Research Article

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Modifying mechanical properties of Shanghai clayey soil with construction waste and pulverized lime

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Abstract: In the present study, the effect of construction waste and pulverized lime on the strength of Shanghai clayey soil is investigated. The unconfined compressive strength and direct shear tests have been carried out on reinforced soils with different combinations of construction waste and pulverized lime over various curing periods. The results from unconfined compressive tests show that the compressive strength increases after introduction of construction waste and pulverized lime, and the longer the curing period the higher the strength of treated soil. The results from direct shear tests show that the shear strength parameters increase to different degree after mixing with construction waste and pulverized lime. The tests also show the increase in compressive strength is insignificant with the addition of construction waste alone, but ductility increases. The conclusions drawn from the present study are important not only for designing and construction of geotechnical engineering projects in practice, but also for making good use of waste material, sustainable development and environmental protection.

Keywords: recyclable resources; calcium-based stabilizer; Shanghai clayey soil; unconfined compressive strength; direct shear strength

1 Introduction

Many regions in the world, especially in alluvial plain and river delta area are prone to geotechnical problems before, during and after construction because of the ground property that is poor in compressive and shear strength, and vulnerable to being deformed under loads. Shanghai, the biggest commercial metropolis in China, is just located in one of such areas. It is situated at the mouth of Yangtze river delta of the east most of China. It was discovered by Yan and Shi [1] and Li [2] that most of the Shanghai areas are covered by soft clayey soils, the average overburden thickness of which is approximately 75m. Shanghai soft clayey soil has poor permeability and good plasticity [3–5]. A number of methods have been used to handle the strength problem of Shanghai clayey soil, such as down-hole dynamic compaction, soil replacement cushion, dynamic consolidation, sand and gravel pile method, vibroflotation process, deep mixing method, etc. [6].

However, mixing additives with soft soil can also be used to effectively improve the properties of soil, including ductility as well as compressive and shear behaviors [7, 8]. Construction waste is an inevitable product in the fast urbanization and industrialization with huge amount of demolition of discarded buildings and structures. Although a small fraction of construction waste has been used for backfilling on the construction site, the rest of it is mostly dumped on already scarce landfill site that poses a threat to environmental protection. Thus construction waste causes land, resource and material depletion and environmental deterioration [9, 10]. The Australian construction industry alone produces approximately 38% waste for landfills each year [11].

Globally growing concern over environmental safety has driven researchers worldwide to find more sustainable solutions to these problems and reuse waste materials. Researchers from many countries have also worked to find alternative materials for achieving soil stabilization, including the use of several industrial by-products [12–14]. Lachimpadi and Pereira [15] have been dedicating to study how to reduce the production of construction waste from a viewpoint of construction method. Some other researchers are calling for constraining the unbridled production of construction waste from a viewpoint of legislation [16]. Other researchers have explored the stabilization of soft soil with relevant binding materials

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(such as cement) as well as construction waste for the purpose of not only making use of waste materials but simultaneously improving the quality of environment [17–19]. In view of weak and easy-deforming characteristics of Shanghai clayey soil, the pulverized lime is used to increase the bonding force among soil particles. The pulverized lime is a white powder material, which is predominantly chemically composed of calcium oxide. It is a common material that is widely used in construction industry. If the pulverized lime is proportionally added to soil alone, the compressive strength of soil can be effectively improved [20, 21], while it may also increase the brittleness of soil at the same time [22]. Authors from many countries have studied the lime and the feasibility of its application in stabilizing the soil [23–30].

Considering the huge imprint of construction waste on environment, and the need of recycling waste material to sustainably protect our dwelling environment, the construction waste and the lime are selected as additives to improve the mechanical and physical properties of Shanghai clayey soil, because few researches in the past were focused on these two additives. It is expected to provide the fundamental data for related design and construction of civil engineering projects.

2 Materials and methods

2.1 Test design

This study mainly employs the techniques of both mechanical stabilization through the introduction of recycled construction waste, and chemical stabilization by introducing pulverized lime, in controlled proportions. The flowchart of the research work is presented in Figure 1.

2.2 Materials and Sample Preparation

2.2.1 Shanghai clayey soil

The soil was collected from a construction site in Zhangjiang High-tech Park in east of Shanghai, China. Table 1 shows the physical and water-physical characteristic of Shanghai clayey soil.

2.2.2 Construction waste

Construction waste was obtained from a demolition site in Shanghai, which mainly consists of crushed concrete, tiles and masonry works that had been sieved by the supplier to remove the wood and glass residues. The construction waste was stored in a plastic container before it was oven dried for 24 h at a temperature of 105°C and sieved. The particles passing 4.75 mm sieve and retaining on 0.1 mm sieve were selected for the purpose of this study. The physical characteristics of construction waste are shown in Table 2.

2.2.3 Pulverized lime

The pulverized lime utilized for this study was obtained commercially from a Shanghai-based architecture company. It is sieved to ensure that the size of the lime is less than 2mm. The physical and chemical properties of pulverized lime are shown in Table 3. Figure 2 shows the grading curve of Shanghai clayey soil, construction waste and pulverized lime analyzed by Laser Particle Sizer from Malvern Instruments Ltd. Shanghai.

2.3 Sample preparation

Different percentages of the two additives (construction waste and pulverized lime) have been used to separately and jointly investigate the influence of each additive and their combination on the unconfined compressive strength and direct shear strength over a number of different curing periods. The planned test combinations and the curing periods are shown in Table 4 for unconfined compressive test, and in Table 5 for direct shear tests.

Lower construction waste proportions have been chosen to prevent segregation of construction waste particles within the specimen matrix. The optimum moisture content by weight of the dry specimen is used for all the specimens to deduce comparative data for assessing the effects of the aforementioned two controlling factors. A manual mixing technique is adopted to mix the additives into the soil mass. The mixtures are then prepared in a large tray by constantly spraying water at amounts calculated for the optimum moisture content through a spray bottle and mixing with the help of spatula till a homogeneous appearance is attained. Then the stabilized clay mixes are compacted in standard cylindrical steel molds to produce specimens with sizes of 80mm in height × 39mm in diameter for unconfined compressive test, and with sizes of 61.8mm

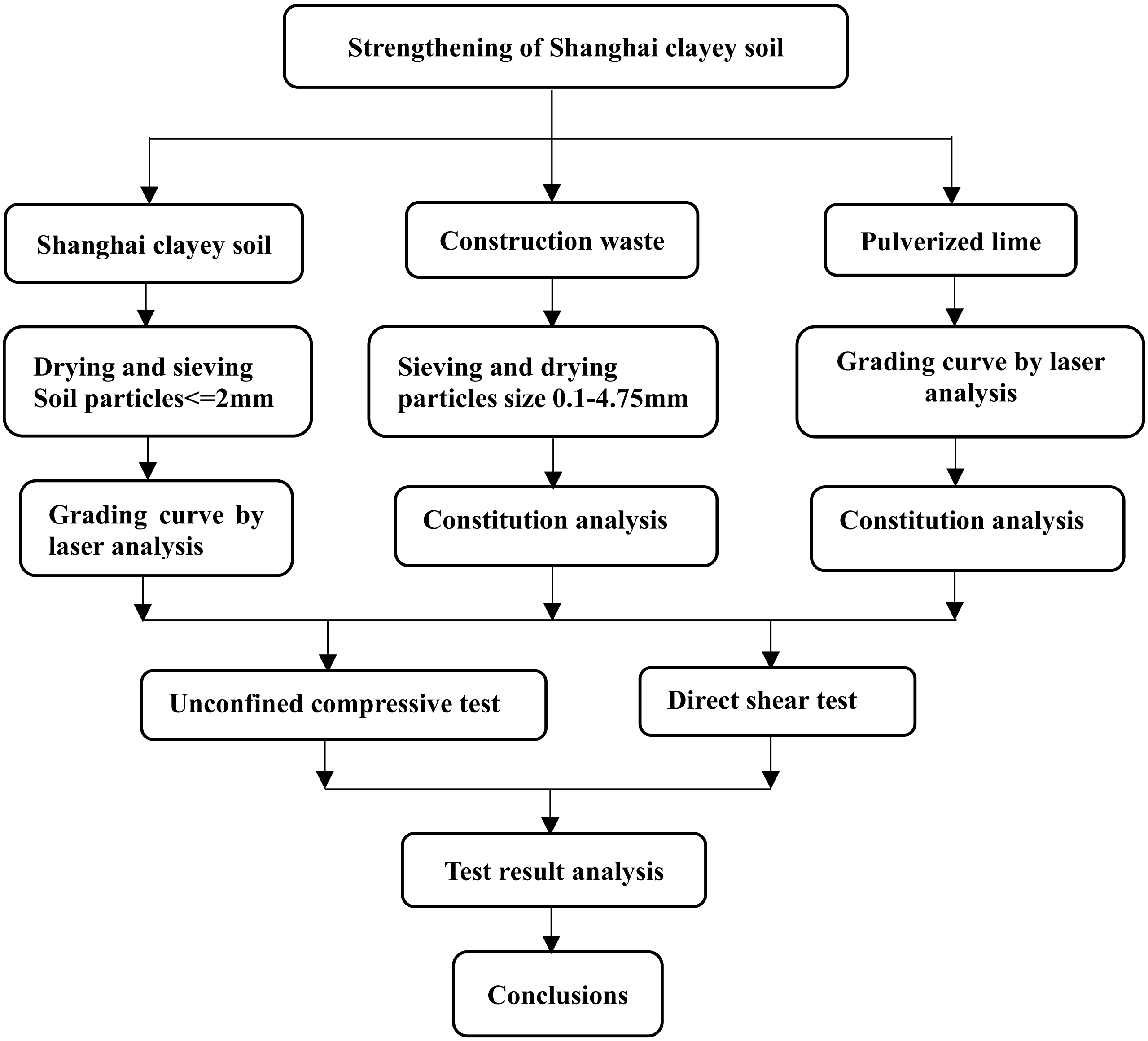

Figure 1: Flowchart of the research scheme

Table 1: Physical and water-physical properties of Shanghai clayey soil

Liquit limit (W_L/%)	Plastic limit (W_P/%)	Maximum dry density (ρ_{dmax}/kg·m^{-3})	Specific gravity (G_s)	Uniformity coefficient (c_u)	Optimum water content (W_{opt}/%)
39.4	19.3	1650	2.72	4.33	19.4

Table 2: Physical characteristic of construction waste

Recycled concrete (%)	Fragment of brick (%)	Rubble of tile (%)	Particle size distribution (mm)	Max. dry density (ρ_{dmax}/kg·m^{-3})
59	28	13	0.1-4.75	2.49

Table 3: Physical and chemical characteristic of pulverized lime

CaO (%)	MgO (%)	$Ca(OH)_2$ (%)	Ingredients (%)	Whiteness (%)	Activated CaO (%)	Particle size (mm)
70.27	3.64	>65	1	90	>30	<2

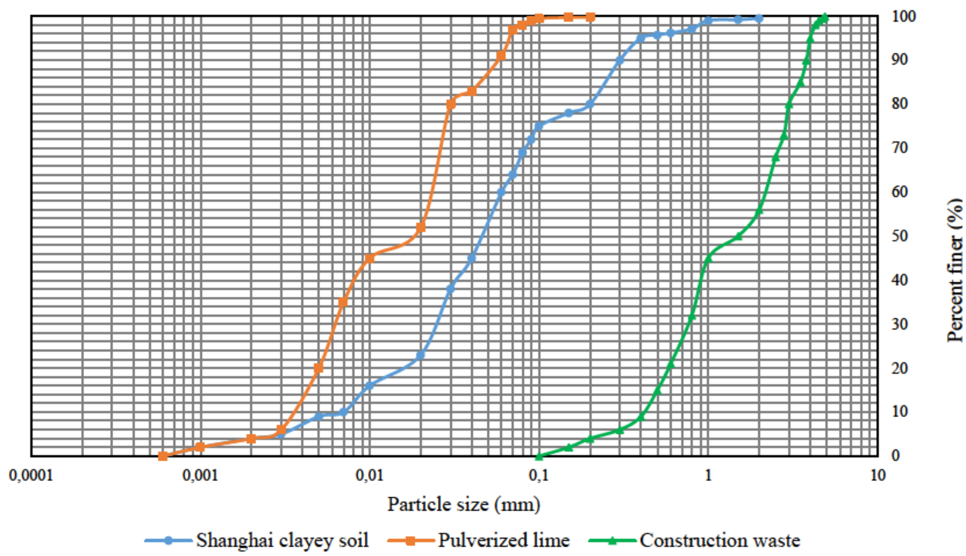

Figure 2: Particle size distribution of Shanghai clayey soil, construction waste and pulverized lime

Table 4: Test specimen matrix for unconfined compressive tests (average value of 3 repeated tests is selected for calculation)

Curing period (days)			7	14	21	28
	Construction waste (%)	Lime (%)	(MPa)	(MPa)	(MPa)	(MPa)
Group 1						
	0	0	1.71	1.82	1.91	1.95
	10	0	1.76	1.88	1.95	1.98
	15	0	1.78	1.89	1.96	2.00
	20	0	1.73	1.83	1.95	1.97
Group 2						
	0	3	1.83	1.97	2.15	2.29
	0	4	1.93	2.08	2.25	2.38
	0	5	2.10	2.19	2.36	2.49
Group 3						
	10	3	1.85	1.99	2.14	2.26
	10	4	1.96	2.15	2.25	2.32
	10	5	2.13	2.22	2.32	2.39
Group 4						
	15	3	1.98	2.12	2.26	2.35
	15	4	2.12	2.23	2.31	2.43
	15	5	2.17	2.30	2.39	2.52
Group 5						
	20	3	2.05	2.21	2.37	2.51
	20	4	2.27	2.38	2.50	2.63
	20	5	2.13	2.30	2.44	2.58

Table 5: Test specimen matrix for direct shear tests

Curing period (days)			7
	Construction waste (%)	Lime (%)	(MPa)
Group 1			
	0	0	1.71
	10	0	1.76
	15	0	1.78
	20	0	1.73
Group 2			
	0	3	1.83
	0	4	1.93
	0	5	2.10
Group 3			
	10	3	1.85
	10	4	1.96
	10	5	2.13
Group 4			
	15	3	1.98
	15	4	2.12
	15	5	2.17
Group 5			
	20	3	2.05
	20	4	2.27
	20	5	2.13

in diameter × 20mm in height for direct shear tests under the standard compaction effort following ASTM2166 and ASTM 3080, respectively. The extracted specimens are then wrapped with thick plastic sheets and placed in a storage room for the respective curing periods to limit the effects of any external factors on the specimens.

2.4 Laboratory Tests

2.4.1 Unconfined compressive test

The unconfined compressive strength tests are performed as per ASTM 2166 [34]. An axial load is applied at the continuous rate of 2.5 ± 0.1 mm/min. Once the load is applied, the specimen undergoes deformation. A reduction in the length of the specimen is observed, whereas the cross-sectional area increases under the influence of the applied compressive loading. The compressive strength of the specimen is associated with above two parameters, which are used to calculate the related parameters.

2.4.2 Direct shear test

The direct shear tests are performed as per ASTM 3080 [2004]. The device used for this purpose is EDJ-1 electrical strain controlled direct shear apparatus that is manufactured by Zhejiang Soil Instrument Company Limited, which mainly consists of shear box, shear gearing actuator, vertical loading cell, dynamometer and displacement measuring device. The shear velocity used is 0.8mm/min, with measuring range for shearing strain being 20mm.

3 Results and discussions

3.1 Effect of construction waste on strength of soil

Table 4 shows the test arrangement and testing results from unconfined compressive test. Because there is approximately the same change trend, and 7d of curing time is the stage for initial formation of strength, to save space, the authors only select the condition for curing time of 7d to explain the results. Figure 3 shows the stress-strain curve for samples with different content of construction waste after curing time of 7 d. It can be seen from Figure 3 that the axial stress first climbs up and then declines with the increase of axial strain for not only control samples but also samples mixed with construction waste. Compared with control samples, the treated samples have the similar peak strength. The increase in peak strength due to additive of construction waste can be ignored. Among the treated samples, the samples with additive content of 15% present very slightly higher strength. In addition, with the increase in content of additive, the axial strain at the peak strength becomes larger and larger. At the period of slowing down for the curves, the speed of slowing down with plain sample is fastest of all samples, while the samples with additive content of 20% have the lowest speed of slowing down. This demonstrates that the ductility of samples has been increased after mixing with construction waste with the reduced brittleness at the same time.

Further, the higher the additive percent is, the more perfect the failure shape is, which means that the ductility has been increased with treated sample over control sample. The axial strain at the peak strength with samples of 20% is largest, which is increased by 75% compared with that of control sample. For stiffness, there is also a big variation with samples of different content. In general, with the increase of content, the stiffness declines. Figure 4 shows this trend of development. The stiffness of control

Table 6: Relationship between unconfined compressive strength and curing time with samples mixed with construction waste alone

S. no.	Content (%)	7 d (MPa)	14 d (MPa)	21 d (MPa)	28 d (MPa)
1	0	1.71	1.82	1.91	1.95
2	10	1.76	1.88	1.95	1.98
3	15	1.78	1.89	1.96	2.00
4	20	1.73	1.83	1.95	1.97

Table 7: Relationship between increase rate in unconfined compressive strength and curing time with samples mixed with construction waste alone

S. no.	Content (%)	7 d	14 d	21 d	28 d
1	0	1.71 MPa	1.82 MPa	1.91 MPa	1.95 MPa
2	10	2.9%	3.3%	2.1%	1.5%
3	15	4%	3.8%	2.6%	2.5%
4	20	1.2%	0.5%	2.1%	1.0%

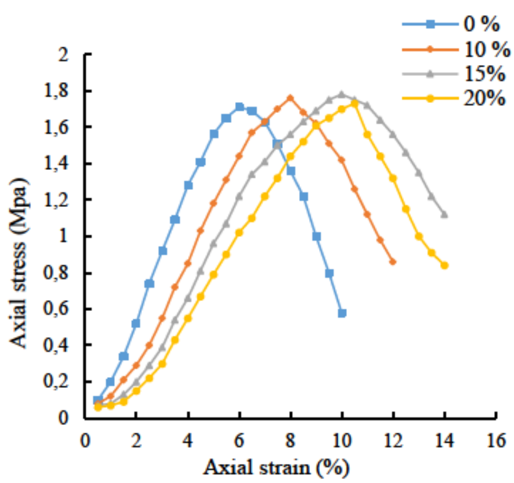

Figure 3: Stress-strain curves of treated samples with construction waste at 7d

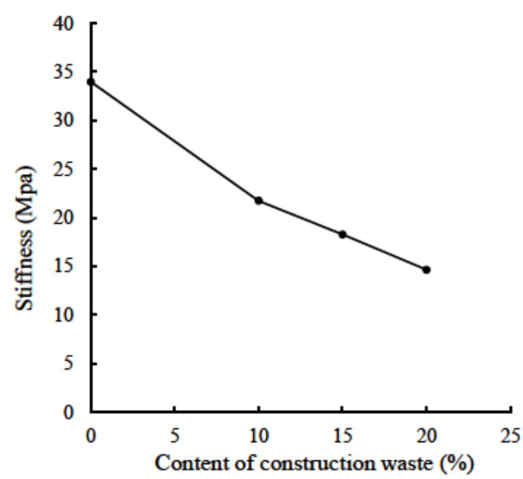

Figure 4: Relationship between stiffness and content of additive

sample is 34 MPa, while the stiffness with sample of 30% is 14.66 MPa, declines by 56.9%. The stiffness is derived from the half point of peak strength at the initial stage of stress-strain curve, stiffness = (half peak strength) / (corresponding strain).

Figure 5 shows effect of curing time on unconfined compressive strength of the samples. It can be observed that the strengths of all samples increase with the increase in curing time. The detailed information about the strength increase with curing time is shown in Table 6. The increase rates for samples with different content and curing time compared with control sample are shown in Table 7. It is observed that the increase in compressive strength is the highest with samples of 15% content of construction waste.

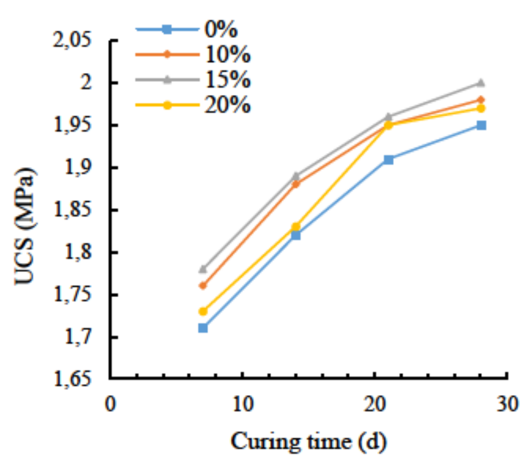

Figure 5: Effect of curing time on unconfined compressive strength (UCS) with samples mixed with construction waste alone

3.2 Influence of pulverized lime on strength of soil

Figure 6 shows the stress-strain curve for samples mixed with pulverized lime alone with different content. It can be observed from Figure 6 that there is a peak point in the stress-stain curve for all samples, no matter whether we examined treated samples or control samples. However, the samples treated with the lime have relatively higher peak stress than control samples. The samples treated with 5% of pulverized lime have the highest peak stress of 2.08 MPa, increased nearly by 22%. The corresponding stiffness is also increased from 31 MPa of control sample to 52 MPa of samples with 5% of lime, increasing rate being approximately 68%. The soils mixed with lime proportionately can really increase the strength, but at the same time, the ductility of treated soil are declined with more possibility of brittleness failure. This trend intensifies with increase in lime content.

Figure 7 shows the relationship between curing time and the compressive strength with samples mixed with pulverized lime alone. It can be seen from the diagram that the unconfined compressive strength for all samples increases with the increase in curing time. The increase in strength with treated samples is detailed in Table 8 and 9. So it is seen that, when content of lime is 5%, the increase in compressive strength is the highest. The pulverized lime can really increase the compressive strength but with the declining in ductility of treated soil. However the plastic index of treated soil is declined that leads to the lower ductility of soil, which makes soils more prone to the brittle failure [31].

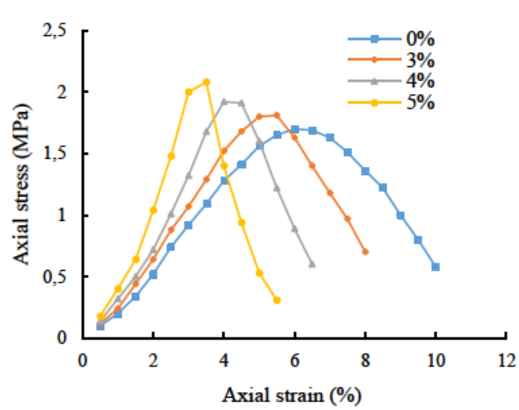

Figure 6: Stress-strain relationship with samples mixed with pulverized lime alone

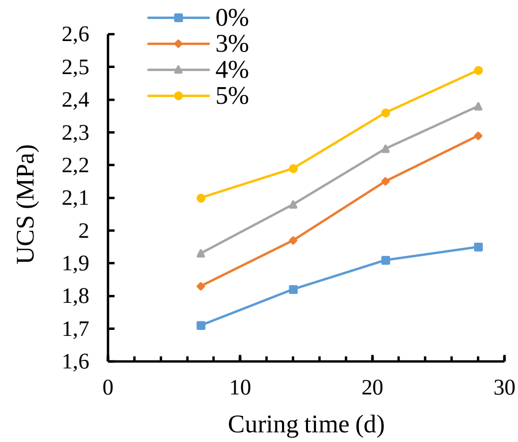

Figure 7: Relationship between unconfined compressive strength (UCS) and curing time with samples mixed with pulverized lime alone

Table 8: Relationship between unconfined compressive strength and curing time with samples mixed with pulverized lime alone

S. no.	Content (%)	7 d(MPa)	14 d(MPa)	21 d(MPa)	28 d(MPa)
1	0	1.71	1.82	1.91	1.95
2	3	1.83	1.97	2.15	2.29
3	4	1.93	2.08	2.25	2.36
4	5	2.10	2.19	2.36	2.49

Table 9: Relationship between increase rate in unconfined compressive strength and curing time with samples mixed with lime alone

S. no.	Content (%)	7 d	14 d	21 d	28 d
1	0	1.71 MPa	1.82 MPa	1.91 MPa	1.95 MPa
2	3	7%	8.2%	12.6%	17.4%
3	4	12.9%	14.3%	17.8%	22.1%
4	5	22.8%	20.3%	23.6%	27.7%

3.3 Integrated influence of lime and construction waste

Figure 8 shows the stress-strain curve for different combination of contents of construction waste and pulverized lime for curing time of 7 d. Figure 8 (a) shows the stress-strain curve under different content of lime when the additive of construction waste is 10%. It is seen that the compressive strengths of treated samples are higher than that of the control sample. While stiffness is increased, the ductility declines with the increase of lime in content. But

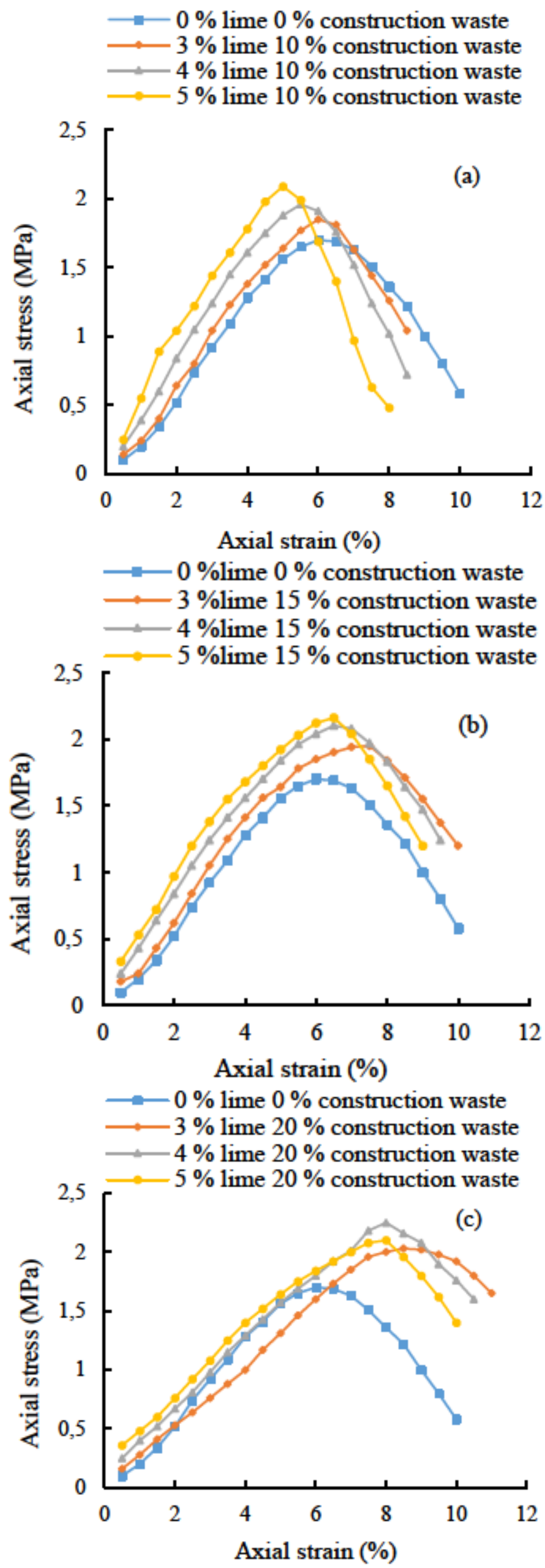

Figure 8: Stress-strain curve with samples of different content combination of construction waste and lime at curing time of 7d

when the content of lime is 5%, the strength is maximized. Figure 8 (b) has the similar development trend, that is, the strength is maximized when the lime content is 5%. For Figure 8 (c), there are slight differences, that is, the compressive strength is maximized when lime content is 4%. It can also be seen from Figure 8 (a-c) that the compressive strengths are slightly increased with the increase in content of construction waste. It is worth noting that in Figure 8 (c) the increase in compressive strength is larger than in Figure 8 (a and b). With 20% of construction waste, the strength with 4% of lime is 2.27 MPa, and the strength with 0 percent of lime is 1.73 MPa, and therefore the increase is approximately 31%.

Figure 9 shows the relationship between curing time and unconfined compressive strength for samples with combination of different lime content and content of construction waste. It can be observed from Figure 9 that the unconfined compressive strength increases with the increase in curing time, and the strength of treated samples by lime and construction waste is generally higher than that of control sample as is shown in Table 10 and 11. The unconfined compressive strengths of soil are generally increased with the increase of content of lime under almost all contents of construction waste. As to the shape of samples after failure, the treated samples with both lime and construction waste simultaneously need more deformation before failure than that of samples treated with either lime or construction waste alone. On the other hand, the samples with longer curing time need more deformation to fail than that of shorter. This may be because the cement solidification has functioned during the period of curing time after adding the construction waste to soil, which leads to the rise of mechanical property and ductility of soil. In the present study, samples with construction waste of 20% and lime of 4% have the largest increment in compressive strength, which can be taken as the optimum composition for strengthening the soil. The pulverized lime and construction waste are proportionately complementary in improving the bonding among the soil particles. Too large or too small in rate of content in both additives may inversely lead to declining in strength of soil. Of course, curing time is another key factor.

3.4 Influence on shear strength

The influence of the combination of both pulverized lime and construction waste on shear strength of soil is also investigated with the equipment for direct shear test. Samples with all combinations in content of both lime and construction waste under 3 normal stress of 100, 200, 400 KPa

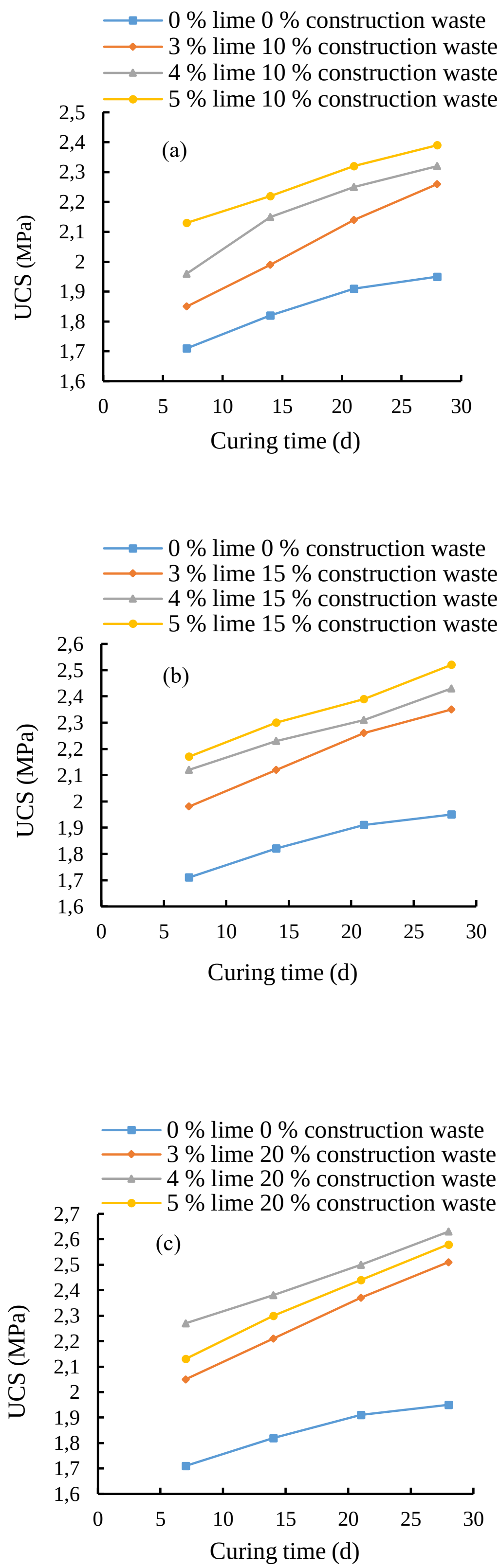

Figure 9: Influence of curing time on samples with different combination of construction waste and pulverized lime

applied by direct shear apparatus have been tested. Because most of them have the similar development trend, the only normal stress of 200 KPa is selected for explanation. Moreover, 200 KPa is usually more suitable for most of practical engineering.

Figure 10 shows the relationship between shear deformation and shear stress of samples with different combination of both lime and construction waste under normal stress of 200 KPa. From the diagram we can see that the shear strength of samples with 3% of lime and 10-15% of construction waste is the highest. Compared to the control samples its shear strength is increased by approximately 37%. The shear rigidity of treated samples also increases to varying degree.

Figure 11 shows the curve between shear deformation and shear stress of samples with 4% of lime and varied percent of construction waste under normal stress of 200 KPa. It can be observed that shear strengths of treated samples are all larger than that of control sample. Among them, the shear strengths of samples with 4% of lime and 15% of construction waste is the largest, increased by approximately 43%, with shear rigidity increased by 506% from 33 to 200 KPa/mm.

Figure 12 shows the curve between shear deformation and shear stress of samples with 5% of lime and varied percent of construction waste under normal stress of 200 KPa. It can be observed that shear strengths of treated samples are all larger than that of control sample. Among them, the shear strength of samples with 5% of lime and 10-15% of construction waste is the largest, increased by approximately 50%, with shear rigidity increased by 703% from 33 to 265 KPa/mm. From above, it is discovered that, when the content of construction waste is approximately 15% with lime content being 5%, the shear strength and the shear rigidity of samples are maximized.

3.5 Influence on cohesion and internal friction

Figures 13-15 show the relationship between normal stress and shear stress in direct shear test for samples with 15% of construction waste alone, 5% of lime alone and the combination of both 15% of construction waste and 5% of lime, respectively. It can be calculated from Figure 13 that the cohesion and internal friction angle of treated samples with 15% of construction waste alone are increased by 4.6% and 18.8%, from 56.4 to 59 KPa, from 23.75° to 28.23°, respectively.

It can also be calculated from Figure 14 that the cohesion and internal friction angle of treated samples with 5%

Table 10: Relationship between curing time and unconfined compressive strength with samples mixed with different combinations of construction waste and lime

S. no.	Lime content (%)	Construction waste content (%)	7 d(MPa)	14 d(MPa)	21 d(MPa)	28 d(MPa)
1	0	0	1.85	1.99	2.14	2.26
2	3	10	1.85	1.99	2.14	2.26
3	4	10	1.96	2.15	2.25	2.32
4	5	10	2.13	2.22	2.32	2.39
5	3	15	1.98	2.12	2.26	2.35
6	4	15	2.12	2.23	2.31	2.43
7	5	15	2.17	2.3	2.39	2.52
8	3	20	2.05	2.21	2.37	2.51
9	4	20	2.27	2.38	2.5	2.63
10	5	20	2.13	2.3	2.44	2.58

Table 11: Relationship between curing time and increase rate in unconfined compressive strength with samples mixed with different combinations of construction waste and pulverized lime

S. no.	Lime content (%)	Construction waste content (%)	7 d	14 d	21 d	28 d
1	0	0	1.71 MPa	1.82 MPa	1.91 MPa	1.95 MPa
2	3	10	8.2%	9.3%	12%	15.9%
3	4	10	14.6%	18.1%	17.8%	19%
4	5	10	12.46%	22%	21.5%	22.6%
5	3	15	15.8%	16.5%	18.3%	20.5%
6	4	15	24%	22.5%	21%	24.6%
7	5	15	27%	26.4%	25.1%	29.2%
8	3	20	20%	21.4%	24.1%	28.7%
9	4	20	32.7%	30.8%	30.9%	34.9%
10	5	20	24.6%	26.4%	27.7%	32.3%

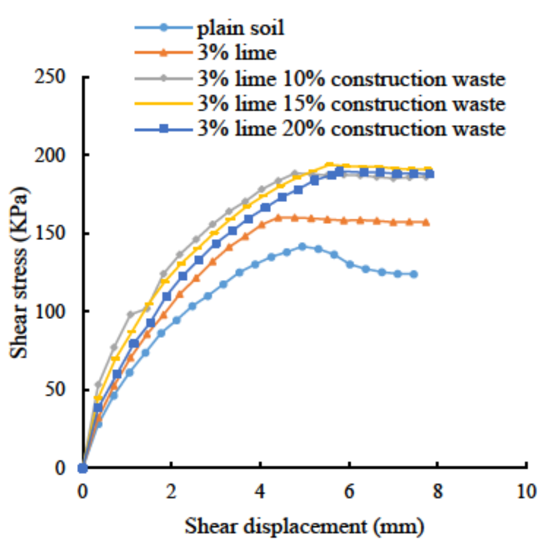

Figure 10: Relationship between shear stress and shear displacement

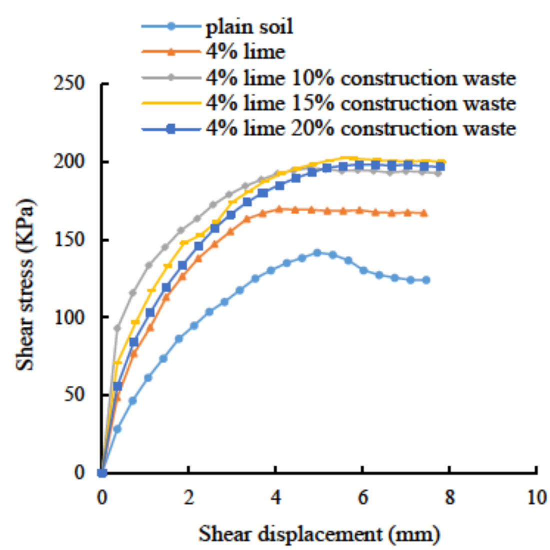

Figure 11: Relationship between shear stress and shear displacement

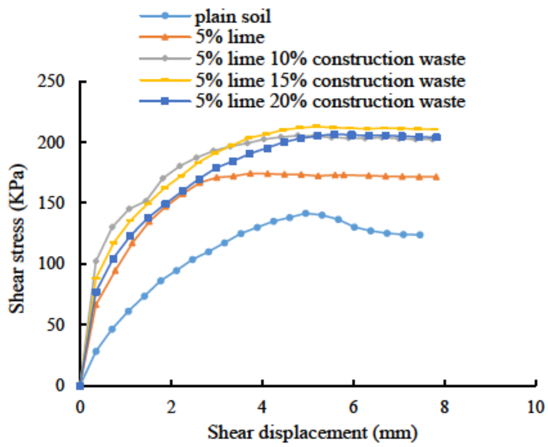

Figure 12: Relationship between shear stress and shear displacement

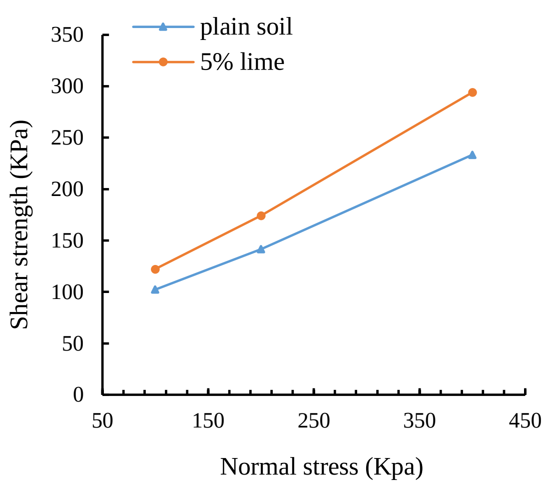

Figure 13: Relationship between normal stress and shear strength with samples mixed with lime alone

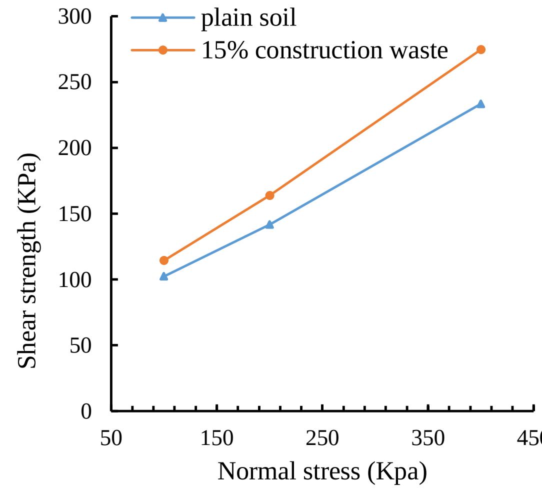

Figure 14: Relationship between normal stress and shear strength with samples mixed with construction waste alone

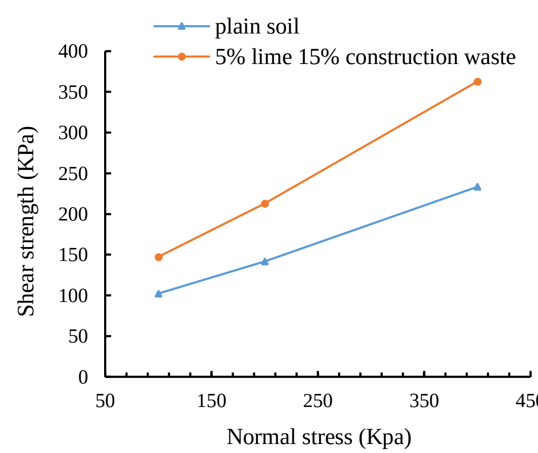

Figure 15: Relationship between normal stress and shear strength with samples mixed with combination of construction waste and lime

of lime alone are increased by 10.73% and 26.14%, from 56.4 to 62.45 KPa, from 23.75° to 29.96°, respectively.

It can be calculated from Figure 15 that the cohesion and internal friction angle of treated samples with a combination of both 15% of construction waste and 5% lime simultaneously are increased by 28.3% and 58.69%, from 56.4 to 72.35 KPa, from 23.75° to 35.85°, respectively. Therefore, it is in the case of combination of both additives that the strength parameters, that is, cohesion and internal friction angle, have the maximum increase, where the contents of them are 15% of construction waste and 5% of pulverized lime, respectively.

3.6 Strengthening Mechanism

The adding of construction waste to soil can effectively improve the unconfined compressive strength and shear strength that are shown by our tests. The mechanism of soil strengthening can be explained in two ways. Firstly, from the view point of macroscopy, the compressive strength and shear strength of concrete debris and fragments of brick and tile that consists of the main components of construction waste are much higher than those of soil particles. Therefore, after the construction waste is added to the Shanghai clay soil that is similar to adding of a relatively strong objects into a soft system, the restructured system is bound to be higher in strength than original system. This analysis is only based on the difference in strength between individual materials, therefore, it is relatively macroscopic.

On the other hand, we can analyze the interaction between the soil particles and construction waste, especially the interface between two types of particles, that is, the friction and interlock among particles. In soils the friction and interlock between particles are relatively small and homogeneous. After adding of particles of construction waste and considerable compaction, the fine skeleton of construction waste is closely encircled by soil particles. Because the surface of the skeleton of construction waste is not smooth with protrusions and depressions, the soil particles can fill up the sunken on the surface, which make the soil particles and skeleton of construction waste form an integrated system. When the integrated system is forced by external loading, the soil particles and particles of construction waste combine closely to resist against the loading together, then the increased friction and interlock between soil particles and the fine skeletons of construction waste effectively work, which much greatly improve the compressive strength and shear strength of the integrated system.

Based on the results from previous Researchers [32–34], the function mechanism of pulverized lime improving the strength of Shanghai clay soil can be explained based on the following 4 points. Firstly, when the lime (CaO) is added to soil with the presence of moisture, the following chemical actions may appear: $CaO + H_2O = Ca(OH)_2$. This is a chemical reaction with huge amounts of heat released, which urge the other chemical reaction that lead to the closer compaction among particles. Secondly, the ion exchange of $Ca(OH)_2$. With presence of moisture, $Ca(OH)_2$ can be electrolyzed producing large amounts of Ca^{2+}. While soil particles are generally in a negative status in the whole, the soil particles can combine closely with the Ca^{2+} due to attraction of charge. That finally leads to the increase in strength. Thirdly, after a series of chemical reactions, there is certain $Ca(OH)_2$ in soils. When it exposes to the air, it reacts with CO_2 in the air, $Ca(OH)_2 + CO_2 = CaCO_3$, forming $CaCO_3$ that is much higher in strength than soil and further bonding the particles, which finally lead to the increase in the strength. Fourthly, except for CaO, there are some other components in lime, such as MgO, Al_2O_3 et al., which can also react with SiO_2 from soil to form the aluminum silicate and calcium silicate etc., that have much higher bonding. That could lead to the further improvement of soil strength.

4 Conclusion

From the above analysis, it can be concluded that:

(a) When construction waste is added to soil alone, there is only a little increase in compressive strength no matter what content is applied in unconfined compressive test. In addition, there is significant relationship between curing time and compressive strength. The compressive strength after curing time of 28d is averagely increased by 13% compared to that of 7d, no matter what content of construction waste is applied.

(b) When pulverized lime is added to soil alone, there is an obvious increase in compressive strength, which is increased by 22.8% as lime content is 5%. In addition, there is also a definite relationship between curing time and compressive strength. The compressive strength after curing time of 28d is averagely increased by 16% compared to that of 7d, no matter what content of pulverized lime is applied.

(c) When a combination of both pulverized lime and construction waste is simultaneously applied to soil, there is more significant increase in compressive strength, which is increased averagely by 32% as lime content is 4% and construction waste 20%. In addition, there is also definite relationship between curing time and compressive strength. The compressive strength after curing time of 28d is averagely increased by 20% compared to that of 7d, no matter what content of pulverized lime and construction waste are applied.

(d) As to the direct shear test, the shear strength is increased averagely by 15% under the condition of normal stresses of 100, 200, 400 kPa as 15% of construction waste is added to soil alone, compared to the control sample. The cohesion and internal friction angle of samples are increased by 4.6% and 18.8% respectively, when construction waste is 15%.

(e) The shear strength is increased averagely by 23% under the condition of normal stresses of 100, 200, 400 kPa as 5% of pulverized lime is added to soil alone, compared to the control sample. The cohesion and internal friction angle of samples are increased by 10.73% and 26.14%, respectively, when pulverized lime content is 5%.

(f) The shear strength is increased averagely by 50% under the condition of normal stresses of 100, 200, 400 kPa as 15% of construction waste and 5% of pulverized lime are simultaneously added to soil, compared to the control sample. The cohesion and internal friction angle of samples are increased by 28.3% and 58.69%, respectively.

The fast development of urbanization and industrialization has led to large quantity of construction waste from demolition of structure that may ever-increasingly pose a huge threat to living environment and sustainable development for human society. At the same time, the large amount of soils needs to be stabilized before the start of most of the civil engineering projects. Therefore, the construction waste used in the soil consolidation can effectively and satisfactorily deal with the challenging from environmental impact of construction waste and the stabilizing of the ground for construction engineering, which can perfectly serve the goal for sustainable or green development for our globe.

Data availability statement: All data are available from the corresponding author by request: qujiliqwq@163.com

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