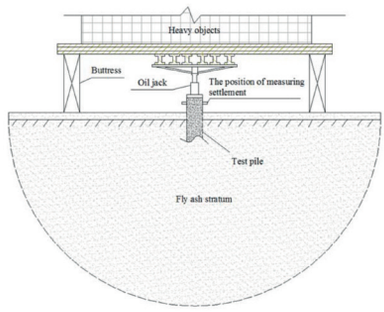
Fly ash foundation reinforced by cement–soil mixing piles



Cimentación de cenizas volantes reforzadas con pilotes de mezcla cemento-tierra

Zhou Shengquan[1], Zhang Yongfei[1], Zhou Dawei[1], Wang Weijian[1], Ke Zhaibang[2] and Sudipta Halder[3]

[1] School of Civil Engineering and Architecture, Anhui University of Science and Technology, Huainan 232001, China
[2] Anhui Key Laboratory of Green Building and Assembly Construction, Hefei 230032, China
[3] Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar 788010, India

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RESUMEN

- Los pilotes de mezcla cemento-tierra se han utilizado comúnmente para mejorar la capacidad portante del estrato de cenizas volantes y mitigar los daños causados por el asentamiento en el medio ambiente circundante. Sin embargo, sólo el cemento se utiliza como agente de curado en estos pilotes. La tasa de crecimiento de la resistencia de los pilotes de mezcla cemento-tierra disminuye con el aumento del contenido de cemento. Por consiguiente, es necesario explorar los efectos combinados de varios agentes de curado sobre la resistencia de los pilotes de mezcla cemento-tierra. Sin embargo, se han realizado estudios poco frecuentes sobre el efecto de refuerzo del estrato de cenizas volantes mediante el uso de cal o yeso como materiales de sustitución eficaces del cemento en los pilotes cemento-tierra. En este estudio, se realizaron pruebas de laboratorio para comparar las leyes de variación de la resistencia a la compresión no confinada y a la cizalladura de las muestras de prueba antes y después del reemplazo. Luego, se evaluó el efecto de refuerzo de los pilotes de mezcla cemento-tierra en diferentes proporciones de cal-cemento y yeso-cemento. Los resultados demuestran que los pilotes de mezcla cemento-tierra con un 12% de contenido de cemento no sólo mejoran la capacidad portante de los pilotes de mezcla cemento-tierra, sino que también disminuyen la cantidad de cemento. Cuando la relación de reemplazo de yeso a cemento es de 1:2, la resistencia de 28 días de las muestras de ceniza de yeso y cemento y mosca alcanza el valor máximo de 4.5 Mpa. Cuando la relación de reemplazo de cal a cemento es de 1:1, la resistencia a la compresión no confinada de 28 días de las muestras de ceniza de mosca de cemento de cal es de 6.6 Mpa, la cual aumentó en un 46% en comparación con las de las muestras de ceniza de mosca de cemento puro. Por lo tanto, la resistencia de los pilotes de mezcla de cemento y suelo en el estrato de cenizas volantes puede mejorarse gracias a la combinación de cal y cemento. La racionalidad del diseño de los pilotes de mezcla de cemento y suelo sobre el factor se verifica aún más en la prueba de campo. Los resultados de este estudio pueden ser referenciados para la aplicación de pilotes de mezcla cemento-suelo en el estrato de refuerzo de cenizas volantes.
- **Palabras clave:** Pilotes de mezcla cemento-tierra, Resistencia a la compresión no confinada, Resistencia al cizallamiento, Estrato de cenizas volantes.

ABSTRACT

Cement-soil mixing piles have been commonly used to enhance the bearing capacity of fly ash stratum and mitigate the settlement damage to the surrounding environment. However, only cement is used as curing agent in traditional cement-soil mixing piles. The growth rate for strength of cement-soil mixing piles decreases with the rise in the cement content. Accordingly, it is necessary to explore the combination effects of various curing agents on the strength of cement-soil mixing piles. However, rare studies for the reinforcement effect of fly ash stratum have been conducted by using lime or gypsum as effective replacement materials of cement in cement-soil mixing piles. In this study, laboratory tests were performed to compare the variation laws of unconfined compressive and shear strength of test specimens before and after replacement. Then, the reinforcement effect of cement–soil mixing piles at different lime–cement and gypsum–cement replacement ratios was evaluated. Results demonstrate that the cement–soil mixing piles with 12% cement content not only enhance the bearing capacity of cement-soil mixing piles but also decrease the amount of the cement. When the gypsum-to-cement replacement ratio is 1:2, the 28-day strength of gypsum–cement–fly ash specimens reaches the peak value of 4.5 MPa. When the lime-to-cement replacement ratio is 1:1, the 28-day unconfined compressive strength of lime–cement–fly ash specimens is 6.6 MPa, which increased by 46% compared with those of pure cement–fly ash specimens. Thus, the strength of cement–soil mixing piles in fly ash stratum can be improved due to the lime–cement combination. The rationality of design in cement-soil mixing piles on the factor is further verified by the field test. The results of this study can be referenced for the application of cement–soil mixing piles in the stratum of fly ash reinforcement.

Keywords: Cement–soil mixing piles, Unconfined compressive strength, Shear strength, Fly ash stratum.

1. INTRODUCTION

Fly ash, a byproduct of coal combustion in thermal power plants, exhibits a light, porous and loose structures. Fly ash stratum refers to a type of weak stratum characterized by high moisture content and compressibility which is laid by fly ash [1–3]. These characteristics of fly ash stratum often lead to problems like serious subsidence and length time of settlement in engineering. Therefore, fly ash stratum must be reinforced as a bearing layer of the foundation. Existing engineering cases suggest that cement–soil mixing piles are often applied to stratum with high water content and compressibility as they can effectively enhance the bearing capacity and inhibit settlement [4–7]. The traditional cement–soil mixing piles adopt single cement as the curing agent, however, the strength of the cement-soil mixing piles increase slowly in the later period, thereby leading to the excessive use

of cement. As a result, the reinforcement effect is often limited [8–9]. So, the reinforcement of cement–soil mixing piles should be researched by the joint use of cement and other curing agent like lime or gypsum in detail.

As two commonly used curing agents, the mechanisms of lime and gypsum in improving the strength of cement–soil mixing piles have been investigated by many scholars. The mechanism can be summarized in the two aspects: (1) When gypsum is added into the fly ash, they can react with a small amount of active SiO_2 and Al_2O_3 in fly ash to produce hydration products (ettringite and sulfoaluminate). The reaction products constantly fill the pores and overlap with each other to continuously enhance the compactness of the structures [10–12]. (2) When lime is added into the fly ash, the surface of fly ash particles dissolve continuously in the alkali solution generated by lime to produce the ions $Al_2O_4^{2-}$ and SiO_3^{2-}. Ions $Al_2O_4^{2-}$ and SiO_3^{2-} interact with Ca^{2+} to form ettringite and calcium silicate hydrate, respectively. The resulting cementitious material overlaps with unhydrated fly ash particles to produce dense and hard solids [13–15]. Besides, lime can facilitate the early hydration reaction of cement as well as the later hydration effect of fly ash to reinforce the strength of mixing piles. The addition of lime or gypsum leads to different reinforcement results in cement-soil piles However, the reinforcement result is limited in the fly ash foundation because the increasing rate of strength is reduced in the later period with the rise of the single curing agent [16–19]. Accordingly, these results provide a theoretical basis for the study of adding gypsum or lime to the cement-soil mixing piles in fly ash stratum.

2. STATE OF THE ART

Cement–soil mixing piles refer to a method to reinforce fly ash stratum. Mohammad et al. [20] studied the compressive strength of cement–fly ash specimens under different cement contents. They found that the strength of the specimens was reinforced with the cement content. Telesca et al. [21] analyzed the mineral composition of cement–fly ash specimens. They found that increasing amount of $Ca(OH)_2$ was generated with the rise in cement content to promote the pozzolanic reaction and reinforce the strength of specimens. Moreover, the addition of gypsum could effectively reduce the shrinkage of specimens. Li et al. [22] studied the microstructure of cement–fly ash specimens and reported that the increase of strength in the cement–fly ash cementing system was attributed to the combination of particles with hydration products. Khatib et al. [23] compared the effects of the porosity and pore size of cement–fly ash specimens under different gypsum contents. They found that the rise in gypsum content only affected the pore volume slightly. Most of the mentioned studies focused on the variation laws in strength of the specimens formed by the reaction between fly ash and other curing agents like cement and gypsum. They also verified the variation laws of cement and gypsum on the expansibility of the specimens. These studies were mostly concentrated on the reaction of cement or gypsum with fly ash on the strength of the cementing system and the conclusions could lay a basis for the gypsum–to–cement replacement. However, the strength of cement–fly ash under a small amount cement which was replaced by gypsum has been rarely discussed. In the meantime, there is no description of curing time on the strength and the conclusions are not broadly applicable.

The addition of lime based on the cement greatly affects the fly ash stratum reinforcement. Prasanna et al. [24] compared the results of different lime contents (0%, 5%, 7%, and 10%) on the strength of lime–cement–fly ash specimens. They found that the unconfined compressive strength reached the peak value under 7% lime content, while the processability was reduced. Guan et al. [25] studied the early hydration reaction of cement and lime by using the thermal conductivity method and concluded that the nucleation effect of lime and cement up–regulate the speed of early hydration reaction. Guo et al. [26] explored the effect of curing time on strength by the unconfined compressive test. According to the results, the strength of lime–fly ash specimens was found to increase with the lime content. The strength maintained a rapid increasing rate in later curing time. Xiang et al. [27] found that the shear strength and cohesion of lime–fly ash specimens were greater than those of pure fly ash specimens. However, no great difference was observed in the internal friction angle. Compared with those of cement–fly ash specimens, the shear strength of lime–fly ash specimens with the same mixing ratio was higher. The mentioned studies above focused on the strength variation laws of lime-cement–fly ash or lime-fly ash specimens, while neglected the strength of cement–fly ash specimens which part of the cement was replaced by lime.

Accordingly, the stress–strain relationships of cement–fly ash specimens were analyzed in this study. The effects of different lime-to-cement and gypsum-to-cement replacement ratio on fly ash specimens were investigated. Subsequently, the shear test was performed to study the change laws of cohesion and internal friction angle. The relative properties of cement-fly ash specimens replaced by lime and gypsum were compared, according to the standard of *Technical code for ground treatment of buildings* (JGJ 79–2012), the change laws of cement-soil mixing piles by analyzing the relationship of unconfined compressive strength of specimens and vertical load capacity of single cement–soil mixing pile, the design was then verified accurately by performing a vertical compressive static load test. And then, a foundation was laid for the further investigation of cement–soil mixing piles.

The remaining parts of this study are organized as follows. Section 3 presents the detailed experimental scheme and specific steps. Section 4 analyzes the experimental data. Section 5 gives the summary and conclusions.

3. METHODOLOGY

3.1. EXPERIMENTAL MATERIALS

The fly ash employed in this study was collected from the Shangyao backfill fly ash yard in Huainan City, China. Besides, ordinary Portland cement with a strength level of 32.5 was adopted. The physical properties, basic chemical compositions, and particle size compositions of fly ash are listed in Tables I, II, and III, respectively.

Table I shows that the specific gravity of fly ash is 2.18, lighter than that of consolidated clay or sandy soil. The void ratio is larger than 1, and the liquid limit is 48.9, both higher than those of sandy soil. After being dried in the laboratory, fly ash specimens are prepared with 46.5% moisture content. The cohesive value c is 10.8 kPa, and the internal friction angle value φ is 28.52°.

Table II shows that SiO_2, Al_2O_3, and Fe_2O_3 takes up 85% of the fly ash composition, and the contents of C_ao, MgO and SO_3 are low. Thus, fly ash is considered low-calcium fly ash without self-hardening capacity. Table III indicates that the particle size of fly ash ranges from 0.25 to 0.075 mm, taking up 82.5%. No clay particles are present. Thus, the engineering properties of fly ash are similar to those of the sandy soil.

Basic Index	Moisture Content	Natural Gravity	Specific Gravity	Dry Density	Void Ratio	Saturation	Liquid Limit
	ω(%)	γ(kN/m³)	G_s	ρ_d(g/cm³)	e	Sr	W1(%)
Sample Size	10	10	10	10	8	10	8
Average	46.50	14.60	2.18	0.93	1.45	76.80	48.90

Table I: Physical properties of fly ash

Chemical Composition	SiO_2	AL_2O_3	Fe_2O_3	CaO	MgO	SO_3	Loss on Ignition
Average	51.75	32.30	7.56	3.87	0.93	0.60	1.44

Table II: Chemical compositions of fly ash (%)

Particle Size Group	2–0.5	0.5–0.25	0.25–0.075	0.075–0.005	<0.005
Sample Size	8	8	8	8	8
Interval Value	0.7–3.3	8.5–12.3	79.6–83.6	2.3–6.8	0
Average	2.1	10.1	82.5	5.3	0

Table III: Particle size compositions of fly ash

3.2. EXPERIMENTAL APPARATUS

The unconfined compressive test and the shear test were accomplished using the WDT–100 machine and EDJ–2 shear apparatus. According to the standard of *Technical code for ground treatment of buildings* (JGJ 79–2012), the experiments were made in the test. The experimental apparatus and specimens are shown in Fig.1.

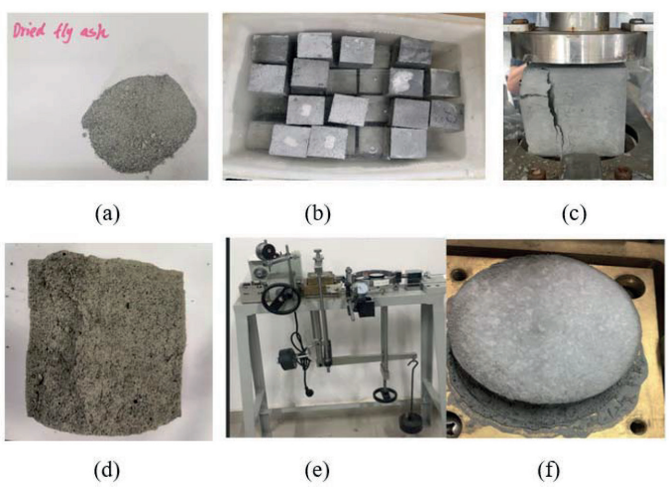


Fig. 1: Experimental apparatus and specimens. (a) Dried fly ash. (b) Maintenance condition. (c) Unconfined compressive test. (d) Failure form of specimens. (e) Shear apparatus (f) Specimens for shear test

3.3. EXPERIMENTAL SCHEME

Dried fly ash was added with water and the moisture content was kept to 46.5%. According to literature [28], the proper cement content in the cement–soil mixing piles taken up 6%–20%. The experimental scheme in this study was employed to replace cement with lime and gypsum in a certain proportion to obtain the optimal replacement ratio. Table IV lists the relevant parameters of cement–fly ash specimens, where a_w denotes cement content. The replacement ratio and other parameters in the unconfined compressive strength test are listed in TableV. The replacement ratio corresponds to the mass ratio of lime or gypsum to cement. The replacement ratio at 1:1 reveals that the mass of lime or gypsum takes up 50% of the total curing agent mass. The 1:2 replacement ratio reveals that lime or gypsum takes up 33.33% of the total curing agent mass. The 1:3 replacement ratio suggests that the mass of lime or gypsum is 25.00% of the total curing agent mass. For the unconfined compressive strength test, the cube mold with 70.7 mm length were taken. After the optimal cement, lime, and gypsum contents were obtained, the specimens were performed to a shear test. The shear test specimens were prepared by a cutting ring with an inner diameter of 61.8 mm and a height of 20 mm. Corresponding parameters in the direct shear test are listed in Table VI.

3.4. EXPERIMENTAL STEPS

The fly ash was dried in a high-temperature oven and then screened out through a 5 mm standard sieve. The experimental schemes in Table IV and V suggest that cement–fly ash, lime–cement–fly ash and gypsum–cement–fly ash were placed in a mortar mixer to mixed evenly, and the mixture was place in the mold (with release agents applied on the inner wall of the mold evenly). The mold with mixture was placed on the vibration table and then vibrated until no bubbles were discharged. Specimens were smoothed with a geotechnical knife and then covered with a fresh-keeping film. The specimens are placed in a saturated $Ca(OH)_2$ solution for curing. The specimens for shear test were made by a cutting ring. Lime–cement–fly ash and gypsum–cement–fly ash were mixed evenly according to table VI. Three specimens were taken from each group to conduct the unconfined compressive strength test. The loading rate was 0.5

Cement content a_w/%	Curing Time T/days			Moisture content ω/%
6	7	28	60	46.5
8	7	28	60	46.5
10	7	28	60	46.5
12	7	28	60	46.5
15	7	28	60	46.5

Table IV: Cement–fly ash specimens

Curing Agents %	Ratio of lime replacement cement	Ratio of gypsum replacement cement	Curing Time T/days		Moisture content ω/%
12	1:1	1:1	7	28	46.5
12	1:2	1:2	7	28	46.5
12	1:3	1:3	7	28	46.5

Table V: Parameters of gypsum and lime replacement cement

Curing Agents %	Ratio of lime replacement cement	Ratio of gypsum replacement cement	Curing Time T/days	Moisture Content ω/%
0	0	0	7	46.5
12	1:1	1:2	7	46.5

Table VI: Shear test parameters

mm/min. In the shear test, each group contained four specimens, and the specimens were tested at 0.8 mm/min shear rate.

4. RESULT ANALYSIS AND DISCUSSION

4.1. UNCONFINED COMPRESSIVE STRENGTH ANALYSIS

Based on research results [28], the unconfined compressive strength of the indoor test can be used for the estimation of single cement–soil mixing pile characteristic vertical load capacity. The formula is

$$R_a=\eta \cdot f_{cu} A \quad (1)$$

R_a- the characteristic vertical load capacity of single cement soil pile, kN;
η- strength reduction factor, 0.20-0.33;
f_{cu}- unconfined compressive strength of test specimens, kPa;
A- cross section area of the pile, m^2.

Equation 1 gives the relationship between the characteristic vertical load capacity of single cement–soil mixing pile and the unconfined compressive strength of the specimens, indicating that the vertical standard load capacity of the single pile is proportional to the compressive strength of the specimens. By analyzing the variation law of the unconfined compressive strength of the test specimens, the variation characteristics of the vertical standard load capacity of the cement–soil mixing piles can be obtained.

Fig. 2 presents the stress–strain curves of cement–fly ash specimens with the increasing cement contents of 6%, 8%, 10%, 12%, and 15% for 7 and 28 days.

Fig. 2 suggests that the stress–strain curves of cement–fly ash specimens with low cement contents (6%, 8% and 10%) increases approximately linearly before failure and then decreases slightly after the failure strength is reached. A noticeable plastic failure occurs. With the rise in cement content, the strength of the specimens is enhanced, and the specimens gradually exhibits brittle failure.

Fig. 3 shows the effect of curing time on the strength of cement–fly ash specimens with cement contents of 6%, 8%, 10%, 12%, and 15% for 7, 28, and 60 days.

Fig. 3 shows that the unconfined compressive strength of cement–fly ash specimens with 6%, 8%, and 10% cement contents at the curing time of 7 days is 0.6, 0.7, and 0.8 MPa, respectively, and strength increase slowly. The unconfined compressive strength of the specimens with the cement contents of 12% and 15% reaches 1.5 and 2.5 MPa, respectively. Compared with 10% specimens cement content, strength increased by 87.50% and 212.50%. Under the curing time of 28 days, the unconfined compressive strength for the specimens with 6% and 8% cement contents is 1.6 and 2.4 MPa, respectively, and the latter increased by 0.8 MPa more than the former. The unconfined compressive strength with 10% cement content is 2.8 MPa, which increased by 0.4 MPa compared with that of the 8% cement content. The strength of specimens with 12% and 15% cement contents is 4.5 and 5.6 MPa, with an increase of 1.7 and 1.1 MPa, respectively. Thus, strength is significantly improved.

At the curing time of 60 days, the unconfined compressive strength with the cement content of 6% and 8% is 2.1 and 3.9 MPa, respectively. The latter increased by 1.8 MPa compared with the former. The strength of the specimens with 10% cement con-

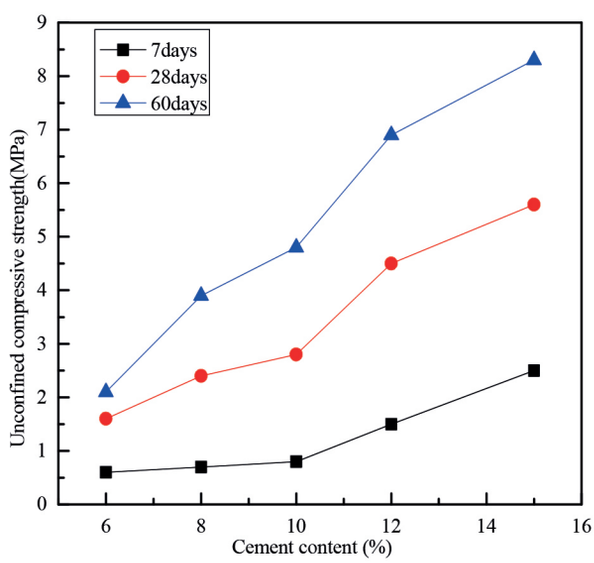


Fig. 3: Effect of curing time on the strength of cement–fly ash specimens

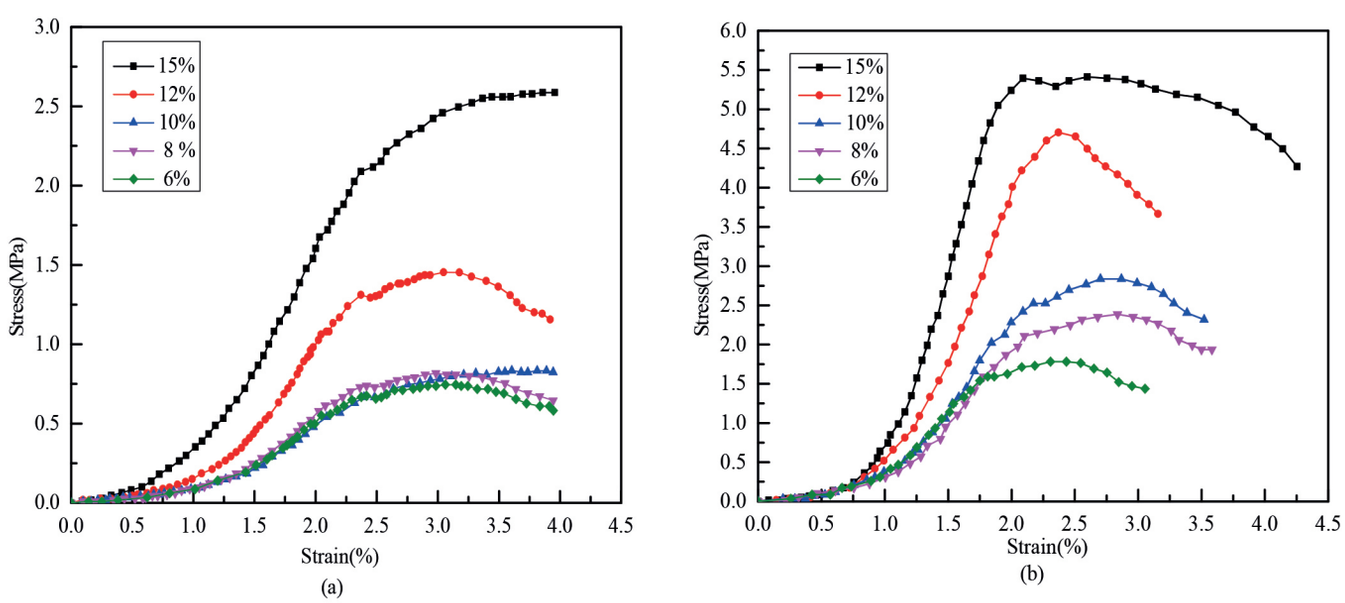


Fig. 2: Stress strain curves of cement–fly ash specimens. (a) 7 days. (b) 28 days

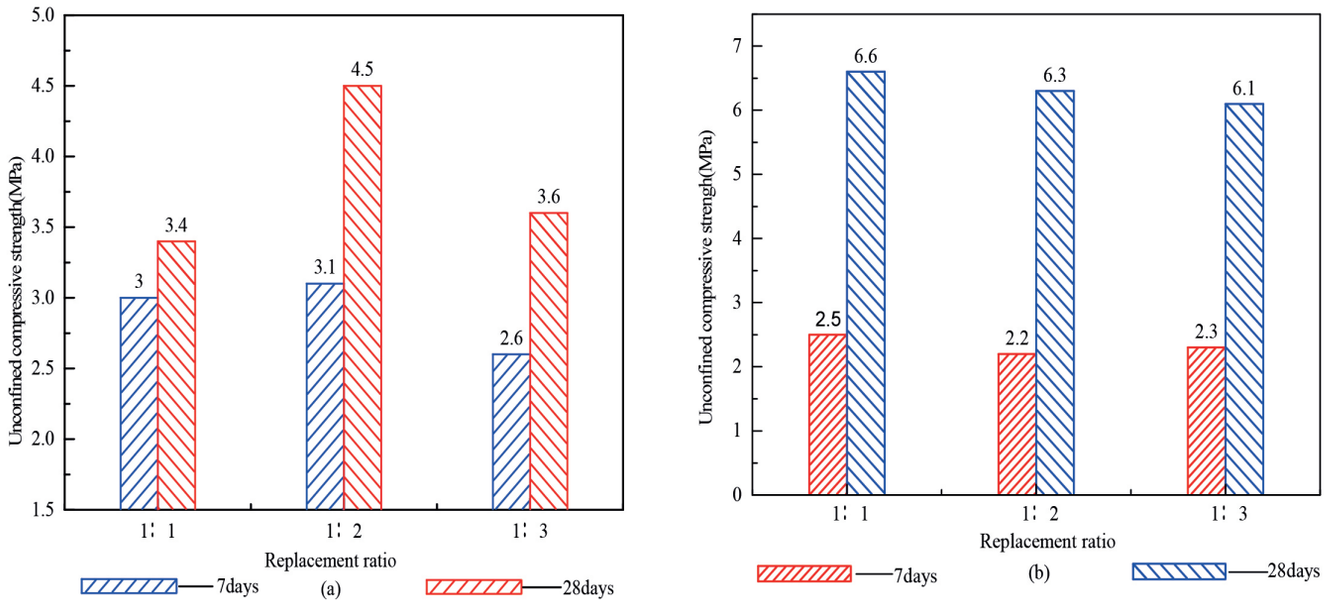


Fig. 4: Effect of the different curing agents on the unconfined compressive strength of specimens. (a) Gypsum–cement–fly ash specimens. (b) Lime–cement–fly ash specimens

tent is 4.8 MPa, marking a rise in 0.9 MPa compared with the cement content of 8%. The improvement of the strength is insignificant. The strength of the specimens with 12% cement content is 6.9 MPa, an increase of 2.1 MPa compared with the cement content of 10%, thereby presenting obvious improvement in strength. The strength of the specimens with 15% cement content is 8.3 MPa with an increase of 1.4 MPa compared with the cement content of 12%. These results reveal that the strength of specimens with 12% cement content at the curing time of 28 and 60 days has the greatest improvement, reaching 1.7 and 2.1 MPa, respectively. Considering the amount of cement in construction, the cement content of 12% is taken as the optimal and basic content of the later test. Given 12% of the basic ratio of the curing agent weight in cement-soil mixing piles, the unconfined compression tests were performed on the specimens prepared at part of cement which was replaced by gypsum or lime according to the experimental scheme (Table V). The results are shown in Fig. 4.

As is shown in fig. 4(a), under the condition of gypsum, the strength of gypsum-cement–fly ash specimens in the early curing time reaches high value. Under the curing time of 7 days, the unconfined compressive strength of gypsum–cement–fly ash specimens with the replacement ratio of 1:1, 1:2, and 1:3 is 3.0, 3.1, and 2.6 MPa, respectively. With the replacement ration is up-regulated from 1:1 to 1:3, the strength of the gypsum–cement–fly ash specimens shows the rule of fluctuation. The strength of the specimens increased by 100.00%, 106.69%, and 73.33%, respectively, compared with the cement–fly ash specimens with 12% cement content. At the curing time of 28 days, with the gradual decrease in the gypsum content, the strength of the specimens first rises and then decreases. When the gypsum-to-cement replacement ratio is 1:2, the unconfined compressive strength of gypsum–cement–fly ash specimens reaches the peaked value of 4.5 MPa, indicating no obvious change compared with the cement–fly ash specimens with 12% cement content. The results suggest that the replacement of cement with gypsum reinforces the early strength of cement–soil mixing piles which can shorten the construction period and improve engineering efficiency. However, with the increase of curing time, the long–term strength is slightly reinforced.

The variation laws of the strength are shown in fig. 4 (b). Under the condition of lime, the strength of lime–cement–fly ash specimens gradually decreases with the rising replacement ration. When the curing time is 7 days, the unconfined compressive strength of lime–cement–fly ash specimens with the replacement ratio of 1:1, 1:2 and 1:3 is 2.5, 2.2, and 2.3 MPa, respectively. However, the strength of the lime–cement–fly ash specimens is up-regulated by 66.67%, 46.67%, and 53.33% compared with the cement–fly ash specimens with a cement content of 12%. At the curing time of 28 days, the unconfined compressive strength of lime–cement–fly ash specimens is reduced from the initial 6.6 MPa to the final 6.1 MP, but compared with the cement–fly ash specimens with 12% cement content, the strength increased by 46.67%, 30.00%, and 35.56% At the lime–to–cement replacement ratio of 1:1, the unconfined compressive strength of lime–cement–fly ash specimens is peaked value, indicating that the lime-to-cement replacement positively affects the enhancement of cement–soil mixing piles strength.

4.2. DATA ANALYSIS OF SHEAR TEST

According to table VI, the shear test was performed with the specimens of fly ash, cement–fly ash, lime–cement–fly ash, gypsum–cement–fly ash. The results are illustrated in Fig. 5.

Figure 5 shows the internal friction angle and the cohesion of the fly ash specimens under the moisture content of 46.5% reach 28.52° and 10.8 kPa, respectively, while under 12% pure cement content are 45.21° and 176.2 kPa, marking a significant increase by 58.50% and 1500%. Under the condition of gypsum, the internal friction angle and the cohesion of the gypsum–cement–fly ash specimens are 38.7° and 207.6 kPa with the replacement ratio of 1:2, which increased by 35.63% and 17.8% compared with those of cement–fly ash specimens. After the addition of lime, the change of internal friction angle and the cohesion in lime–cement–fly ash specimens are obviously affected, under the replacement ration of 1:1, the internal friction angle and the cohesion marking reach peaked value of 48.5° and 242.65 kPa. The mentioned results reveal that the internal friction angle and the cohesion of the lime–cement–fly ash specimens at the lime–to–cement replacement ratio of 1:1 significantly rise, and the lime–to–cement replacement positively reinforces the strength of cement–soil mixing piles (the test data were obtained using the specimens at the curing time of 7 days).

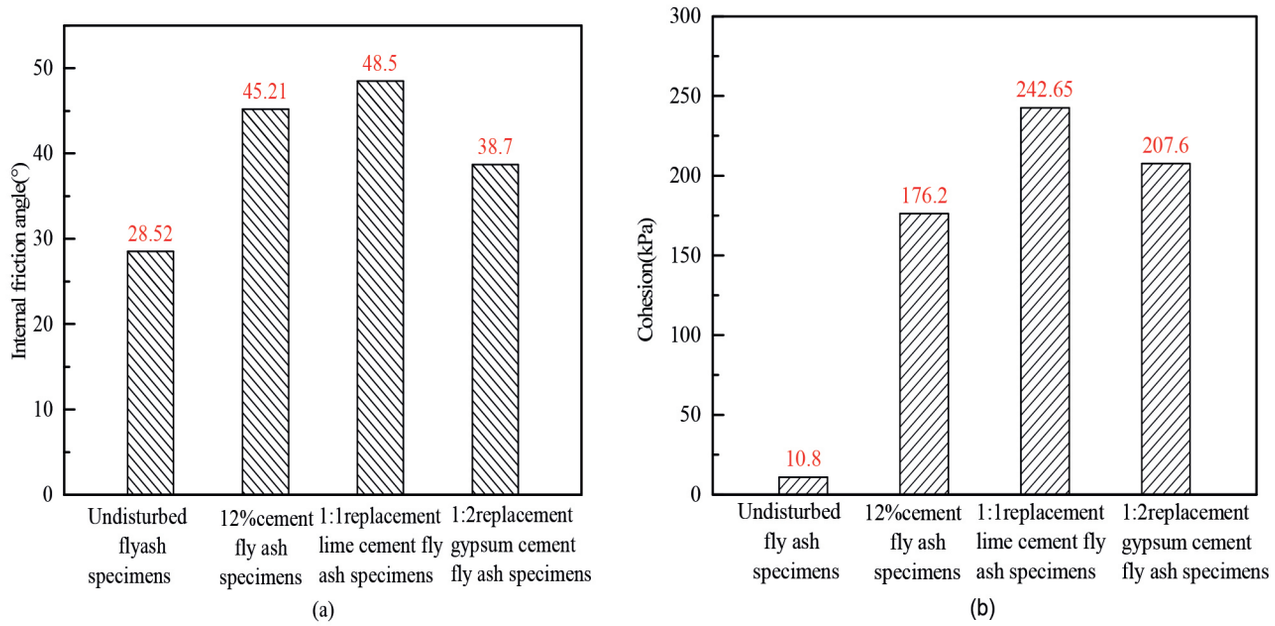


Fig. 5: Effect of different curing agents on the shear strength of specimens. (a) Effect of different curing agents on the internal friction angle of specimens. (b) Effect of different curing agents on the cohesion of specimens

4.3 TEST ON THE VERTICAL LOAD CAPACITY OF CEMENT-SOIL MIXING PILES

4.3.1. Experimental devices

The cement–soil mixing piles project in fly ash stratum is in the Shangyao, Huainan city, China. The content of cement is 12% in cement-soil mixing piles, the design value of vertical load capacity in a single cement-soil mixing pile is 100 kN. As is shown in the figure 6, the single pile vertical load capacity was detected by performing vertical compressive static load test. In the test, loads were applied using an oil jack, and the counterforce was provided by the upper heavy objects. The devices used in the test included JCQ–302 static loading device, MC–50 displacement sensor. The jack was placed vertical to apply the vertical load, two displacement meter were placed symmetrically at two sides of the testing pile to measure its displacement under vertical loads.

4.3.2 The test principle and method of vertical load capacity

Single-pile vertical load capacity test is performed by measuring settlement of the observation point under different vertical forces. In this method, the vertical load–pile top settlement relation curves are illustrated. The method of vertical compressive static load test is adopted according to *Technical code for testing of building foundation piles* (JGJ 106–2014). In the test, loading process was accomplished in accordance with the staged method of equivalent increment, the staged load value was the 1/10 of the maximum test loads. The first stage load value was twice as much as staged load. After each staged loading, the load was kept constant by 2 hours, and vertical settlement was measured every 30 minutes with 2 hours. Then the next staged load was loaded until the design load was reached.

4.3.3. Result analysis and discussion

The diameter of cement-soil mixing pile is 500 mm, and the pile length is 15000 mm, seven cement-soil mixing piles were tested by using vertical compressive static load test, they are numbered P1~ P7 respectively. The experimental results are shown in figure 7.

As is shown in figure 7, after load was increased to the maximum design value of 200 KN, the pile top settlement reached the standard. According to *Technical code for testing of building*

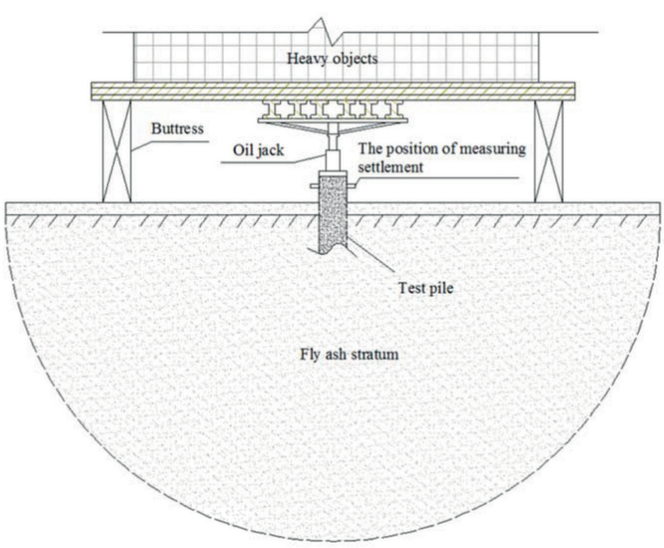


Fig. 6: Schematic diagram of vertical compressive static load test

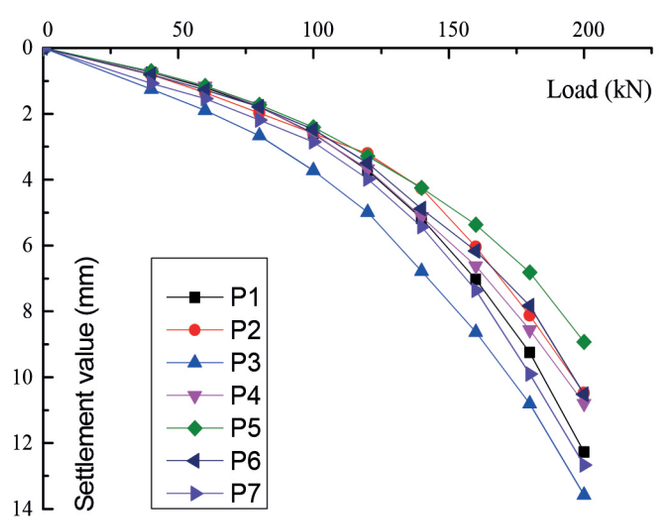


Fig. 7: Q-S curves of cement-soil mixing piles

foundation piles (JGJ 106-2014), the test was stopped. The Q-s relationship curve of cement-soil mixing pile varies gradually. The value of vertical ultimate load capacity in single pile is 200 kN, the characteristic vertical load capacity is 1/2 of the vertical ultimate load capacity, is 100 kN. The vertical compressive static load test indicates the cement-soil mixing piles with cement content of 12% meet the design requirements.

5. CONCLUSION

The optimal cement content was obtained first, and the unconfined compressive and shear test were performed on the lime–cement–fly ash specimens and gypsum–cement–fly ash specimens with different replacement ratio based on the different curing time. Lastly, a vertical load capacity of cement-soil mixing piles test was performed on seven cement-soil mixing piles. The characteristic value of vertical load capacity for the test piles was achieved through the curves of vertical load–pile top settlement. The following conclusions could be drawn.

The stress–strain curves of cement–soil mixing piles primarily display three stages (elastic, plastic, and failure). The strength of cement-soil mixing piles with 12% cement content is reinforced most significantly. Adding gypsum can improve early strength, the addition of lime in cement–soil mixing piles can effectively improve the later bearing capacity. The vertical characteristic load capacity of the cement-soil mixing piles is achieved on the basis of the field test. Combined with the result of field test and the formula 1, for replacement part of cement by lime when replacement ratio is 1:1, the vertical load capacity of cement-soil mixing piles increases significantly.

In this study, the effects of replacing cement with different curing agents on the reinforcement of cement–soil mixing piles in fly ash stratum are explored. The optimal replacement ratio of cement which is replaced by lime is obtained. This study can be referenced for engineering applications. However, as a curing agents, the engineering stability of lime is unremarkable. In the present study, the stability of lime–cement–fly ash specimens is not considered, and the durability of lime–cement–fly ash specimens requires further investigation.

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