Research Article

Qu Jili*, Wang Junfeng, Batugin Andrian, and Zhu Hao

Characterization and Comparison Research on Composite of Alluvial Clayey Soil Modified with Fine Aggregates of Construction Waste and Fly Ash

<https://doi.org/10.1515/secm-2021-0008>

Received Oct 25, 2020; accepted Jan 18, 2021

Abstract: Fine aggregates of construction waste and fly ash were selected as additives to modify the characteristics of Shanghai clayey soil as a composite. The laboratory tests on consistency index, maximum dry density, and unconfined compressive strength were carried out mainly for the purpose of comparing the modifying effect on the composite from fine aggregates of construction waste with that from fly ash. It is mainly concluded from test results that the liquid and plastic limit of the composites increase with the content of two additives. But their maximum dry density all decreases with the additive content. However, fine aggregates of construction waste can increase the optimum water content of the composites, while fly ash on the contrary. Finally, although the two additive all can increase the unconfined compressive strength of composites, fly ash has better effect. The current conclusions are also compared with previous studies, which indicates that the current research results are not completely the same as those from other researchers.

Keywords: composite, fine aggregates of construction waste, fly ash, consistency index, unconfined compressive strength

1 Introduction

As most of the engineers in geotechnical engineering knows, there is a significant influence of soil physical and water-physical property on civil engineering construction and sustainable development of a society. In southeast China, alluvial deposit is predominant due to its being mostly located in nearby region of Yangtze River delta. The depth of alluvial deposit in the area is mostly larger than one hundred meters. There are a high content of moisture, low strength and easy deformation with this type of soil [1]. It cannot meet the need for construction engineering in its natural state in most cases [2]. Shanghai is China's largest city not only in economy but in population, which is just located in the center of the Yangtze River Delta. Fast and large scale infrastructure construction in recent decades leads to the strong demand for good soil characteristics [3]. Therefore it has become a top priority to modify the characteristics of local soil to make it adapt to the emerging needs from engineering construction and sustainable development in society and economy [4]. Among many traditional stabilizers, fly ash has been proven effective in improving the physical and water-physical characteristics of soil, such as improving shear strength, decreasing shrink-swell potential and reducing construction waste [5]. In general, fly ash is a waste, fine ash collected from exhaust gas produced by coal combustion or thermal power plant, which has a low rate of recycling and a heavy metal pollution, incurring severely adverse influence on surrounding environment [6]. The fly ash is mainly composed of pozzolanic materials, which is fine in particle size, large in specific surface area, and relatively strong in activity. It is usually used not only in improving soil mechanical properties as curing agent, in foundation filling materials [7], but also used in strengthening the soft soil roadbed and enhancing the water physical properties of soil [8]. The effect of fly ash with different content on soil compressive strength was analyzed by unconfined compressive tests, which discovered that there was only slow growth in strength of treated soil with fly ash [9]. So far, numerous studies have been carried

*Corresponding Author: **Qu Jili:** School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai, 200093, China; Email: qujiliqwq@163.com

Wang Junfeng, Zhu Hao: School of Environment and Architecture, University of Shanghai for Science and Technology, Shanghai, 200093, China

Batugin Andrian: Professor, Department of Mining safety and Ecology, National University of Science and Technology MISIS, Moscow, 119049, Russia, Distinguished Professor of University of Shanghai for Science and Technology; Email: as-bat@mail.ru

out to identify the function of fly ash in improving the construction materials, such as all types of mortars, concretes and soft soils [10–18]. However, most of the related studies are centered on the stabilization of coarse aggregates with fly ash, and few were focused on stabilization of alluvial clayey soil with fly ash, which is just the unique feature of the current research.

Construction waste is a product from industry upgrading, fast urbanization as well as swift migration of population from countryside to urban area all over the world, which accounts for 30~40% of total urban waste, being unsustainable and low recyclable, detrimental to environment [19]. The detrimental influence of construction waste to environment has been discussed from a perspective of nano particle [20]. On the other hand, the reuse and recycling of construction waste in engineering are gaining ever more attention due to the continuing reduction of natural resources. The practical application of the fine aggregate of recycling concrete included in construction waste was also probed [21]. And the recycling fine aggregates of construction waste had been used to reinforce the bentonite soil and it was discovered that the treated bentonite become a little bit higher in compressive strength but significantly increase in ductility [22]. When construction waste was mixed with Shanghai clayey soil, the ductility of treated soil is significantly increased, and as 4% of pulverized lime and 20% of construction waste were simultaneously mixed with clayey soil, the compressive strength and ductility are max-

imized [23]. In addition, other studies on the application of construction waste on construction materials, such as mortar, concrete, and soft soil have showed that construction waste is significantly effective not only technically but also economically [24–31].

The particle size of construction waste used in previous researches is mostly great than 2 mm. In the present study, the size of <1 mm of construction waste is used in the tests. And the composite of study is a special type of local soil – Shanghai clay, an alluvial clayey soil modified with specific additives. Therefore it is expected that applying smaller size of construction waste particles to modifying the clayey soil would make a difference. This is actually one of the objectives of the present study. Another objective is to compare the effect of the fine aggregates (<1 mm) of construction waste with that of fly ash in reinforcing and modifying the soil, due to their similarity in particle size. Finally, it also compares between the current results and previous conclusions.

2 Materials and methods

2.1 Shanghai clayey soil

The soil selected for the purpose of this test was collected from a construction site in Zhangjiang High-tech Park in east of Shanghai, China. Figure 1 shows the sampling site

Figure 1: The sampling location of Shanghai clayey soil.

Figure 2: Particle size distribution of Shanghai clayey soil, fine aggregates of construction waste and fly ash.

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

Optimum water content ($W_{opt}/\%$)	Liquid limit ($W_L/\%$)	Plastic limit ($W_P/\%$)	Plastic index (I_P)	Maximum dry density ($\rho_{dmax}/\text{kg} \cdot \text{m}^{-3}$)	Specific gravity (G_s)	Uniformity coefficient (c_u)	Coefficient of curvature (c_c)
19.4	33.3	18.9	14.4	1754	2.73	4.33	1.97

Table 2: Basic characteristic of fine aggregates of construction waste.

Recycled concrete (%)	Fragment of brick (%)	Rubble of tile (%)	Particle distribution (mm)	Max. dry density ($\rho_{dmax}/\text{kg} \cdot \text{m}^{-3}$)
83	11	6	0-1	2690

for Shanghai clayey soil. The soil obtained then has been air-dried and sifted through 2 mm sieve. Table 1 shows the physical and water-physical characteristic of Shanghai clayey soil. Figure 2 shows the grading curve of Shanghai clayey soil, fine aggregates of construction waste and fly ash used in this tests, which were analyzed by Laser Particle Sizer from Malvern Instruments Ltd. Shanghai China.

2.2 Fine aggregates of construction waste

Construction waste was obtained from a demolition site in Shanghai, which mainly consists of crushed concrete, a few of interspersed broken bricks, tiles and masonry works that had been sieved by the supplier to remove the wood, little

gravels and glass residues. Then the construction waste obtained from above procedure was re-crushed further into finer aggregates by mechanical force and repeatedly ground in a mortar. The construction waste after being treated in this way was stored in a plastic container. Then they are oven dried for 24 hours at a temperature of 105°C and sieved. The particles passing through 1 mm were selected for the purpose of this study. The particle size distribution of fine aggregates of construction waste is presented in Figure 2. The basic characteristics of the fine aggregates of construction waste are shown in Table 2. The main chemical composition of fine aggregates of construction waste is shown in Table 3.

Table 3: Main chemical composition of fine aggregates of construction waste.

SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)	K ₂ O (%)	Na ₂ O (%)	SO ₃ (%)	Loss of ignition
53.21	11.90	4.72	12.15	2.42	2.31	1.08	0.68	10.4

Table 4: Chemical composition of fly ash.

SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	CaO (%)	MgO (%)	K ₂ O (%)	Na ₂ O (%)	TiO ₂ (%)	P ₂ O ₅ (%)
49.96	26.51	4.32	3.04	1.15	1.18	0.31	1.04	0.15

Table 5: Physical and water physical characteristic of fly ash.

Liquid limit (W_L /%)	Plastic limit (W_P /%)	Plastic index (I_P)	Specific gravity (G_s)
34.2	27.1	7.1	2.47

2.3 Fly ash

The fly ash used for this study was obtained from Shidongkou Coal-fired Power Plant, 270# Shengshi Rd. Baoshan district, Shanghai, China. It was produced from the burning of lignite during the generation of electricity as a side-product. It is overall grayish black in color. The structure of the particles is mainly in multi-pore honeycomb, with a big specific surface area, a strong water absorbing capacity, and an extremely high adsorption activity. The mineral composition in the fly ash was dominated by quartz, mullite, anorthite, enstatite and hematite, which were determined by means of X-ray diffraction. Table 4 shows the chemical composition of the fly ash used. And Table 5 presents the basic physical and water-physical property of it. The particle size distribution of the fly ash is presented in Figure 2.

2.4 Tests performed

2.4.1 Liquid and Plastic limit

The soil of approximately 2000 g was oven dried at 105°C for 24 h, then crushed and sifted through a 0.5 mm sieve. After above procedure, the soil is divided into 7 parts. It is approximately 285 g for each part. One part was used for control that means there is no any additive mixed. Three parts of soils were dry mixed randomly and evenly with fine aggregates of construction waste as composites at a content of 8, 12, 16% in weight, respectively. Another 3 parts were mixed with fly ash in the same way as fine aggregates of construction waste. Then the liquid and plastic limit are tested

for the 7 parts of samples according to ASTM D4318-00 [32]. The plastic index was calculated from the difference between liquid and plastic limit. The apparatus used is the combined liquid-plastic tester of type STYS-1, which is produced by Zhejiang Soil Instrument Manufacturing Company Ltd. Shangyu city, China. The above test procedure was repeated for 3 times for the purpose of eliminating the test error as much as possible. Finally, the average of 3 tests was taken for later calculation in the study.

2.4.2 Maximum dry density and optimum water content

The soil was oven dried at 105°C for 24 h, then crushed and passed through a 5 mm sieve. After above procedure, the soil was divided into 7 parts. One group was used for control that means there was no any additive mixed. Three parts were dry mixed evenly and randomly with fine aggregates of construction waste as composites at a content of 8, 12, 16% in weight, respectively. Another three parts were dry mixed with fly ash in the same way as construction waste. Then the maximum dry density and optimum water content were tested for the 7 parts of samples according to ASTM 2000, D698 [33]. The apparatus used is the Standard Portable Tamper of type JDS-3, which is produced by Nanjing Soil Instrument Manufacturing Company Ltd. Nanjing city, China. The above test procedure was repeated for 3 times for the purpose of eliminating the test error as much as possible. Finally, the average of 3 tests was taken for later calculation in the study.

2.4.3 Unconfined compressive strength

Similar to above 2 subsections, the soil was oven dried at 105°C for 24 h, then crushed and passed through a 2 mm sieve. After above procedure, the soils were divided into 7 parts. one was used for control that means there is no any additive mixed. Three were dry mixed with fine aggre-

gates of construction waste as a composite at a content of 8, 12, 16% in weight, respectively. Another 3 parts were dry mixed with fly ash as another composite at a content of 8, 12, 16% in weight, respectively. Then the unconfined compressive tests on the above two composites were carried out for each of the 7 parts according to ASTM 2000, D2166 [34]. The apparatus used is the Strain-controlled unconfined compression tester of type PY-3, which is produced by Nanjing Soil Instrument Manufacturing Company Ltd. Nanjing, China. An axial load was applied at the continuous rate of 2.5 ± 0.1 mm/min. It is worth noting that unconfined compressive test on the specific composite has also been carried out for each of the following 5 curing time of 0, 7, 14, 21, 28 days for each composite above. In addition, the above test procedure was repeated for 3 times for the purpose of eliminating the test error as much as possible. The average of 3 tests was taken for later calculation in the study. The test arrangement, part of results and the road map of test scheme on the composites are shown in Table 6 and Figure 3 respectively.

Figure 3: Road map for test scheme on the composites (The numbers in the box mean number of sample used. Each test is repeated 3 times).

3 Results and discussions

3.1 Consistency indexes

In order to compare the effect of fine aggregates of construction waste and fly ash on the consistency index of Shanghai clay, the composites with different content of the two above additives are tested with combined liquid-plastic limit apparatus. The test results on the composites are shown in Table 6. The variations of consistency indexes (liquid limit, plastic limit and plastic index) for the composites are shown in Figure 4. It can be seen from Figure 4(a) that with the increase of construction waste content, the liquid limit and plastic limit of the composites all increase. Compared with control sample, the liquid and plastic limits of the composite are increased by 15.6% and 29.1%, respectively when the content of construction waste is 16%. But it can also be seen that there is an obvious minimum point with plastic index of the composites as the content of construction waste is 8%. It may mean that the plasticity of the composite is minimized at this point. Overall, the increase of liquid and plastic limit of the composites with content of construction waste suggests that the water bearing capacity of composite has been significantly increased. The cause may be related to stronger activity of fine aggregates of construction waste that tends to possess bigger specific surface area. In addition, It can be seen from Figure 4(b) that due to the adding of fly ash to soil, the liquid limits of composites are slightly increased. As the content of fly ash is 16%, the increases of liquid limit is only 6.9% compared to control sample, while that of the plastic limit is 23.8%. The increase in plastic limit is much greater than that of liquid limit, which directly leads to the decrease in plastic index in the same changing range. It may suggest that the plasticity of it is also decreased. Compared to the condition of fine aggregate of construction waste where there is no significant decrease in plasticity, there is an obvious decrease in plasticity with fly ash added composite. It may be related to the finer particles of fine aggregate of construction waste than that of fly ash. The increase in liquid and plastic limit may mean the increase in water bearing capacity, which are meaningful for agricultural production, sustainable development and improvement of geo-ecological environment. Phanikumar *et al.* [35] added fly ash into an expansive clay and concluded that its liquid limit decreases by 22%, while its plastic limit increases by 3.5% when fly ash content is 20%. The common ground between the results from Phanikumar and the present study is that their plastic limits are all up, but their difference lies in the development trend of liquid limit. The current result is that liquid limit slightly increases, but that

Table 6: Arrangement of test and part of test result (all values are average for 3 parallel tests).

Clay	Cons.waste	Fly ash	Repeated time	Plastic limit ($W_P/\%$)	Liquid limit ($W_L/\%$)	Plastic index (I_P)	Maximum dry density ($g \cdot cm^{-3}$)	Optimum moisture content (%)
100%	0	0	3	18.9	33.3	14.4	1.754	19.4
92%	8%	0	3	22.1	34.5	12.4	1.687	22.3
88%	12%	0	3	23.2	36.7	13.5	1.665	21.2
84%	16%	0	3	24.4	38.5	14.1	1.634	20.4
92%	0	8%	3	20.8	34.2	13.4	1.694	18.7
88%	0	12%	3	21.8	34.7	12.9	1.684	18.3
84%	0	16%	3	23.4	35.6	12.2	1.655	17.8

Figure 4: Change of clay consistency indexes under different contents of fine aggregates of construction waste (a), and fly ash (b).

of Phanikumar *et al.* [35] is on the contrary. This may be due to the soil type used being different. The soil type used in the current research belongs to Shanghai alluvial soil that contains large amount of coarse grain, when the relative fine-grained fly ash, which has relatively high activity (high specific surface area), is added, the liquid limit and plastic limit are all increased. However, the expansive soil used by Phanikumar *et al.* [35] contains large amount of fine grains, when the fly ash, which is relatively mostly coarser (therefore relatively lower specific surface area and lower activity) than the grain of expansive soil, is added to expansive soil, its liquid limit decreases. Sharma A. and Sharma R. K. [36] added construction waste into high plastic clay and concluded that the liquid limit and plastic limit all decrease due to the same reason as above. As high plastic clay has finer grain than that of construction waste.

Although the liquid and plastic limit increase with the increase in content of both fine aggregates of construction

waste and fly ash, the change trends of plastic indexes for both additives are different. This is because the liquid limit for fine aggregates-reinforced samples increases faster than that for condition of fly ash, while the increasing slopes of plastic limits are similar for the two conditions. It results in that the plastic index for condition of fine aggregate of construction waste almost keeps constant (down first and then up) within the additive content range of 0-16%, while it is downward consistently for condition of fly ash within the same range. Actually this phenomenon can also be easily explained from Figure 4(b). Because the particle size of fine aggregates of construction waste are generally finer than those of fly ash (Figure 2), the activity of fine aggregates of construction waste may be stronger than that of fly ash, which leads to higher water bearing capacity and plasticity of the composites. The particle size of fly ash is mostly greater than 0.03 mm, while there is 40% of fine aggregates particles of construction waste is less than 0.03 mm, and

this may be just the source of difference in plasticity. It is interesting that some other researchers also obtained the similar result from test on expansive soil reinforced with fly ash [36]. This finding is significant because the characteristics of the composites modified by different additives can be used in different practical engineering that needs different targets. For example, in arid or semi-arid area, soil can be modified by fine aggregates of construction waste to increase its water bearing capacity, which is helpful to growth and diversity of vegetation.

3.2 Compaction test

For the purpose of understanding the effect of fine aggregates of construction waste and fly ash on the compaction behavior of the treated soil, compaction test was carried out on composites with different content of fine aggregates of construction waste and fly ash, respectively. The test result is shown in Table 6. The variation of the maximum dry density and optimum water content is presented in Figure 5. Among them, Figure 5(a) is for construction waste while Figure 5(b) is for fly ash. It can be seen from Figure 5(a) that the maximum dry density is decreased with increase of construction waste. As content of construction waste changes from 0 to 16%, the maximum dry density is decreased by 6.8%. However the optimum water content shows increase at the initial stage, but decrease after a peak value. As the content of construction waste is 8%, the optimum water content is maximized that is 22, an increase of 14.9% compared with the control sample that is 19.4. It can be seen from Figure 5(b) that for condition of fly ash, the maximum dry density is also decreased with increase of fly ash content. As content of fly ash changes from 0 to 16%, the maximum dry density is decreased by 5.6%. However the optimum water content shows the constant decrease. As the content of fly ash changes from 0 to 16%, the optimum water content is decreased by 8.2%. It is a contrast to the condition of construction waste that climb up first and then decline. This phenomenon appeared on the composites may be related to the difference between the fine aggregates of construction waste and fly ash in particle size distribution. This is in line with the result from consistency test, namely, the treated sample (composite) with fine aggregate of construction waste has higher water bearing capacity than that of samples treated with fly ash. The common decline in maximum dry density with both additives is meaningful for keeping soil from packing together, increasing the workability of soil, increasing agricultural productivity and even the sustainable development and diversity of plants and animals. Mir B. A. [37] studied the effect of fly ash on the

(a)

(b)

Figure 5: Compaction curve of clay with different content of fine aggregates of construction waste (a) and fly ash (b).

compaction properties of an expansive soil, and concluded that its maximum dry density decreases with the content of fly ash, which is similar to the results of the present study. Phanikumar B. R. [35] also concluded the same results as the present study, namely the maximum dry density decreases with the content of fly ash, while optimum water content also decreases with fly ash content up to 30% of fly ash content that is completely the same as the present result. Sharma A. and Sharma R. K. [38] concluded that the maximum dry density and optimum water content all decrease with the content of construction waste, which is not completely the same as the present study. But it should be noted that the particle size of the construction waste used is different from each other. Less than 55% particle size used

in the present study of construction waste is greater than 0.1 mm, but over 90% particle size of construction waste used by Sharma is greater than 0.1 mm, which may be the reason of the difference.

Due to the specific gravity of fine aggregate of construction waste and fly ash being all less than that of soil, the composites all possess lower maximum dry density than that of control sample, regardless of the type of additives. However, the optimum water contents of the composites mixed with fine aggregate of construction waste are all larger than those of control samples to some degree. But on the contrary, the optimum water contents of composites mixed with fly ash are all smaller than those of control samples, and the more the content of fly ash, the smaller the optimum water content. Although the maximum dry densities are all dropped with two types of additives, but the drop with fine aggregates of construction waste is even steeper (6.8%) than that with fly ash (5.6%) within the same range of change in content of additives (0-16%). That is actually implicitly suggesting that the composites reinforced with fly ash may have higher unconfined compressive strength than that reinforced with fine aggregates of construction waste. What's more, the drop of optimum water content with samples reinforced with fly ash also suggests that the thickness of absorbed water layer around the surface of soil particles becomes thinner, which may strengthen the binding force among particles. This perfectly explains the discrepancy between results with two additives. However, tracing origin, it should be said that the root causes for the result difference for two types of additives in tests may be: 1) difference in particle size distribution (Figure 2); 2) difference in chemical composition (Table 3 and 4).

3.3 Unconfined compressive strength

Table 7 presents results of unconfined compressive strength test on the composites that shows the peak strength of composites with different content of fine aggregates of construc-

tion waste and fly ash, respectively for different curing time of 0, 7, 14, 21, 28 d. Figure 6 shows the stress-strain curve of composite reinforced with fine aggregates of construction waste for 7 and 28 d, respectively, while Figure 7 shows the stress-strain curve of composite reinforced with fly ash for 7 and 28 d, respectively. Because treated soil with curing time of 7 d is perceived as the initial formation of soil strength while 28 d is perceived as soil strength that approximately keep constant, therefore, to save space the authors only select the condition of 7 and 28 d for interpretation, ignoring other curing times. From Table 7(a,b), it can be seen that except for the condition of curing time of 0 d, for both construction waste and fly ash, the unconfined compressive strength of the composite increases with the increase of not only the content of the additive but the curing time. As curing time is 28 d, the unconfined compressive strength increases by 46% from 144.05 to 210.38 kPa when the content of construction waste changes from 0 to 16%. While for fly ash, it increases by 74% from 144.05 to 251.01 kPa when the content changes from 0 to 16%. However, when the content is 16%, the unconfined compressive strength of soil reinforced with construction waste increases by 33% as curing time changes from 7 to 28 d. For fly ash, this figure is 60%. This shows that curing time is an important factor for strength development of the composite as well.

Regardless of type of additive, there is a general trend that unconfined compressive strength of the composites all increase with both the content of additive and the curing time (Figure 6, 7). When curing time changes from 7 to 28 d, the unconfined compressive strength of control sample increases by approximately 26%, while those figures are 33% and 60% for fine aggregates of construction waste and fly ash, respectively, when content of additive is 16%. It demonstrates that there is a maximum increasing amplitude with fly ash, secondary with construction waste, but they are all greater than that of control sample. This also suggests that whether construction waste or fly ash, there is a relatively

Table 7: Unconfined compressive strength of clay samples reinforced with different admixtures (kPa).

material	Content(%)	0d	7d	14d	21d	28d
Shanghai clay	0	93.22	114.60	126.57	137.19	144.05
	8	113.13	130.02	147.28	162.52	177.75
	12	125.60	142.20	165.06	180.38	197.39
	16	136.48	158.26	176.17	191.57	210.38
fine aggregates of construction waste	8	89.63	122.37	146.13	166.76	180.06
	12	86.40	137.89	175.81	199.94	225.22
	16	82.94	157.25	201.66	230.96	251.01
fly ash	8	89.63	122.37	146.13	166.76	180.06
	12	86.40	137.89	175.81	199.94	225.22
	16	82.94	157.25	201.66	230.96	251.01

(a)

(b)

Figure 6: Stress-strain curve of soil reinforced with fine aggregates of construction waste for 7 d (a) and 28 d (b).

good stabilization effect with the soil, although to different degrees.

As to the formation of strength for two additives, there is a faster formation of strength with fine aggregates of construction waste than that of fly ash (Table 7). Within curing time of 7 days, the unconfined compressive strengths at all 3 contents of 8, 12 and 16% with fine aggregates of construction waste are all greater than those with fly ash (Figure 9a), however beyond the 7 days, most of the corresponding strengths are on the contrary (Figure 9b). Especially at content of 16%, and curing time of 28 days, the unconfined compressive strengths with fly ash are obviously larger than those with fine aggregates of construction waste instead. From above analysis, it can be initially concluded that the composites mixed with fine aggregates of

(a)

(b)

Figure 7: Stress-strain curve of soil reinforced with fly ash for 7 d (a) and 28 d (b).

construction waste have faster formation of strength than those mixed with fly ash. But the latter has higher final strength. Sharma *et al.* [39] also used construction waste as additive to stabilize the clay soil, which is similar to Shanghai clay, and drawn similar result that the UCS increases by about 25% when construction waste content is 22%. The root cause of the UCS increase of clay soil when mixed with construction waste may be resided in that construction waste may contain a variety of material composition, including discarded cement, lime, rubble fragment etc., which typically have either higher strength in itself or possess good cementing ability. Therefore it is presumable that when they are added into clay soil, the strength of clay soil has a high probability to increase. In our study, for two additives, the unconfined compressive strength increases

with content within limit of 16% (Figure 8), but what about beyond that limit? The authors expect further researches.

3.4 Ductility

It can also be seen from Figure 6 that regardless of curing time, the ductility of the composites is greater than that of control sample. Ductility is a measure of a material's ability to undergo significant plastic deformation before rupture. The authors use ductility ratio to express the magnitude of ductility for the composites. Ductility ratio (DR) can be defined by the following formula.

$$DR = \frac{\Delta_r}{\Delta_u}$$

Where Δ_r is axial failure strain of amended soil sample and Δ_u is the axial failure strain of unreinforced soil sample. Although the ductility of treated samples is all increased compared to that of control sample, but when content of construction waste is 8%, the ductility is maximized. It is 1.63 for curing time of 7 d, while it is 1.75 for curing time is 28 d. However, for fly ash, although the unconfined compressive strengths are all increased but their ductility decreases as shown in Figure 7. When curing time is 7 d, the ductility is significantly decreased. When content of fly ash is 16%, the ductility ratio is 0.5. For curing time of 28 d, the ductility ratios for different contents of fly ash decrease to some degree, even though they are not so much. It suggests that the extended strain is needed for the composite to be broken. From above analysis, it is considered that both the two materials of fine aggregates of construction waste and fly ash are much different in modifying the property of Shanghai clayey soil. They vary significantly with the content, type of additive and curing time. Ansary M. A. [40] concluded the same results as the present study after investigating two type of coastal soil that the brittleness of the composites of coastal soil and fly ash increases with the increase in the content of fly ash, namely the ductility decreases with the content of fly ash. Sharma A. [38] investigated the effect of construction demolition waste on the property of a poor clayey soil and concluded that the addition of construction demolition waste can increase the ductility of the composites, which happens to have the same results as the present study.

3.5 Curing time

Figure 8(a) and 8(b) show effect of curing period on unconfined compressive strength of the composites of clay soil modified with fine aggregates of construction waste and fly

Figure 8: Effect of curing period on unconfined compressive strength of fine aggregates of construction waste (a) and fly ash (b).

ash, respectively. It can be seen from Figure 8 that regardless of the type of additive, the unconfined compressive strengths are all increased with the increase of curing time. However, for construction waste, the strength formation is faster than that of fly ash at the initial stage. When curing times are 0 and 7 d, the unconfined compressive strengths of composite reinforced with construction waste are generally higher than that for fly ash for different contents. On the contrary, when curing time is 28 d, the unconfined compressive strengths for construction waste are generally lower than that for fly ash for different contents. And even when the curing time is 0 d, the unconfined compressive strengths decrease with increase of content for fly ash (Table 7). It means that the formation of strength needs enough time for fly ash, but the strength can be formed

(a)

(b)

Figure 9: Relationship of unconfined compressive strength to content of additives during different curing times. (a) for 7 d, (b) for 28 d.

much faster for construction waste. This can be clearly seen from Figure 8(a,b). This is another difference between fine aggregates of construction waste and fly ash. In order to distinguish more definitely between above two additives, the authors plot the strength-content relationship for 7 and 28 d for two additives as shown in Figure 9(a,b). Abhishek [41] concluded the similar results to the present study, that is, the unconfined compressive strength increases with the curing time, up to 28 day. Jha A. K. [42] studied the effect of fly ash on a red mud and concluded that the unconfined compressive strength increases with the curing time up to 28 days, but decreases with the content of fly ash. This may be because the matrix used is different. Kumar used red mud, while the Shanghai alluvial clay is used in the present

study. Red mud and Shanghai alluvial clay are completely different in properties.

In Figure 9(a), when curing time is 7 d, the unconfined compressive strengths of the composite for fine aggregates of construction waste are all stronger than those for fly ash for different contents. By contrast, they are all weaker than those of fly ash for different contents when curing time is 28 d as shown in Figure 9(b). In other words, the formation of strength is faster at initial stage, but its increasing rate with time is slower with fine aggregate of construction waste. And its strength formed at 28 d is much lower than that of fly ash at all contents.

4 Conclusions

The findings from the lab tests on modification of property of Shanghai clayey soil mixed with fine aggregates of construction waste and fly ash as composites can be summarized as follows:

- 1) The liquid and plastic limit of the composites increase with the increase in content of both the fine aggregates of construction waste and fly ash, although to different degrees. But the change trend of plastic indexes with fine aggregates of construction waste is uncertain, while that with fly ash keeps downward consistently.
- 2) The composites all possess lower maximum dry density than that of control sample, but the maximum dry density with fine aggregates of construction waste drops slightly steeper than that with fly ash. However, the optimum water contents of samples mixed with fine aggregate of construction waste are all larger than those of control samples to some degree. But on the contrary, with fly ash, they are all smaller than those of control samples.
- 3) Regardless of the additive type, the unconfined compressive strength of the composites all increase with both content of additive and curing time. And ductility rate of treated soil is also increased to different degrees.
- 4) The development of strength for the composite is faster with fine aggregates of construction waste at initial stage (within 7 d) than fly ash. However, the final unconfined compressive strength (28 d) with fly ash is significantly higher than that with fine aggregates of construction waste, therefore the fly ash has better effect of stabilization than construction waste.

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

Acknowledgement: The authors thank Shanghai Shiyi Information Management Company, Shanghai, China (coded 1y-00-307-026) and Project of High-End Foreign Expert Talent Introduction, Shanghai Municipal Foreign Expert Affairs Bureau (coded 20WZ2502400) for financial support.

References

- [1] Gao YB, Li H, Zhang AJ. Influence of soil structure on secondary compression behavior of Shanghai soft clay. *Shanghai Land & Resources*. 2011;32(04):73-77.
- [2] Chen C. Analysis on the application of urban hydrology in Shanghai. *Science & Technology*. 2013;(03):111-112.
- [3] Yan XX, Shi YJ. Shanghai engineering geological structure characteristics. *Shanghai Land & Resources*. 2006;(4):19-24.
- [4] Qu JL, Zhu H. Modifying mechanical properties of Shanghai clayey soil with construction waste and pulverized lime. *Science and Engineering of Composite Materials*. 2020;27:163-176.
- [5] Siavash M, Susana LQ, Ali BJ. Effect of class F fly ash on fine sand compaction through soil stabilization. *Heliyon*. 2017;3:e00274.
- [6] Zhang LC, Zan YT, Zhang HM, Zhang XL, Li Y. Review on the research progress of fly ash properties and Eco environmental effects. *Jiangxi Hydraulic Science & Technology*. 2018;44(05):330-333.
- [7] Yang AW, Xiao M, Zhou MY. Experimental Study on Lime-fly Ash to Cure Tianjin Marine Soft Soil. *Chinese Journal of Underground Space and Engineering*. 2019;15(01):60-67.
- [8] Liu Y, Li YL, Yang L. Study on the stability test of improved soft soil roadbed with fly ash. *Fly Ash Comprehensive Utilization*. 2018;(05):96-98.
- [9] Murat AO. Improvement in bearing capacity of a soft soil by addition of fly ash. *Procedia Engineering*. 2016;143:498-505.
- [10] Sarah H, Pedram S. Recycled gypsum powder from waste dry-walls combined with fly ash for partial cement replacement in concrete. *Journal of Cleaner Production*. 2020;274:122785.
- [11] Wang DX, Zhu JY, He FJ. CO₂ carbonation-induced improvement in strength and micro-structure of reactive MgO-CaO-fly ash-solidified soils. *Construction and Building Materials*. 2019;229:116914.
- [12] Ankur M, Rafat S, Togay O, *et al.* Fly ash and ground granulated blast furnace slag-based alkali-activated concrete: Mechanical, transport and microstructural properties. *Construction and Building Materials*. 2020;257:119548.
- [13] Debabrata P, Lopamudra M, Jijnasa B, Bandana P, Sidhant SB. Physiological response of metal tolerance and detoxification in castor (*Ricinus communis* L.) under fly ash-amended soil. *Heliyon*. 2020;6:e04567.
- [14] Jhonathan FR, Armando O, Nuno C, *et al.* Fly ash-based geopolymer as A4 type soil stabilizer. *Transportation Geotechnics*. 2020;25:100409.
- [15] Chee LW, Kim HM, Alengaram UJ, Soon PY. Mechanical strength and permeation properties of high calcium fly ash-based geopolymer containing recycled brick powder. *Journal of Building Engineering*. 2020;13:101655.
- [16] Mona Z, Khashayar J, Farshad R. Properties and durability of concrete containing fluidized bed combustion (FBC) fly ash. *Construction and Building Materials*. 2020;258:199663.
- [17] Muhammad AN, Babar A, Liaqat AQ, *et al.* Effect of sulfate activator on mechanical and durability properties of concrete incorporating low calcium fly ash. *Case Studies in Construction Materials*. 2020;13:e00407.
- [18] Shinhyu K, M TL, Zane L, Taehwan K. Using the Particle Model to predict electrical resistivity performance of fly ash in concrete. *Construction and Building Materials*. 2020;261:119975.
- [19] Liu ZG, Yu J, Qin YJ. Research and development status of waste concrete recycled fine aggregate. *Research & Application of Building Materials*. 2013;06:9-12.
- [20] Marcos LSO, Maria I, Xavier Q, Roy NL, Binoy KS, Luis FOS. Nanoparticles from construction wastes: A problem to health and the environment. *Journal of Cleaner Production*. 2019;219:236-243.
- [21] Shi JH. Research on Application of Recycled Concrete Fine Aggregate. *Jiangxi Building Materials*. 2014;19:4-5.
- [22] Umair H, Amin C, Mochamad AB, Hamid N. Experimental Evaluation of Construction Waste and Ground Granulated Blast Furnace Slag as Alternative Soil Stabilizers. *Geotechnical and Geological Engineering*. 2016;34:1707-1716.
- [23] Zhu MS, Qu JL. Influence of construction waste fines and lime powder on compressive strength of clay in Shanghai. *Journal of Water Resources and Water Engineering*. 2018;29(05):229-235.
- [24] Wen HF, David IM, Kim W. Evaluation of Recycled Concrete as Aggregates in New Concrete Pavements. *Transportation Research Record Journal of the Transportation Research Board*. 2015;73-78.
- [25] Christos GF, Panagiota EAP, Panos DK, *et al.* Effects of Recycled Concrete Aggregates on the Compressive and Shear Strength of High-Strength Self-Consolidating Concrete. *Journal of Materials in Civil Engineering*. 2012;24(4):356-361.
- [26] Vijayan DS, Parthiban D. Effect of Solid waste based stabilizing material for strengthening of Expansive soil- A review. *Environmental Technology & Innovation*. 2020;20:101108.
- [27] Kennedy CO. Review on the role of solid waste materials in soft soils reengineering. *Materials Science for Energy Technologies*. 2019;2:46-51.
- [28] Zhang XR, Lia WG, Tang Z, Wang XF, Sheng DC. Sustainable regenerated binding materials (RBM) utilizing industrial solid wastes for soil and aggregate stabilization. *Journal of Cleaner Production*. 2020;275:122991.
- [29] Syed ARS, Zarnish M, Aqsa N, Muhammad A, Amjad F, Muhammad W. Compaction performance analysis of alum sludge waste modified soil. *Construction and Building Materials*. 2020;230:116953.
- [30] Silvaa RV, Britoa JD, Dhir RK. Use of recycled aggregates arising from construction and demolition waste in new construction applications. *Journal of Cleaner Production*. 2019;236:117629.
- [31] Javier T, José RJ, Jesús A, María JS, Enrique FL. Functional and structural parameters of a paved road section constructed with mixed recycled aggregates from non-selected construction and demolition waste with excavation soil. *Construction and Building Materials*. 2018;164:57-69.
- [32] ASTM D4318-10. Standard test methods for liquid limit, plastic limit, and plasticity index of soils. *Annual book of ASTM Standards*. 2000;04:08.

- [33] ASTM D 698-07e1. Standard test methods for laboratory compaction characteristics of soil using standard effort. Annual book of ASTM Standards. 2000;04:08.
- [34] ASTM D2166-13. Standard test methods for unconfined compressive strength test for soils. Annual book of ASTM Standards. 2000;04:08.
- [35] Phanikumar BR, Nagaraju TV. Effect of Fly Ash and Rice Husk Ash on Index and Engineering Properties of Expansive Clays. *Geotechnical and Geological engineering*. 2018;36:3425-3436.
- [36] Sharma A, Sharma RK. Effect of addition of construction-demolition waste on strength characteristics of high plastic clays. *Innovative Infrastructure Solutions*. 2019;4:27.
- [37] Mir BA, Sridharan A. Physical and Compaction Behaviour of Clay Soil–Fly Ash Mixtures. *Geotechnical and Geological engineering*. 2013;31:1059-1072.
- [38] Sharma A, Sharma RK. Strength and Drainage Characteristics of Poor Soils Stabilized with Construction Demolition Waste. *Geotechnical and Geological engineering*. 2020;38:4753-4760.
- [39] Sharma RK, Hymavathi J. Effect of fly ash, construction demolition waste and lime on geotechnical characteristics of a clayey soil: a comparative study. *Environmental Earth Sciences*. 2016;75:377.
- [40] Ansary MA, Noor MA, Islam M. Effect of fly ash stabilization on geotechnical properties of Chittagong coastal soil. *Geotechnical Symposium in Roma*. March 16 & 17, 2006.
- [41] Abhishek, Sharma RK, Bhardwaj A. Effect of Construction Demolition and Glass Waste on Stabilization of Clayey Soil. *International Conference on Sustainable Waste Management through Design*. 2019;87-94.
- [42] Jha AK, Kumar D, Sivapullaiah PV. Influence of Fly Ash on Geotechnical Behavior of Red Mud: A Micro-mechanistic Study. *Geotechnical and Geological engineering*. 2020;38:6157-6176.