Influence of Organic Content on the Mechanical Properties of Organic-Rich Soils Stabilized with CaO-GGBS Binder and PC

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Abstract: Organic-rich soil is a typical special soil often encountered in foundation treatment. Previous research has revealed that Portland cement (PC) not only pollutes the environment but is significantly affected by organic matter during its hydration and cementation. Although quicklime (CaO)-GGBS binder (CG) is an effective alternative to PC, its efficiency in treating organic-rich soils has not been studied. In this study, organic-rich soil was treated with two binders of CG and PC. The physical, mechanical, and chemical characteristics of the stabilized soils were tested at various organic contents, binder contents, and curing ages. The results show that the cracks in two treated soils increase with the increase in organic content and the reduction in binder content. CG-treated soils are more likely to shed big lumps after damage than PC-treated soils. The unconfined compressive strength (q_u) and deformation modulus (E_{50}) of stabilized soils increase with the increasing curing age and binder content but the decreasing organic content. The E_{50} of PC-treated soil is about 22~73 times q_u, and the E_{50} of CG-treated soil shows an excellent linear relationship with q_u. The moisture content of two treated soils increases as the organic content grows, but it falls as the curing age and binder content increase. The soil pH rises with the increasing organic content and binder content, but it declines with increased curing age. The strength development of organic-rich soils treated by the CG binder has an evident attenuation with the organic content. Given its possible environmental benefit, alkali (especially low calcium)-activated binder is appropriate for practical engineering with modest strength needs.

Keywords: CaO-GGBS binder; PC; organic-rich soil; sodium humate; unconfined compressive strength

1. Introduction

The treatment of soft soil has been a challenging subject in geotechnical engineering, partly because there is high content of organic matter (OM) in soft soil [1,2]. A small amount of OM has a minimal effect on soil improvement. However, when the amount of OM in the soil surpasses a particular level, the OM will have a significant negative impact on the engineering characteristics of soft soil. In geotechnical engineering, the soil containing 5 to 20% OM is named organic soil, while the soil containing more than 20% OM is known as peat or muck [3]. OM contributes to the poor engineering properties of organic soils, such as low strength, high water content, and high compressibility [4,5]. As a result, foundation soil with a high content of OM cannot be utilized directly in engineering construction [6]. Furthermore, approximately 42,000 km^2 of land contains OM in China, and organic-rich soil is common in geotechnical engineering, which makes it critical to investigate a treatment approach for organic-rich soil [7,8].

In recent years, the solidification/stabilization technique has been increasingly applied to the improvement and reinforcement of special weak soil because there is no need to

excavate and buy high-quality gravel fillers to replace it. In the solidification/stabilization of soft soil, Portland cement (PC) is one of the significant cementitious materials due to its simple and convenient construction. The strength gain of the PC-stabilized soils is primarily attributed to the formation of cementitious materials such as calcium silicate hydrates. However, PC, widely used in the solidification of soft soil, fails to achieve the desired effect in treating organic-rich soils [9]. For example, Hélène et al. [10] used PC to treat 13 soils with various types of OM (OM = 10%). The results showed that the presence of OM significantly hampered the production of hydration products and the strength development of the treated soils if the pH of the pore liquid was lower than 9.0. Kolay et al. [11] observed that the strength of the stabilized peat soil grew with an increase in the binder dosage and curing age when the natural peat soil with approximately 42~96% OM was mixed with a mixing binder of fly ash, quicklime, and PC. Wang et al. [12] used PC, lime, and fly ash to treat the natural marine silt (approximately 4.7% OM). The results showed that the stabilized soil gradually changed from plastic to brittle according to the stress–strain relationship. Moreover, the essential issues related to the high energy consumption and carbon emissions of PC production are also often considered in the engineering application of PC. According to statistics, the generation of each ton of PC is associated with 5000 MJ of energy consumption and ~0.95 tons of CO_2 emission, accounting for more than 5% of all anthropogenic global emissions [13,14]. Therefore, it is necessary to seek a low-carbon and effective material to replace PC in treating organic-rich soil [15,16].

The resource utilization of industrial by-products has attracted extensive attention in geotechnical engineering, among which ground granulated blast furnace slag (GGBS) is the most widely used [17]. In contrast to PC, GGBS as a single binder has a relatively slow natural hydration rate and low efficacy, frequently exhibiting low early strength [18,19]. Numerous studies demonstrated that alkaline substances (such as PC, CaO, NaOH, MgO, Na_2CO_3, and $Na_2O \cdot nSiO_2$) could effectively improve the chemical activity of GGBS [15,17,20], and quicklime (CaO) has been proved to activate GGBS well [21]. When the CaO-GGBS binder was used to stabilize the marine sediment, lower water content and higher strength were produced compared to PC [21]. The sulfate-bearing soil (>10,000 ppm) stabilized with lime gained more than three times the expansion potential compared to natural soil, but its flexibility and expansion capability was enhanced when it was treated by the CaO-GGBS binder [22]. The good effect of the CaO-GGBS binder was attributed to the fact that CaO sped up the hydration of GGBS and the early strength development, whereas GGBS partially prevented CaO from expanding throughout the treating process, which was also confirmed by Sujit et al. [23].

Although previous studies demonstrated that the CaO-GGBS blend could be used as a binder for the solidification of soft soil, the impact of organic matter (OM) on the solidification of soft soil has not been studied up until now. Natural OM contains complex components and categories, which brings great challenges to treating organic-rich soil with CaO and GGBS. Therefore, two binders of PC and CaO-activated GGBS were utilized in this investigation to treat the synthetic organic-rich soil. The mechanical properties, including unconfined compressive strength and deformation modulus, were evaluated, and then the strength development was explained by various physical, mechanical, and chemical properties. The results have essential engineering significance for optimizing the selection of curing agents and widening the treatment methods of organic-rich soil.

2. Materials and Methods

2.1. Materials

The soil used in this investigation was obtained from the Nanjing Forestry University campus in Nanjing, China. Table 1 displays the basic physical–chemical properties of natural soil. The natural moisture content of the soil (the weight ratio of water to dry soil) was determined by drying it in a 105 °C oven for 24 h. The Atterberg limits (including the liquid limit and the plastic limit) were measured by a liquid–plastic combined tester according to ASTM D4318-17e1 (2017). The specific gravity was measured by a pycnometer

method according to ASTM D854-14 (2014). The grain size distribution was measured by a Mastersizer 2000 laser diffractometry analyzer from UK. The soil was classified as low-liquid silty clay according to its Atterberg limits and grain size distribution (ASTM D2487-17e1, 2017). The soil pH of the pore liquid was measured by a portable AS218 pH meter based on ASTM D4972-19 (2019). The quicklime (CaO) used in this study was acquired from Xinyu City in Jiangxi Province, China. Ground granulated blast furnace slag (GGBS) with S95 grade was produced by water purification Material Co., Ltd. in Gongyi city, Henan Province, China. Portland cement (PC, 42.5#) was developed in a Jiangnan cement factory in Nanjing, Jiangsu, China. Based on the BET test, the specific surface area of CaO and GGBS was 3.63 m^2/g and 1.55 m^2/g, respectively. The primary chemical compositions of soil, CaO, GGBS, and PC, as measured by an X-ray fluorescence spectrometer (XRF), are shown in Table 2. Humic acid was the primary component of OM in natural organic soil, and sodium humate (HA-Na) belonged to humic acid with good solubility [24,25]. Therefore, sodium humate (HA-Na) was chosen as an organic matter supplement in this study to make the organic-rich soil closer to its natural state. Sodium humate, a black powder with 85% of water solubility, contained a high content of humic acid, accounting for about 50~60% of the total weight. The appearance of all materials is shown in Figure 1.

Table 1. Physico-chemical properties of soil.

Property	Natural Moisture Content, w/%	Liquid Limit, w_L/%	Plastic Limit, w_P/%	Plasticity Index, I_P/%	Specific Gravity, G_S	Grain Size Distribution/%			pH
						<5 μm	5–75 μm	>75 μm	
Value	29.2	41.4	20.7	20.7	2.67	17.4	69.4	13.2	7.85

Table 2. Main chemical compositions of the materials.

Materials	MgO	Al$_2$O$_3$	CaO	SiO$_2$	Fe$_2$O$_3$	SO$_3$	K$_2$O	TiO$_2$
Silty clay	1.22	10.22	6.41	71.76	3.57	0.27	2.16	0.65
CaO	2.62	0.71	94.00	1.59	0.14	0.67	0.09	-
GGBS	6.01	10.70	34.00	34.50	1.03	1.64	0.60	0.95
PC	5.9	5.53	62.0	18.3	2.69	4.31	0.69	0.18

(**a**) (**b**) (**c**) (**d**) (**e**)

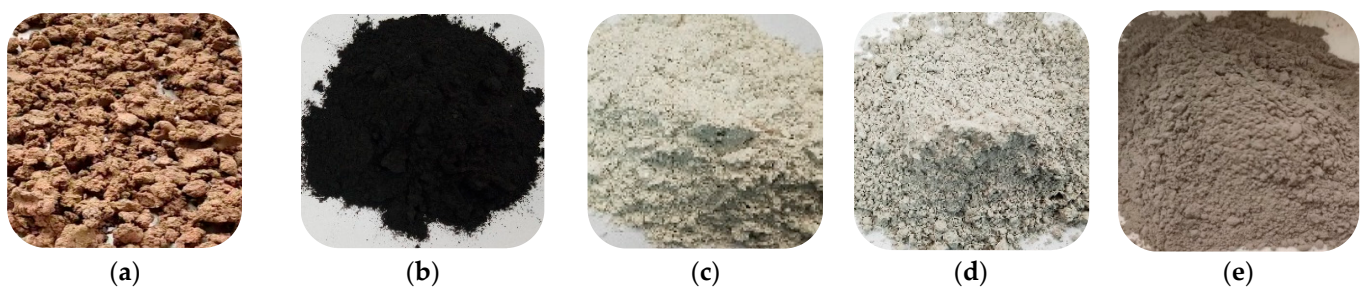



Figure 1. Appearance of all materials. (**a**) Soil, (**b**) OM, (**c**) CaO, (**d**) GGBS, and (**e**) PC.

2.2. Test Scheme

According to the Code for Investigation of Geotechnical Engineering (GB50021-2001), the soils with more than 5% of OM were defined as organic soil. However, some literature showed that the soils with 2~6% OM were also categorized as low organic soils [1,3]. Therefore, three variables of 0%, 3%, and 6% were set to investigate the stabilization effect of OM content on organic-rich soils in this study. According to previous research, PC with a content of 5–30% was frequently used to stabilize organic-rich soils [26]. As a result, the two binders, PC and CaO + GGBS, were used, respectively, to stabilize the synthetic organic-rich soils, and binder dosages of 10%, 15%, 20%, and 25% were used to determine the treatment outcome of organic-rich soil. Then, the curing age was set as 7 d, 28 d, and 56 d. Moreover, the initial moisture content and the CaO to GGBS ratio were set as 30% and

0.25, respectively. The specific test scheme is shown in Table 3, where PCBxOy represents the samples containing x% PC binder and y% OM in the soil, while CGBxOy represents the samples containing x% CG binder (i.e., 20% CaO + 80% GGBS) and y% OM.

Table 3. Test scheme under different conditions.

No.	Binder	Binder Content/%	Organic Matter Content/%	Curing Age/d
PCB20O0	PC	20	0	7/28/56
PCB20O3	PC	20	3	7/28/56
PCB20O6	PC	20	6	7/28/56
CGB20O0	CaO + GGBS	20	0	7/28/56
CGB20O3	CaO + GGBS	20	3	7/28/56
CGB20O6	CaO + GGBS	20	6	7/28/56
PCB10O6	PC	10	6	7/28/56
PCB15O6	PC	15	6	7/28/56
PCB20O6	PC	20	6	7/28/56
PCB25O6	PC	25	6	7/28/56
CGB10O6	CaO + GGBS	10	6	7/28/56
CGB15O6	CaO + GGBS	15	6	7/28/56
CGB20O6	CaO + GGBS	20	6	7/28/56
CGB25O6	CaO + GGBS	25	6	7/28/56

2.3. Specimen Preparation and Test Method

The soils were first dried in a 105 °C oven, crushed, and screened through a 1 mm sieve. Then, the dry ingredients, including soil, OM, CaO, and GGBS, were thoroughly mixed based on the specified proportion of each component. Next, the tap water was weighed and mixed with the dry mixtures evenly for 5 min. After that, the wet mixture was layered and packed three times into a mold with an inner diameter of 50 mm and a height of 50 mm. There were three parallel samples for each parameter, and the unmoulded samples were placed in a curing box (temperature of 20 ± 5 °C, relative humidity of 50%) for 3-day curing. After that, the samples were removed from the mold and placed in the curing box for the specified curing periods. After the specified curing ages, the specimens were removed from the curing box, and their weight, diameter, and height were measured to evaluate the changes in density and volume. Next, according to ASTM D2166M-16 (2016), the unconfined compressive strength was tested at a loading speed of 1 mm/min using a microcomputer-controlled electronic universal testing machine (CMT4204), where the failure appearance of the specimens was then documented by taking photographs. Then, small parts were removed from the damaged specimens to test the moisture content and pH. The moisture content was tested under 60 °C to prevent the volatilization of OM from organic-rich soils, and the measurement of soil pH was conducted using a portable AS218 pH meter according to a soil–water ratio of 0.5 as per ASTM D4972-19 (2019).

3. Results and Analyses

3.1. Apparent Pattern after Failure

Figure 2a,b shows the failure patterns of the CaO-GGBS and PC stabilized specimens under varying OM content and binder dosage, respectively. It can be found from Figure 2a that the width of the surface crack increases with the increase in OM content when the specimens reach failure. This indicates that the cementation between soil particles becomes poorer as the amount of OM in the soil increases, resulting in a decrease in the overall compactness of soils. As the curing age increases, the number of cracks in the stabilized soils drops, but the depth of crack rises, suggesting the failure mechanism of the specimen from small local cracks to massive fissures. Compared with PC-stabilized organic-rich soils, the soil blocks of CaO-GGBS (CG) stabilized organic-rich specimens are easier to fall off after failure, demonstrating that PC-treated soils have higher cementation and integrity. The longer the curing age is, the more significant the brittle failure is. Figure 2b shows that

the number of side cracks on the failure specimens reduces while the width and depth of the cracks rise as the binder dosage increases. Compared with PC-stabilized specimens, the CG-treated soil produced deciduous lumps with the increase in CG dosage, showing that the rise of CG binder does not considerably improve the cementation of the CG-treated soil. After 28-day curing, more cracks and massive spalling on the specimens appeared, implying that the presence of OM hinders the development of strength.

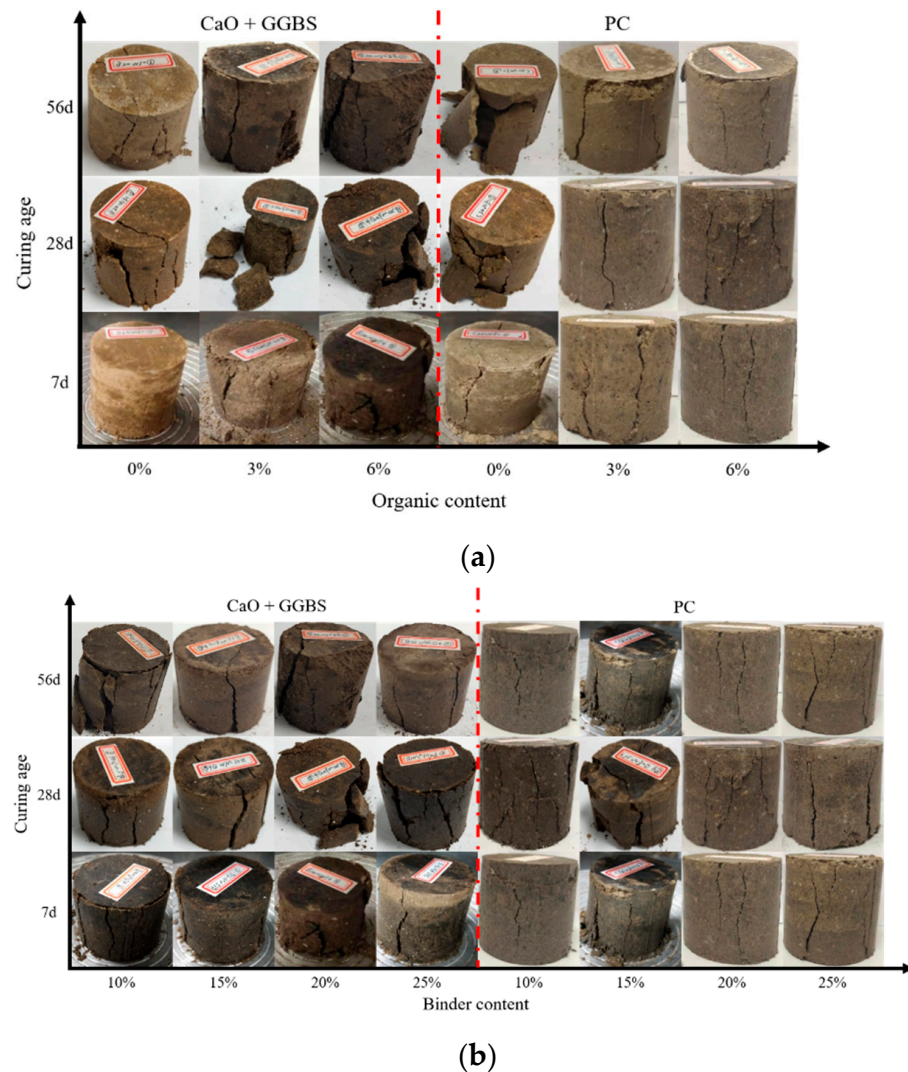



Figure 2. Surface forms of CG/PC-stabilized specimens after failure. (**a**) Influence of organic content. (**b**) Influence of binder dosage.

3.2. Mechanical Characteristics

3.2.1. Unconfined Compressive Strength

As is known to all, OM has a significant aggregation effect on the stabilized soil, leading to the uneven distribution of cementation and low strength. Hence, the mold with an aspect ratio of 1:1 was chosen for sample preparation in this investigation rather than the conventional mold with an aspect ratio of 2:1. Previous studies showed that the unconfined compressive strength (q_u) of the sample with an aspect ratio of 1:1 is approximately 1.12 times greater than that of the sample with an aspect ratio of 2:1 [27]. To facilitate the sample preparation of the low-strength organic soil, specimens with a height–diameter ratio of 1.0 were prepared to reveal the change law of strength in this study. Figure 3a,b shows the original unconfined compressive strength of the CG/PC-stabilized organic-rich soil under the effects of OM content and binder dosage, respectively. It can

be seen from Figure 3a that the unconfined compressive strength of the CG/PC stabilized organic-rich soils gradually falls with increasing OM content, and the longer the curing ages are, the higher the strength is. The main reason is that the presence of OM might prevent the hydration reaction of binders and inhibit the formation and cementation of gels, reducing the strength of the stabilized soils. Moreover, the strength of PC-stabilized organic-rich soils is higher than that of CG-stabilized organic-rich soils, and the strength gap widens as the OM content grows. The influence of OM on the two kinds of solidified soils is different, and the weakening effect of sodium humate on the CG-solidified soil is higher than that on the PC-stabilized soil. When the OM content is 6%, the strength of CG-stabilized organic-rich soils is 19%, 30%, and 45% of that of CG-stabilized soils without OM after 7-day, 28-day, and 56-day curing, while the strength of PC-solidified organic-rich soils is 76%, 82%, and 70% of PC-solidified soils without OM. The above results imply that the curing age has little impact on the strength of PC-treated organic-rich soils, but it has a significant positive impact on CG-treated organic-rich soils.

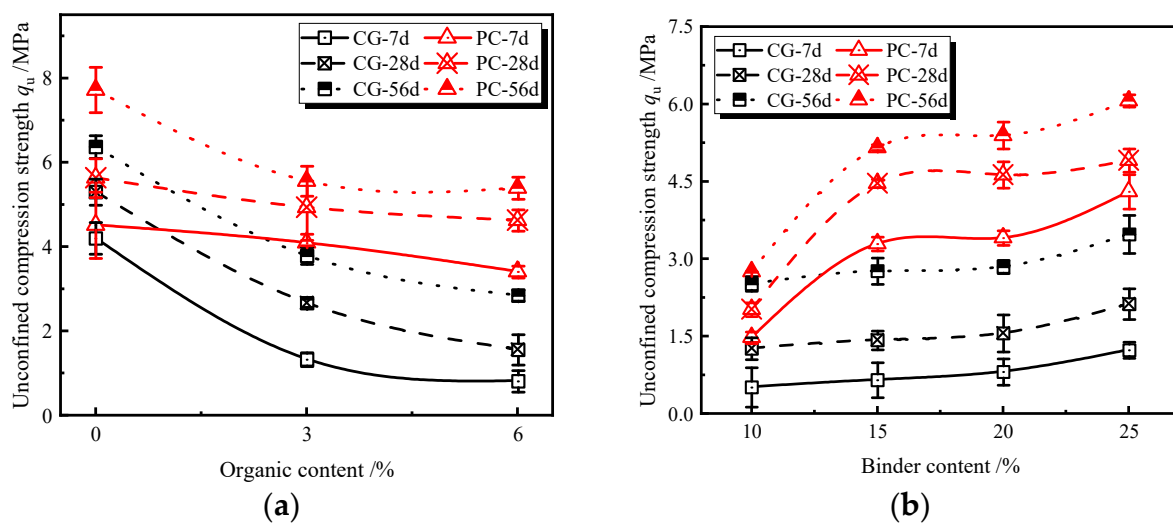



Figure 3. Unconfined compressive strength of CG/PC-stabilized specimens under different conditions. (**a**) Influence of organic content. (**b**) Influence of binder dosage.

Figure 3b describes the strength variation of CG/PC-treated organic-rich soils in relation to binder dosage. It can be found from Figure 3b that the strength of the treated organic-rich soils is significantly affected by the binder type, and it increases as the binder content rises. The strength of PC- and CG-solidified organic-rich soils rises, respectively, by ~251% and ~181% when the binder dosage increases from 10% to 25% under the same curing period. It indicates that the influence of the binder dosage on the strength of PC-treated soils is more significant than that of CG-stabilized soils. Additionally, during the variation process of strength with the binder dosage increasing, the PC-stabilized organic-rich soils mainly correspond to the change range of binder dosage from 10% to 15%, while the CG-stabilized organic-rich soils mainly occur in the change range of binder dosage from 20% to 25%. On the whole, there seems to be a critical amount of binder for the stabilization of organic-rich soils, especially for PC. When PC content exceeds 15%, the strength of the solidified soil does not increase significantly, and the impact of OM on the hydration of the curing agent is significantly diminished.

3.2.2. Stress–Strain Curves

Figure 4a,b depicts the stress–strain curves of typical PC/CG-solidified organic-rich soil specimens under the influence of OM content and binder dosage, respectively. Since the curing age has a significant effect on the stress–strain curve, the stress–strain curves after 7-day and 28-day curing are shown in Figure 4a,b, respectively. All curves show that stress increases slowly with strain, then increases rapidly, and finally decreases after the

peak. It can be found from Figure 4a that the peak stress tends to decrease with the OM content rising when the PC/CG-stabilized soil specimens approach the failure strain. When OM levels reach 6%, the stress–strain curves of PC/CG treated soils alter markedly. That is, the failure strain significantly rises, and the decline of the stress gradually becomes flat with the strain. This phenomenon may be attributed to the fact that the OM wraps the binder particles and prevents the hydration and cementation of the curing agent, slowing down the development of mechanical strength. Meanwhile, the agglomeration of OM also prevents the rapid disintegration of the stabilized samples after failure, resulting in the failure transition from brittle to ductile. It can be observed from Figure 4b that under the same binder, the failure strain of the stabilized organic-rich soils drops with the binder dosage. In contrast, the corresponding peak stress increases, suggesting that the increase in binder dosage can improve the cementation level of the stabilized samples to some extent. In addition, the stress of the CG-stabilized organic-rich soils is much higher than that of the PC-solidified organic-rich soils under the same binder dosage. In combination with Figures 2 and 3, it can be found that after the uniaxial compression test, the CG-treated organic-rich soils tend to display plastic failure, and axial deformation is more significant. However, PC-solidified soils tend to display brittle failure, with small axial deformation and large vertical cracks.

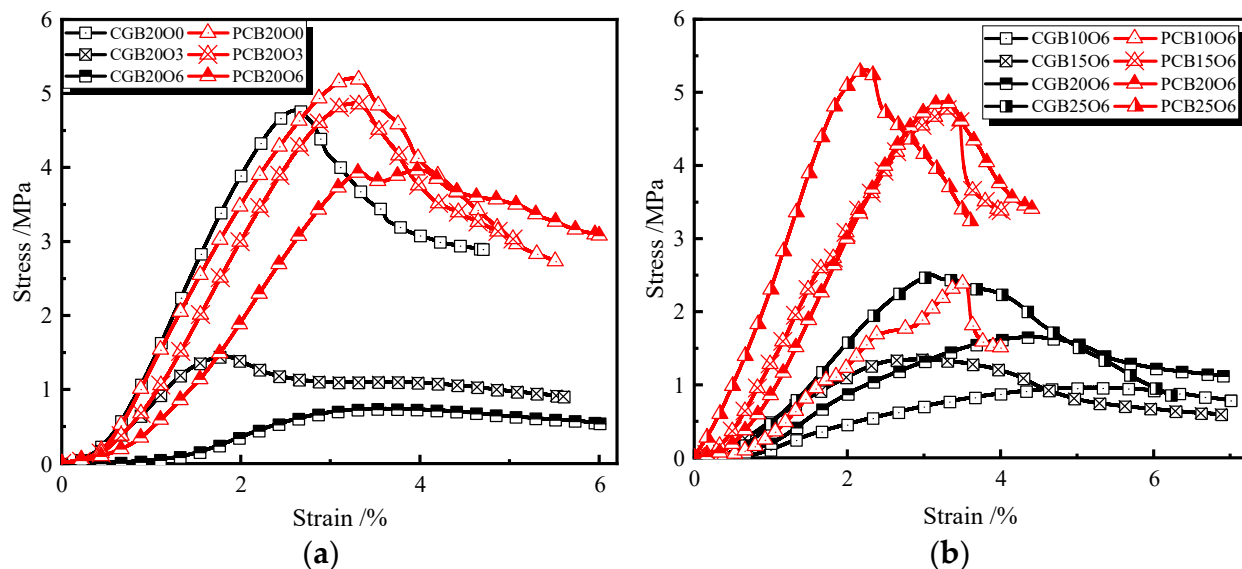



Figure 4. Stress–strain curves of CG/PC-stabilized specimens under different conditions. (**a**) Influence of organic content (7 days). (**b**) Influence of binder content (28 days).

3.2.3. Deformation Modulus

The deformation modulus (E_{50}) is an essential parameter for measuring the engineering qualities of soils and indicates soil resistance to elastoplastic deformation. The E_{50} of the stabilized soils was calculated by Equation (1):

$$E_{50} = \frac{2\sigma_{1/2}}{\varepsilon_{\mathrm{f}}} \tag{1}$$

where E_{50} is the deformation modulus (MPa), $\sigma_{1/2}$ is the corresponding stress when the failure strain reaches half (MPa), and ε_{f} is the failure strain corresponding to peak stress (%).

The calculation results of E_{50} are shown in Table 4. It can be seen from Table 4 that the deformation moduli (E_{50}) of PC/CG-treated soils decrease with the increase in OM content but increase with the binder dosage. When the soils are admixed with the same amount of OM and binder, the PC-treated organic-rich soils have larger moduli and better deformation resistance than the CG-treated organic-rich soils. Furthermore, the change in

OM content has a great effect on the moduli of the stabilized soils under the same curing age, and the influence degree decreases gradually with the curing age.

Table 4. The deformation modulus (E_{50}) of CG/PC-stabilized specimens.

Sample No.	Deformation Modulus, E_{50} (MPa)		
	7-Day Curing	**28-Day Curing**	**56-Day Curing**
PCB20O0	114.24	148.79	455.01
PCB20O3	99.55	122.95	417.99
PCB20O6	95.48	124.65	279.41
CGB20O0	204.30	253.05	256.93
CGB20O3	69.00	115.90	152.27
CGB20O6	26.52	55.79	137.96
PCB10O6	33.83	49.29	149.82
PCB15O6	73.19	122.10	248.48
PCB20O6	95.48	124.65	279.41
PCB25O6	162.09	196.08	350.85
CGB10O6	15.01	36.39	97.67
CGB15O6	29.13	56.90	113.68
CGB20O6	26.52	55.79	137.96
CGB25O6	51.40	91.35	139.47

Existing studies show that there is a proportionate relationship between the deformation modulus (E_{50}) and strength (q_u) for the treated soils [28]. Figure 5a,b shows the relationship between E_{50} and q_u of the CG and PC stabilized organic-rich soils, respectively. It can be observed in Figure 5a,b that the modulus generally increases with the corresponding strength. Figure 5a shows that the modulus and strength of the CG-treated organic-rich soils have a strong linear relationship, which is described by Equation (2). In contrast, Figure 5b illustrates that the E_{50} and q_u of PC stabilized organic-rich soils are broadly dispersed in a triangular zone. Their relationship is approximately expressed by Equation (3). The deformation moduli of the CG/PC-stabilized organic-rich soils are lower than the required values of PC-solidified soils, with 100~120 times the strength according to the Chinese Technical code for the ground treatment of buildings (JGJ 79–2012). Therefore, CG/PC-stabilized organic-rich soils can be utilized in the foundation project with low strength and deformation requirements, such as the filling project.

$$E_{50} = 43.18 \cdot q_u \left(R^2 = 0.98 \right) \tag{2}$$

$$E_{50} = (22 \sim 73)q_u \tag{3}$$

3.3. Moisture Content

Figure 6a,b shows the moisture content of the CG/PC-stabilized organic-rich soils after the different curing ages under the influences of OM and binder dosage, respectively. It can be seen in Figure 6a that the water content of the stabilized soils increases with the OM content under the same curing age, indicating that OM prevents the hydration of binders in the mixtures. Under constant OM content, the water content of both PC-stabilized soils and CG-stabilized soil considerably reduces after 7-day curing. For CG-stabilized organic-rich soils, the moisture content has a relatively slight reduction during the curing periods from 7 to 28 days, while it has a significant decrease from 28- to 56-day curing. However, the moisture content for the PC-solidified organic-rich soils remains considerably stable after 7- to 56-day curing. The changes in moisture content reveal that there are two phases of intense hydration reaction, including 0~7-day curing and 28~56-day curing when the CG binder is employed to treat organic-rich soils; in contrast, there is only one significant hydration stage for PC-solidified organic-rich soils.

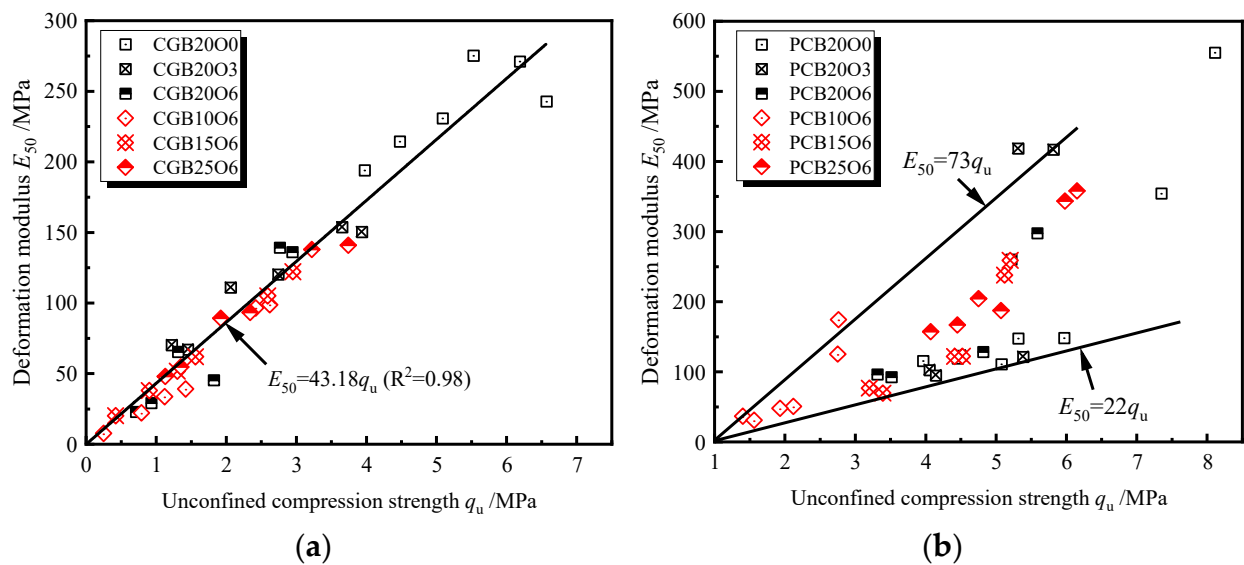



Figure 5. Deformation modulus of CG/PC-stabilized specimens under different conditions. (**a**) CG-treated soils. (**b**) PC-treated soils.

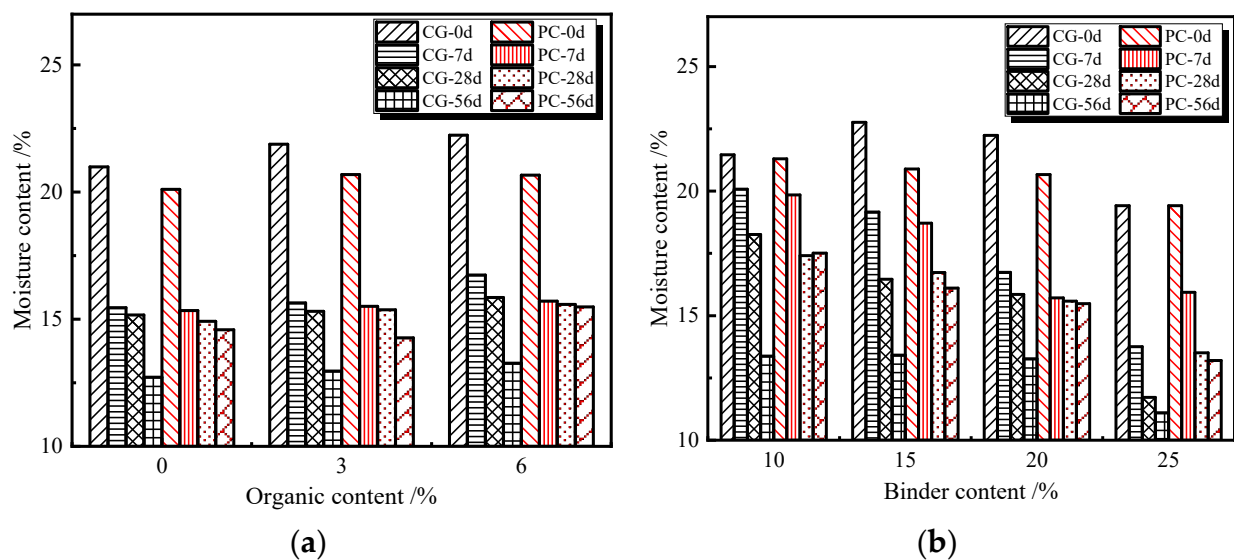



Figure 6. The moisture content of CG/PC-stabilized samples under different conditions. (**a**) Influence of organic content. (**b**) Influence of binder dosage.

It can be found from Figure 6b that under the same OM content, the moisture content of the two PC/CG-stabilized organic-rich soils decreases when the binder dosage increases. Under the same binder dosage and OM content, the moisture content of CG-admixed organic-rich soils before curing is slightly higher than that of PC-admixed organic-rich soils. As the curing age increases, the moisture content of CG-stabilized soils gradually decreases to become lower than that of PC-stabilized soils, and the moisture content of CG-stabilized soils after 56-day curing is far lower than that of PC-stabilized soils. Specifically speaking, when the CG content is 10%, the moisture content of the samples after 7-day curing is reduced by 1.38% compared to no curing and by 4.88% after 56-day curing compared to 28-day curing. When the CG content is 25%, the moisture content of the samples after 7 d reduces by 5.66% compared to no curing and by 0.62% after 56-day curing compared to 28-day curing. Similar to the results shown in Figure 6a,b, under the same binder dosage, the moisture content of CG-stabilized organic-rich soils decreases as the curing age increases. However, the moisture content of PC-stabilized organic-rich soils significantly

reduces from zero-day to 28-day curing, and it tends to gradually stabilize from 28-day to 56-day curing. The difference in moisture content of the two PC/CG-stabilized soils indicates that the influence of OM on the hydration of the two binders of CG and PC is not identical. Under low binder content, the water is mainly absorbed by OM in the mixture at the initial curing stage, while the water is gradually released to take the hydration reaction with the binder as the curing age continues, resulting in a rapid and then slow decrease of water content. However, under high binder dosage, most of the water is used for the hydration of the binder, which delays the hydration reaction in the later stage.

3.4. Soil pH

Figure 7a,b shows the soil pH of the CG/PC-stabilized organic-rich soils after the different curing ages under the influences of OM and binder dosage, respectively. As shown in Figure 7a, the soil pH increases with the OM content rising at a specific curing age because OM (sodium humate) is produced using the strong alkali of NaOH, and its hydrolysis further generates alkalinity. Although the primary component of sodium humate is humic acid, its alkalinity is 9.25 in this study, promoting the soil pH to rise to a degree. Figure 7b shows that the soil pH increases with the binder dosage, which can be explained by the following reasons: (1) when CaO or PC is mixed with water, it hydrolyzes into Ca^{2+} and OH^- (Equation (4)), and (2) the chemical bonds of Ca-O and Mg-O in GGBS break under the alkali conditions, and OH^- is generated by combining with ionized H^+ in solution. As a result, the concentration of OH^- in the soil pore fluid and the soil pH increase in proportion to the amount of binder. The result reveals that OM delays the formation of the hydration products of the CaO-GGBS binder, but it has little impact on the hydration of PC.

$$CaO + H_2O \rightarrow Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-. \tag{4}$$

(a)   (b)

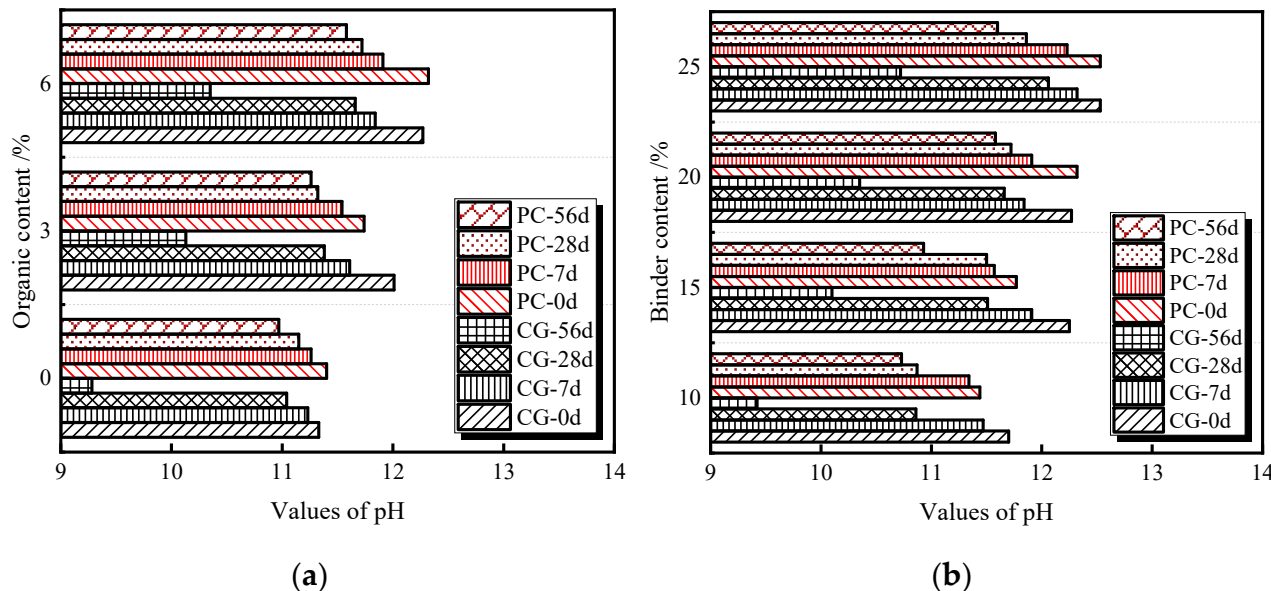
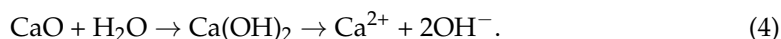
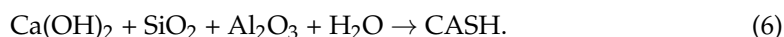



Figure 7. Soil pH of CG/PC-stabilized samples under different conditions. (**a**) Influence of organic content. (**b**) Influence of binder dosage.

It can be seen in Figure 7a,b that the soil pH of the CG/PC-stabilized organic-rich soils decreases as the curing age increases, regardless of the binder type. The reason might be attributed to the consumption of OH^- in the soil to generate hydration products with stable characteristics (such as CSH and CASH). For CG-treated soils, Ca^{2+} and OH^- are released as a result of the hydration of CaO, and reactions with Ca^{2+}, Si^{4+}, and Al^{3+} from GGBS form gel products of CSH and CASH (Equations (5) and (6)) [21]. As is known to all, during the hydration process of PC, tricalcium silicate ($3CaO·SiO_2$, C_3S) and tricalcium

aluminate (3CaO·Al$_2$O$_3$, C$_3$A) supplied by cement clinker are converted to C-S-H and C-A-S-H gels under alkali conditions [29]. Additionally, it can be found in Figure 7a,b that the soil pH of PC/CG-treated organic-rich soils is nearly identical under the curing ages from 0 to 28 days, but the soil pH of CG-treated soils is significantly lower than that of PC-stabilized soils, which is thought to be the result of changes in water content (Figure 6).

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow CSH, \tag{5}$$

$$Ca(OH)_2 + SiO_2 + Al_2O_3 + H_2O \rightarrow CASH. \tag{6}$$

4. Discussion

According to the mechanical results of two PC/CG-treated organic-rich soils (Figure 3), it can be concluded that the final strength of the stabilized soils greatly depends on the amount of OM. To describe the influence of OM on the strength change in detail, the attenuation rate of strength "R_n" is introduced, and it is measured according to Equation (7).

$$R_n = \frac{q_{u0} - q_{un}}{q_{u0}} \tag{7}$$

where R_n is the attenuation rate of the treated soils' strength containing n% OM in comparison to soils without OM, and q_{u0} (q_{un}) is the strength of the treated soils with 0% (n%) OM.

According to Equation (7), the calculation results of R_n are shown in Figure 8. With the increase in organic content, the R_n of organic-rich soils treated by CG/PC binders shows an increasing trend (Figure 8). Compared with PC-treated soils, the attenuation rate of CG-treated soils is more remarkable, and the increase in OM content significantly increases this impact, indicating that the content of OM in soils is limited when the CG binder is used for soil stabilization. In addition, the growth of curing age reduces the R_n of CG-treated soils but increases that of PC-treated soils to a certain extent. Combined with Figure 3a, it can be found from Figure 8 that the curing age can promote the strength development of CG-stabilized organic-rich soils but inhibit PC-solidified soils.

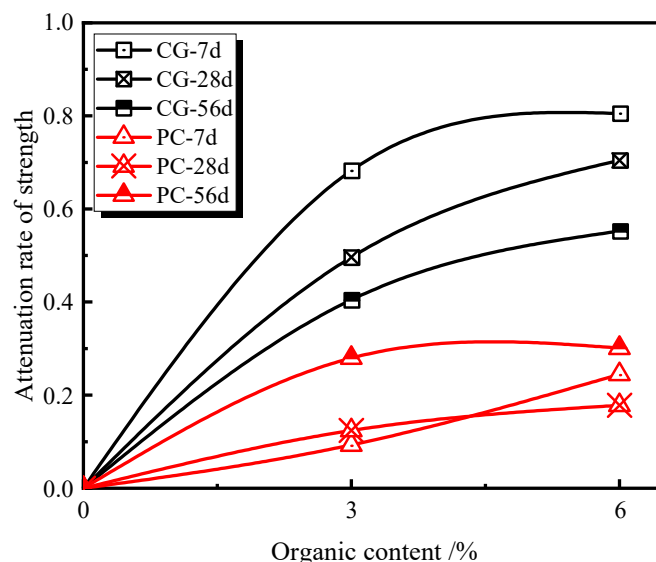



Figure 8. Strength attenuation rate of CG/PC-stabilized soils.

In this study, the strength of organic-rich soils treated by CG binder is lower than that of PC-treated organic-rich soils. The main reason is that humic acid is a substance with multiple active functional groups and a special affinity for Ca^{2+} [1,9,25]. It would take exchange–adsorption reactions with Ca^{2+} to precipitate stable calcium humic acid (Equation (8)). Sodium humic in the soil mostly consists of humic acid, so it has a greater impact on CG binder with higher calcium (Table 3). Theoretically, OM primarily limits the

hydration of the CG binder and the formation of the hydration product CSH. The impact of OM types on binders should be studied due to the complicated composition of natural organic soil, and further investigation needs to involve contemporary analysis and testing technologies, such as X-ray diffraction, scanning electron microscopy, etc.

$$R- \begin{bmatrix} -COOH \\ -COOH \end{bmatrix} + Ca(OH)_2 \rightarrow R- \begin{bmatrix} -COO \\ -COO \end{bmatrix} Ca \downarrow + 2H_2O \tag{8}$$

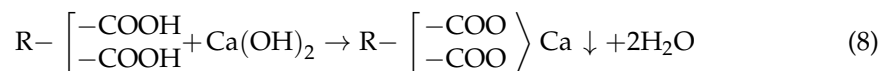



Figure 9 compares the strength of the treated organic-rich soils from different studies under the influence of OM content. Table 5 lists the experimental conditions in these comparative studies [26,30–32]. Compared with previous literature [26,30], it can be found that the strength of CG/PC-treated organic-rich soils in this study is significantly greater than that in other literature, which is due to the higher binder dosage and lower moisture content. This indicates that the combination of PC-quicklime admixture reduces the effect of OM for a single material. Therefore, the use of the quicklime-GGBS binder to treat organic-rich soils may be promising. Other literature shows the effect of Mg-based binders on treating organic-rich soils, showing less effect of OM [31,32]. Although the strength of the CG-treated organic-rich soils is similar to the Mg-cement stabilized organic-rich soils under the presence of OM, the strength of the CG-treated soils significantly increases under no OM. Therefore, the use of Mg-based materials instead of CaO for activating GGBS may decrease the strength attenuation in the treatment of organic-rich soil.

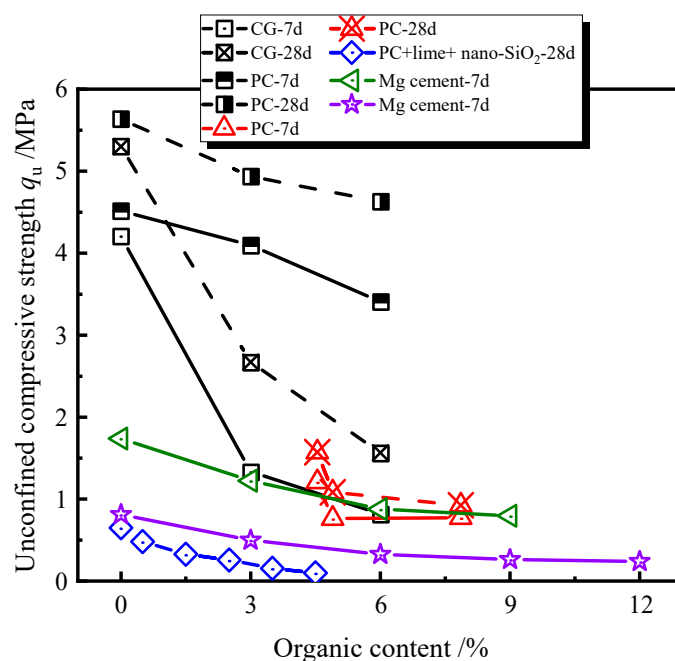



Figure 9. Strength of cement-based materials for treating organic-rich soils under different conditions [26,30–32].

Although CG-treated organic-rich soils have lower mechanical strength than PC-solidified soils, they still have a strength of more than 600 kPa, which meets the strength needs of the foundation. Moreover, CG binder has greater environmental advantages compared to PC. According to statistics, the average energy required per ton of CaO and GGBS is 4771 MJ and 1300 MJ, respectively, and emits 0.72 t and 0.07 t of CO_2 [18,33]. Therefore, the manufacturing of one ton of CG binder requires 1994 MJ of energy and releases 0.2 t of CO_2 based on a mass ratio of CaO to GGBS of 2:8. These values are far less than the average energy consumption (5000 MJ/t) and CO_2 emissions (0.95 t/t) associated with PC manufacture. Therefore, the CG binder is more appropriate for the treatment of organic-rich soils with low strength requirements when taking into account

the environmental advantages. To facilitate the use of low-carbon GGBS, low-calcium activators of GGBS (such as MgO) are used. If the organic-rich soil contains humic acid, the binder should be increased, or another external admixture should be used.

Table 5. Comparison of different conditions for treating organic-rich soils.

Reference	Organic	Organic Content/%	Binder	Binder Content/%	Moisture Content/%	Curing Age/d
This study	Sodium humate	0~6	CaO + GGBS, PC	20	30	7/28
[26]	Natural organic	4.54~7.86	PC	10	15.9~24.21	7/28
[30]	Humic acid	0~4.5	PC + lime + nano-SiO$_2$	15	70	28
[31]	Humic acid	0~9	Mg-based cement	15	60	7
[32]	Humic acid	0~12	Mg-based cement	15	60	7

5. Conclusions

In this study, organic-rich soils were treated using two binders of CG and PC, and the physical, mechanical, and chemical characteristics of stabilized soils were tested at varying organic contents, binder contents, and curing ages. The strength development of two treated organic-rich soils was obtained, showing the influence modes of OM on two binders. Additionally, the advantages of CG/PC binders in treating organic-rich soils were discussed from the aspects of engineering and environmental benefits. The key findings are as follows:

(1) The number of cracks in the two treated soils increases as the organic content rises and the binder content decreases. The 28-day cracks are more than 7-day cracks, and CG-treated soils are more likely to shed big lumps compared to PC-treated soils.

(2) The unconfined compressive strength q_u and deformation modulus E_{50} of stabilized soils increase with the curing age and binder content, but the reduction of OM content. When increasing the OM content from 0 to 6%, the strength of CG-treated soils decreases by 68% at different curing ages, while that of PC-treated soils decrease by 24%. The E_{50} of PC-treated soil is approximately 22~73 times q_u, while the E_{50} of CG-treated soil shows a linear increase with q_u (E_{50} = 43.18 q_u).

(3) The moisture content of the two treated soils increases as the OM content grows, but it decreases with the curing age and binder content. The soil pH increases as the OM content and binder content increase, but it declines with the curing age. After 56 days, the CG-treated soils had a moisture content of less than 15% and a pH of 9~10, but the moisture content and pH of the PC stabilized soils were about 15% and 11, respectively.

(4) The strength of CG-treated organic-rich soil is attenuated compared to PC-treated soils, meeting the foundation treatment with low-strength requirements. The extension of curing age will reduce the attenuation rate of CG-treated soils but will increase that of PC-treated soils. The low-calcium activator is recommended for stabilizing organic-rich soils.

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