minerals such as quartz and muscovite.



Figure 1. Soil particle size distribution.

Figure 2. Mineral composition of the soil.

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Table 1. Physical properties of soil sail	nple.
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Natural dry density (g/cm ³)	Dried moisture content (%)	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Activity of clay	рН
1.64	2.94	2.69	37.8	19.3	18.5	2.02	6.55

112 2.1.2. Compound Calcium-based Stabilizer

113 The calcium-based stabilizer used in the study is composed of cement, lime and fly ash. The 114 cement is Type 325 Ordinary Portland cement, which is produced by local Qianchao Portland Cement 115 Company (Hangzhou, China). The lime used in the research is provided by Hangzhou Tuohai 116 Corporation (Hangzhou, China), which is a finely grounded lime powder with 85% total content of 117 CaO and MgO. The fly ash is high calcium Class C fly ash obtained from Shaoxing Shangyu 118 Hangzhou-union cogeneration Co., Ltd (Shaoxing, China). Table 2 presents the chemical composition 119 of the three additives. The particle size distribution of the mixed calcium-based stabilizer is shown in 120 Figure 3.

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Table 2. Chemical composition of the calcium-based stabilizers.

	Materials	Chemical Compositions (Mass Fraction, %)	
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	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	TiO ₂	SO ₃
PC									
_	18.04	8.79	4.96	54.14	0.12	0.32	3.56	-	1.77
L	-	-	-	86.26	-	-	0.68	-	-
FA	11.61	21.73	1.75	40.28	0.95	1.36	0.49	1.66	0.61
	me percentage (%)								
		/			10		00		
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122 123

Figure 3. Particle size distribution of compound calcium-based stabilizer.

125 2.2. Experimental Program

126 The experimental program includes two parts. First the effects of IWC on the compaction 127 properties and UCS of the soil calcium-based stabilizer mixture were investigated by static 128 compaction tests and unconfined compression tests. Then, the variation of microstructure and 129 composition of the mixture with different IWCs were studied by optical microscope observation, 130 ESEM scanning, ESEM-EDAX analysis, and XRD spectra analysis.





Figure 5. pH variation with cement content.

132 2.2.1. Mixture Design

133 As is shown in Table 1, the soil is slightly acidic with a pH of 6.55. According to former studies 134 [44, 45], cement cannot fully hydrate and harden to form CSH and CAH gels until the pH arrived at 135 a certain value. Therefore, we conducted a series of pH tests using the method presented by Eades

136 and Grim[46] to determine reasonable initial lime and cement content. Figure 4 shows that lime at

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the weight of 1% dry soil can promote the pH of soil slurry up to 12.3 and after that the increase of 137 138 lime content cannot change pH significantly, so the initial lime content was 1% weight of dry soil. 139 Figure 5 indicates that in the cement content range studied, when cement content reaches 4%, the pH 140 value of diluted cement slurry is stable and the cement-soil slurry curve is not far from that of cement-141 soil slurry. Thus 4% weight of dry soil was chosen to be the initial cement content. The content of fly 142 ash which aims to provide pozzolans was set to be 1% weight of dry weight. Considering that fly ash 143 can consume a certain amount of lime by pozzolanic reaction, the lime content was accordingly 144 adjusted to 2% weight of dry soil. Consequently, the mixture was designed to be cement: lime: fly 145 ash: dry soil equal to 4: 2: 1: 100. Afterwards, we conducted a series of unconfined compressive tests 146 with four different combinations of cement, lime, fly ash, and dry soil (4:1:1:100;4: 2: 1: 100; 3: 3: 1: 147 100; 2: 4: 1: 100). The results show that the combination with cement: lime: fly ash: dry soil equal to 4: 148 2: 1: 100 has the highest unconfined compressive strength, thereby adopted as the final mixture 149 proportion for the tests.

150 2.2.1. Molding Points Design

151 As the reference point, the maximum dry density and optimum moisture content of the mixture

152 were tested to be 1.79g/cm³ and 15 %, respectively, by modified Proctor compaction test (Figure 6).
153 Specimens with different IWCs (11%, 13%, 15%, 17%, 19%, 21%) and two dry densities,

Specimens with different IWCs (11%, 13%, 15%, 17%, 19%, 21%) and two dry densities, 1.79g/cm³(100% compaction degree) and 1.72 g/cm³ (96% compaction degree), were made for the

154 1.79g/cm³(100% compaction degree) and 1.72 g/cm³ (96% compaction degree), were made for the 155 tests. The molding points (line A and B) are shown in Figure 6. For each dry density and water

156 content, there are 30 parallel specimens.



157

Figure 6. Modified Proctor compaction curve and the molding points.

158 2.2.2. Specimens Molding Procedures

159 The specimens made in the study were cylindrical, 50mm high and 50mm in diameter. During 160 the molding process, each specimen was strictly made according to the following molding 161 procedures:

• First, the water contents of the oven-dried soil and the calcium-based stabilizer were measured.

- Then, the amount of dry soil and stabilizer needed for 6 specimens (controlled by the blender used) was calculated, weighed and mixed by the blender for about 5 minutes until the dry mixture is uniformly consistent.
- Next, the calculated volume of water was added and mixed for another 5 minutes until a homogenous soil-stabilizer mixture formed. After that, the mixture was carefully covered with a sealing film to prevent moisture loss.
- Finally, the quantity of the mixture for one specimen was weighed and put in the mold that had
 two cylindrical compaction blocks.

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171 2.2.3. Static Compaction Test

172 The compaction test was performed on a 30kN hydraulic pressing machine. After being filled 173 up, the mold was rapidly moved on the pressing machine to be statically compacted. The compaction 174 process was displacement-controlled with a displacement rate of 1mm/min. During the compaction 175 process, the compaction data of all specimens were recorded in detail by the sensors (sampling 176 frequency of 50Hz) installed on the pressing machine. When the specimens were compacted to the 177 designated dimension of 50mm high and 50mm in diameter, the load was kept stable for two minutes 178 before unloading. Then, the specimens were demolded and the mass, height and diameter of each 179 specimen was measured and documented.

180 2.2.4. Specimens Curing Process

181 To make comparisons, after compaction half of the specimens were placed in plastic sealing bags 182 to avoid external moisture intrusion and the other half were not treated. Then all the specimens were 183 transferred to the curing room with temperature at 20 ± 1 °C and humidity at $95\pm5\%$. Each 6 specimens 184 (3 in bags and the other 3 without bags) were marked as a group. Thus, specimens with the same 185 IWC and dry density were divided into five groups which were respectively cured to 1, 3, 7, 14 and 186 28 days. In order to only investigate the effects of IWC, all the specimens were kept as what they were

187 after different curing ages and did not submerge into water to saturate.

188 2.2.5. Unconfined Compression Test

189 The unconfined compression tests were conducted on the 30kN hydraulic pressing machine at 190 a displacement rate of 1mm/min according to ASTM D2166[47]. Before the unconfined compression

191 test, the mass, height and diameter of each specimen were measured again.

192 2.3. *Microstructure and Composition Research*

After the compression test, all the tested specimens were submerged into anhydrous ethyl alcohol for 1 days and oven-dried at 70 °C for another day to terminate the hydration process. Small parts from the unbroken district of the specimens were carefully taken out for microstructure and composition research.

197 2.3.1. Optical microscope observation

To quickly and simply investigate the structure change of the dried soil, calcium-based stabilizer, and soil-stabilizer mixture with the variation of IWC in real time, the optical microscope observation was performed. The optical microscope used in the study is Lecia DM750 equipped with Leica ICC50 digital camera module, which can readily take photos and preserve the images. During observation, the soil, stabilizer, and the mixture were evenly placed on an object slide as a thin layer and there was not a coverslip on them. To protect the microscope, the object lens cannot be pushed too close and thus the magnification times was limited to 40.

205 2.3.2. ESEM scanning and ESEM-EDAX analysis

The morphological structure of the specimens cured in plastic bags, in a much smaller scale than that of optical microscope, was obtained by ESEM scanning. The ESEM used here was FEI Quanta 650 FEG with an acceleration voltage range of 200V - 30kV and maximum beam current of 200nA. The ESEM was also equipped with an EDAX detector, by which the element composition of the designated points of the specimens was acquired.

211 2.3.3. XRD analysis

The mineral change of the specimens with different IWC at different curing ages was analyzed by means of powder XRD. The XRD patterns were collected by PANalytical X'Pert PRO

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214 diffractometer with Cu-K α radiation (λ =1.5418 Å); exploration range 5° to 80° 2 θ ; steps of 0.026 °2 θ ; 215 and goniometer speed of 0.001 °2 θ s⁻¹.

216 **3. Results**

217 3.1. Static Compaction Test Results

218 Although there are some differences among each curve even in the same IWC group, typical 219 compaction curves of specimens with different IWCs are shown in Figure 7. The small horizontal 220 arrows on the curves mark the points where the specimens are compacted to the designated 221 dimension. The curve for IWC at 21% doesn't have an arrow because the specimens were saturated 222 during compaction and couldn't be fully compacted. Figure 8 shows that as the IWC increases from 223 11% to 19%, the maximum compaction force decreases from around 17kN to 12kN, while the total 224 axial deformation increases from about 29mm to 34mm. The slope of each curve, which reflects the 225 soil stiffness under different stress states, also varies slightly with different IWCs. Figure 8 shows the 226 secant slopes from original point to points of half maximum compaction force. It indicates that the 227 mean stiffness of the soil decreases in the form of cubic function as IWC increases from 11% to 19%.





Figure 8. The effect of IWC on secant slope.



228 Figure 9. Results of static compaction test: (a) maximum compaction force; (b) compaction energy.

To better understanding the effects of IWCs on the compaction properties of the mixture, the maximum compaction force (Figure 9 (a)) and compaction energy (Figure 9 (b)) of two groups of specimens at 100% compaction degree are further analyzed. The compaction energy is computed by the integral of the compaction curve with the equation:

$$E_c = \sum_{i=1}^n 0.5(F_i + F_{i-1})(x_i - x_{i-1}), \tag{1}$$

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- 233 where the E_c is the compaction energy; F_i and F_{i-1} are the number *i* and *i*-1 compaction force, 234
- respectively; x_i and x_{i-1} are the number *i* and *i*-1 displacement recorded by sensors.
- 235 It is observed that both the maximum compaction force and compaction energy decrease linearly 236 with the increase of IWC. The largest decline percentages for the maximum compaction force and
- 237 compaction energy are calculated to be 45.9% and 53.4%, respectively.
- 238 3.2. Unconfined Compression Test Results
- 239 Figure 10 presents the relationship between UCS and IWC at different curing ages (1d, 3d, 7d, 240 14d and 28d) under two curing conditions (with and without external water) and two degrees of 241 compaction (100% and 96%). The test results for specimens cured without external water supply are 242 shown in Figure 10(a) (100% compaction degree) and Figure 10(b) (96% compaction degree). Both of
- 243 the two figures show the same variation trend of UCS regardless of the compaction degree:
- 244 At early curing age (1 day and 3 days) the UCS decreases linearly as IWC increases from 11% to 245 19%;
- 246 b) After curing for 7 days and 14 days, the UCS value does not change significantly with the 247 variation of IWC;
- 248 Through a curing time of 28 days, a parabolic relationship between UCS and IWC can be c) 249 observed: the UCS first increases and then decreases with the increase of IWC, reaching peak 250 value at 15% IWC, which is equal to the optimum water content derived from the modified 251 Proctor compaction test.



252 Figure 10. Effects of initial water content on unconfined compressive strength of specimens cured in 253 plastic bags: (a) dry density 1.79 g/cm³; (b)dry density 1.72 g/cm³.



254 Figure 11. Effects of initial water content on unconfined compressive strength of specimens cured in 255 moist air.

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Additionally, it can be found that in the first 7 days the UCS develops fast and the increase rate of UCS accelerates with higher IWC; but afterwards the strength development gets slow and the increase rate first enlarges then reduces in the variation range of IWC, reaching maximum at 15% IWC.

- As a comparison, Figure 11 presents the unconfined compression test results for specimens cured in moist air. It can be clearly found that after a curing time of 14 and 28 days, for specimens
- 262 with 96% degree of compaction, the highest UCS value is obtained when the IWC is 15%, which
- 263 equals the optimum water content of modified Proctor compaction test; whereas under 100% degree
- of compaction, the specimens compacted at lower IWCs (11% and 13%) tend to have higher UCSs.



Figure 12. Structure of wet soil (left) and dry soil (right). Figure 13. Stabilizer on the surface of water.

266 3.3. Optical Microscope Observations

267 Figure 12 shows the comparison of the structure of wet soil and dry soil. When the soil is oven-268 dried to the water content about 3%, smaller particles and aggregates are generally attracted to the 269 surfaces of larger ones by attractive forces (mainly electrostatic forces according to former research[1, 270 48]), forming a spatial and porous structure. However, after water intrusion into the dry soil, the 271 original structure immediately breaks down to a dispersed fabric with clearer particle boundaries 272 and better transparency. When part of the wet soil is moved with the tip of toothpick, the adjacent 273 soil particles do not move. However, when the dry soil is moved in the same way, the adjacent soil 274 matric particles and aggregates in a certain distance move together. This optical microscope 275 observation indicates that water can decrease the attractive force between soil particles and make the 276 soil structure easier to change.



277 278

Figure 14. Reaction products of calcium-based stabilizer (the red arrows pointing); (a) reaction time of 0.5h; (b) reaction time of 2h.

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279 Another interesting phenomenon from . Figure 13 is that when the water boundary gets close to 280 the dry soil, the whole aggregate will be fast pulled into the water, while when the water boundary 281 is approached to the stabilizer in the same way, the stabilizer particles are difficult to be attracted into 282 the water and some of them are even just absorbed on the water surface. According to the theory of 283 surface thermodynamics[49-51], this phenomenon indicates that the soil particles have higher surface 284 energy than the stabilizer particles and can be more easily wetted by water.

285 Figure 14 exhibits some reaction products of the stabilizer and it seems that the reaction products 286 tend to mainly formed on the boundary of the water.

287 3.4. ESEM Scanning and ESEM-EDAX Analysis

288 The microstructure of the specimens was investigated by ESEM scanning (Figure 15). The results 289 show that as the IWC increases, the number of large aggregates and agglomerations reduces while 290 the quantity of individual particles increases; and in turn the number of large inter-aggregate pores 291 decreases, leading to the soil structure getting fine and dense (Figure 15(a)~(d)). In addition, it is 292 observed that in 1day- and 3 day-specimens, the hydration products are too few to be easily found. 293 Only in specimens curing for 7 days will the hydration products of the calcium-based compound 294 stabilizer start to obviously come up. Furthermore, owing to the hydration products mainly 295 generating in the pores of soil matric particles, specimens with higher IWCs which have a more 296 dispersed pore structure seem to have a much more homogeneous structure (Figure 15(b), (d)).



(c) (11%, 7d, magnification: 1000x)

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(e) (11%, 7d, magnification: 6000x)

(f) (17%, 7d, magnification: 6000x)



Figure 15. Effects of initial water content on microstructure.

During the ESEM scanning process, we also used EDAX to identify the element composition of the hydration products in different areas of the specimens (Figure 16(b), (d)). It is found that though the hydration products (which are already known as CSH and CAH) mainly compose of oxygen, silicon, aluminum, and calcium, the percentage of each element in different scanning spots varies a lot even in the same specimen. However, generally, it seems that for the hydration products of specimens with higher IWC, the percentage of oxygen element tends to be a little higher, probably because more free water transforms into structural water during the hydration process.



Figure 16. Effects of initial water content on chemical composition.

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306 3.5. XRD Spectra Analysis

307 Figure 17 presents the results of XRD analysis. It can be found that with different IWCs at various

308 curing ages, the crystalline minerals (principally quartz and muscovite) in the specimens do not

- change obviously, whereas the characteristic peaks of clay minerals get smaller or even disappear.The expected dispersed characteristic peaks of amorphous hydration products, CSH and CAH, are
- The expected dispersed characteristic peaks of amorphous hydration products, CSH and CAH, are not obvious, which maybe attribute to the relatively small addition of calcium-based compound
- 312 stabilizer and insufficient crystallization time.





Figure 17. Effects of initial water content on mineral composition.

314 4. Discussions

Combining the mechanical property study with the microstructure and composition research, the effects of initial water content on the soil-stabilizer mixture studied can be revealed as follows.

317 4.1. The effects of initial water content on the compaction process

318 The results of optical microscope observation identify the foundational effect of the molding 319 water: it breaks down the soil aggregates and agglomerations into individual particles and make the 320 soil structure more easily to be changed. This is also confirmed by other researches[52-54] and can be 321 explained by the diffused double layer (DDL) theory. More water enlarges the thickness of the DDL 322 of the soil particles and even free water will come up, lessening the shear resistance of the soil. As a 323 result, on the scale level of the whole mixture, the stiffness of the mixture declines (Figure 8) and if 324 there is no excess pore water pressure, it will need less force and energy to densify the mixture, which 325 is testified by the static compaction test (Figure 9). In the meanwhile, more water in the mixture means 326 more individual soil particles exists and thus during densification process, small particles can more 327 easily move to the pores between larger particles or aggregates to minify the pores, which was 328 identified by the ESEM scanning (Figure 15) and other relevant researches[52, 55-57]. Therefore, right 329 after compaction, the specimens with different IWCs have different original structures: specimens 330 with higher initial water content have less aggregates and agglomerations, and smaller proportion of 331 large pores.

332 4.2. The effects of initial water content on the strength development

During curing process, the water reacts with the calcium-based stabilizer to produce the bonding gels. Specimens with different IWCs have different reaction rates (Figure 10 and Figure 11). The produced gels change the mixture structure to yield different UCS at different curing ages for different specimens. The UCS is just the reflection of the structural properties of the mixture at a

337 certain time.

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338 For the specimens cured without external water, in the earlier days (1 day and 3 days) of curing 339 process, the stabilizer has not fully reacted and the mixture structure mainly maintained what they 340 were after compaction, which is confirmed by the ESEM scanning. Thus, the strength of the mixture 341 is principally dependent on the strength of the soil structure, which is controlled by the average 342 thickness of the water membrane (DDL and free water). As initial water content increases, the average 343 water membrane is thicker. Consequently, the UCS decreases linearly with the increase of IWC as 344 shown in Figure 10 and Figure 11. However, as water content increases, there is a bigger probability 345 to form continuous water passage, which facilitates the cation exchange, dissolution and diffusion 346 process of the soil-water-stabilizer reaction system and thus, the increase rate of UCS in the first 7 347 days is higher for the specimens with higher IWC. The UCS value does not change significantly with 348 the variation of IWC at the curing age of 7 days. After that, as the pores are gradually filled by reaction 349 products and free water is lacking, the increase rate for all the specimens decreases.

At 28 days curing age, for specimens with lower IWC, there are more large pores and some of them cannot be fully filled and bonded (Figure 15(a), (c)); while in the specimens with higher IWC, though a more homogeneous structure is observed (Figure 15(b), (d)), higher IWC excessively destroy the soil structure and more free water remain in the water membrane of the soil particles. These may be why the UCS first increases and then decreases with the increase of IWC at 28 days curing age.

355 For the specimens cured in moist air, the water is continuously supplied by external water source 356 until the specimens were saturated. Therefore, the inherent aggregates and agglomerations of the soil 357 can be totally wetted during the curing process and the strength contribution of soil structure are 358 weakened. As a result, at the same compaction degree, the UCS of specimens cured in moist air 359 significantly reduced compared to that of specimens cured without external water. Under different 360 compaction degrees at the same curing age, the UCS variation with IWC is different (Figure 11) and 361 this may be attributed to the different original structures after compaction. It can be speculated that 362 there must be an optimum original mixture structure corresponding to certain initial water content 363 under different compaction degrees that is beneficial to the strength development, which needs 364 further investigation.

From the discussions above, it can be concluded that the determination of IWC in soil stabilization practice should consider three issues: compaction, curing environment, and the targeted value of specific engineering properties; rather than only compaction. It is recommended that when a soil is stabilized by a stabilizer that can react with water, for a given dry density and a given curing environment, a series of IWCs should be tested to find the appropriate compaction energy and the optimum IWC.

371 5. Conclusions

Initial water content is an important factor affecting the engineering properties such as strength,
 stiffness and compressibility of the soil stabilized by the calcium-based stabilizer in the research. The
 following conclusions can be drawn from the study:

- In the range of initial water content studied, both the compaction energy and the maximum
 compaction force decrease linearly with the increase of initial water content, and the largest reduction
 is 53.4% and 45.9%, respectively.
- As the initial water content increases from 11% to 19%, there are less soil aggregates or agglomerations, and smaller proportion of large pores in the mixture structure after compaction.
- For specimens cured without external water supply, regardless of the compaction degree, after a curing age of 28 days, the highest unconfined compressive strengths were acquired at initial water content of 15%, which equals to the optimum water content derived from the modified Proctor compaction test. Higher initial water content enlarges the increase rate of the unconfined compressive strength in the first 7 days; after that, the increase rate first increases then decreases, and acquires maximum at initial water content of 15%.
- For specimens cured in moist air, the optimum initial water contents are 11% under 100% compaction

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- degree, and 15% under 96% compaction degree, respectively.
- As the initial water content increases, the percentage of oxygen element tends to increase in the
 reaction products of the calcium-based stabilizer.
- The crystalline mineral of the soil did not change obviously with the variation of initial water content.

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