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Investigation on Compression Behavior of Fly Ash and Metakaolin Treated Soft Soil

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Abstract: To investigate the effects of metakaolin content and curing time on compression properties of fly ash-metakaolin-treated soft soil, this study carried out a series of compression tests on fly ash (20% by weight) and metakaolin treated soft soil tests with different metakaolin contents (0%, 3%, 6% and 12% by weight) and curing times (3h, 7d and 28d). Test results showed that the compressibility of fly ash-metakaolin-treated soft soil is significantly reduced compared with the higher compressibility of pure soil. At the same curing time, the slope of the compression *e-p* curve of the solidified soil sample with high metakaolin content is smaller than that with a low one, and the compression curve with high metakaolin content tends to be more gentle. At a given metakaolin content, the compressibility of samples with higher curing time is lower than that of samples with lower curing time. The longer the curing time, the lower is the compressibility of the treated soft soil. Both metakaolin content and curing time affect the variation of compression indexes. In the pre-yield stage, the compression index is insensitive to the change of metakaolin content and curing time. While in the post-yield stage, the compression index showed a significant decreasing trend with the increase of metakaolin content and curing time. The magnitude of compression index in the pre-yield stage is significantly lower than that in the post-yield stage.

Keywords: Soft soil; fly ash; metakaolin; curing time; compression.

1. INTRODUCTION

Soft soils are weak cohesive soil with fine-grained soil particles (Yin et al. 2021), which are widely distributed worldwide such as in coastal regions (Brand and Brenner 1981). Various kinds of important civil engineering infrastructures have to be built in those coastal areas resting on soft soil foundations (Rankka et al. 2004; Emmanuel et al. 2019). It has been well reported that soft soil always has poor engineering properties such as high water content, high compressibility, low shear strength and low permeability (Deng et al. 2014; Yin et al. 2021). Therefore, it is important to improve the soft soil foundation in the practice of engineering (Horpibulsuk et al. 2010; Ren et al. 2018).

Soil solidification and stabilization method are soil improvement techniques that are widely used in engineering applications. Solidifying agents such as lime, cement, mineral powder, fly ash and other solidified materials are often employed to solidify and stabilize the soil structure (Chen and Lin 2009). Noted that fly ash includes spherical particles of silica oxide, aluminum, iron, and nonoxide carbon from burning coal (Lu et al. 2022), which is a byproduct of burning pulverized coal in electric power generating plants (Yao et al. 2015). In China, the annual output exceeds 600 million tons, accounting for about half of the total output of fly ash in the world (Jiang 2020). Compared with cement and other solidified materials, fly ash is about one-fourth the price of cement (Nochaiya et al. 2010). Furthermore, the fly ash particles are fine, the specific surface area is large, and it is easy to fully mix with soft soil. The active ingredients SiO_2 and Al_2O_3 contained in fly ash have the pozzolanic effect, which can effectively improve the poor engineering characteristics of soft soil (Locat et al. 2014; Bastani et al. 2017; Yu et al. 2017). It has been proved that fly ash is an effective curing agent to enhance soil compressibility and solubility, control soil salinization, and improve the compressive strength and durability of high soft soil foundations (Senol et al. 2006). Studies have shown that the strength of cement soil mixed with fly ash is higher than that of cement-soil samples without fly ash (Jia et al. 2004). When the content of fly ash is 20%, it has a good reinforcement effect (Ma et al. 2010).

On the other hand, metakaolin is an anhydrous form of the mineral kaolin of clay, which is produced by heating and calcining of kaolin containing 40-45% Al_2O_3 and 50-55% SiO_2 (Barbhuiya, et al. 2015; Poon, et al. 2001). It is a pozzolanic material that can be used in concrete as an admixture. China is rich in kaolin mineral deposits, and there are more than 210 proven kaolin mineral deposits (Chu, et al. 2013). Proved kaolin reserves in all major coal mining areas reach 4.339 billion tons (Wang 2018). Deng et al. (2016) found that 3% metakaolin mixing content is the best for 28 days since the strength can reach 2 times the unmixed specimen. Reddy et al. (2018) investigated the enhancement of soil properties by using fly ash and metakaolin. It is conducted to inspect the potential use of fly ash, metakaolin, and fly ash and metakaolin combination of admixtures for the improvement of engineering properties of expansive soil.

Considering the limited studies on the combined effect of fly ash and metakaolin in the treatment of soft soils. This study presented a series of one-dimensional compression tests on treated soft soil samples with various metakaolin contents (0%, 3%, 6% and 12% by weight) and curing times (3h, 7d and 28d). The influences and mechanism of curing agent content and curing time on the compression and strength characteristics of fly ash-metakaolin-treated soft soil were systematically investigated.

2. MATERIALS AND METHODS

2.1 Materials

The soft soil sample is taken from a construction site at Lianyungang city in China. The index properties of soil are determined and summarized in Table 1. According to the unified soil classification system (USCS), the soil sample tested can be classified as clay with high plasticity (CH). X-ray diffraction (XRD) test shows that the mineral composition of the soil sample is composed of 59% montmorillonite, 31% illite, 5% kaolinite, 4% chlorite, and 1% ordered mixing layer. In addition, Class-C fly ash was used in the present study. The basic physical and chemical indexes of fly ash and metakaolin are listed in Table 2.

Table 1 Index properties for testing soil

Natural water content w(%)	Liquid limit w_L(%)	Plastic limit w_p(%)	Plastic index I_p(%)	Natural unit weight (kN/m³)	Specific gravity G_s
48.2~49.5	56.4	28.6	27.8	17.8	2.71

Table 2 Index and properties of fly ash and metakaolin

Material	Chemical composition content (w.t. %)					
	SiO_2	CaO	MgO	Al_2O_3	Fe_2O_3	Other
Fly ash	42.31	21.77	3.16	22.57	4.17	6.02
Metakaolin	47.51	0.77	0.14	44.61	3.24	3.73

2.2 Methods

In this study, fly ash and metakaolin were used as curing agents to treat the soft Lianyungang soft soil. First, the obtained Lianyungang soft soil was air-dried and remolded with adding water to prepare a target initial water content of 56%, which is about 1 time the liquid limit. Then the soft soil sample is fully mixed with metakaolin at different contents (i.e., 3%, 6%, and 12%) and/or 20% fly ash by weight, and stirred using a portable mechanical mixer till the attainment of a homogeneous soil-water-metakaolin and/or fly ash paste. The reason we choose 20% fly ash is that a relatively better treatment effect can be obtained at this content from the previous study (Ma et al., 2010) in which fly ash is used as a stabilizing agent. After mixing evenly, a series of parallel samples are prepared with a steel ring (61.8 mm inner diameter and 20 mm height) for one-dimensional compression tests. The prepared specimens with different metakaolin contents and curing times were placed in the standard curing chamber equipped with a humidifier that maintained an almost constant temperature (20±2) °C and relative humidity of more than 95%. Table 3 shows the oedometer testing program. The loading increment ratio in the test is 1:1. The applied compression pressure is 12.5, 25, 50, 100, 200, 400, 800kPa, and the 24-hour duration under each load was used.

Table 3 One-dimensional compression test program

Fly ash content	Metakaolin content	Curing time	Pressure (kPa)
20%	0%, 3%, 6%, 12%	3h, 7d, 28d	12.5, 25, 50, 100, 200, 400, 800

3. RESULTS AND DISCUSSION

3.1 Compression curve

Fig. 1 shows the semi-logarithmic e-lg$p$ curve of fly ash and metakaolin solidified soft soil specimens with different metakaolin contents at a given curing time. Compared with the straight line of pure soil, fly ash-metakaolin-treated soil specimens show approximately two straight-line e-lg$p$ curves. The slope of the pure soil is the compression index C_c. For fly ash-metakaolin-treated soil, the intersection point of the two straight lines is termed the compression yield stress p_y. Taking the yield stress as the threshold, the compressibility of the soil sample is very small in the pre-yield stage, that is, when the consolidation pressure is lower than p_y, while it increases significantly in the post-yield stage, that is, when the consolidation pressure is greater than p_y. The reason for this phenomenon is that the formation of the structure of the fly ash and metakaolin solidified soil mainly depends on the cementation and filling of the hydration reaction products of the active components in the soil pores. Therefore, the compressibility of the solidified soil before yielding is very small. Once the skeleton formed by the hydration products yields, the structure of the solidified soil will be destroyed rapidly, resulting in the rapid increase of the compressibility of the solidified soil.

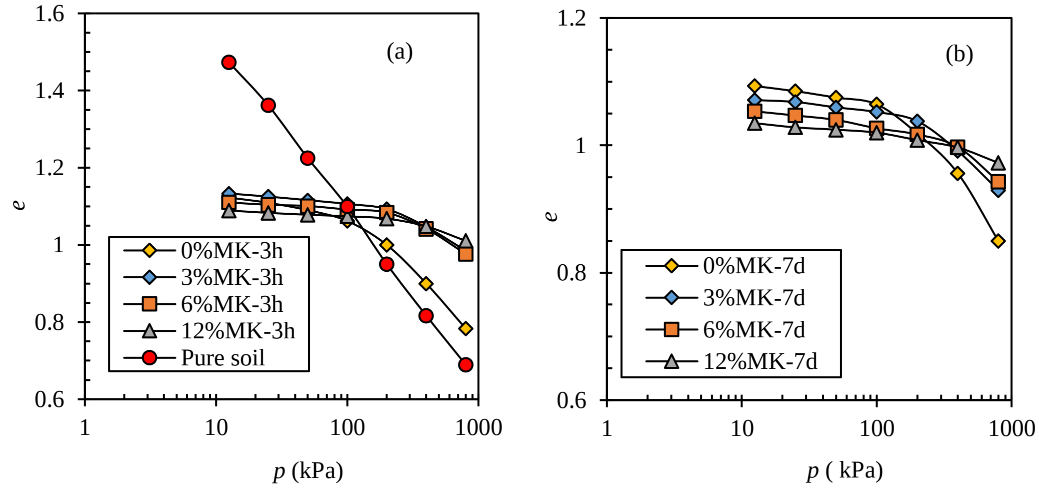

Fig. 1 *e*-lg*p* compression curves of fly ash-metakaolin-treated soft clay specimens with different MK contents at the curing time of (a) 3h, (b) 7d, and (c)28d

3.2 Effect of metakaolin content

As an important indicator for predicting the compressibility of soil and estimating how much settlement that is occurred due to loads of different engineering structures, the compression index C_c is widely used. The compression curve of the fly ash-metakaolin-treated soft soil specimens shows an obvious two-straight-line characteristic, as shown in Fig. 1. In the present study, it is defined that the slope of the straight line in the pre-yield stage of the sample as pre-yield compression index C_c, and the slope of the straight line in the post-yield stage as post-yield compression index C'_c. By analyzing the changes of C_c value and C'_c value with metakaolin content, its influence on compression characteristics of fly ash-metakaolin-treated soil in the pre-yield and post-yield stage can be investigated and the results are shown in Fig. 2.

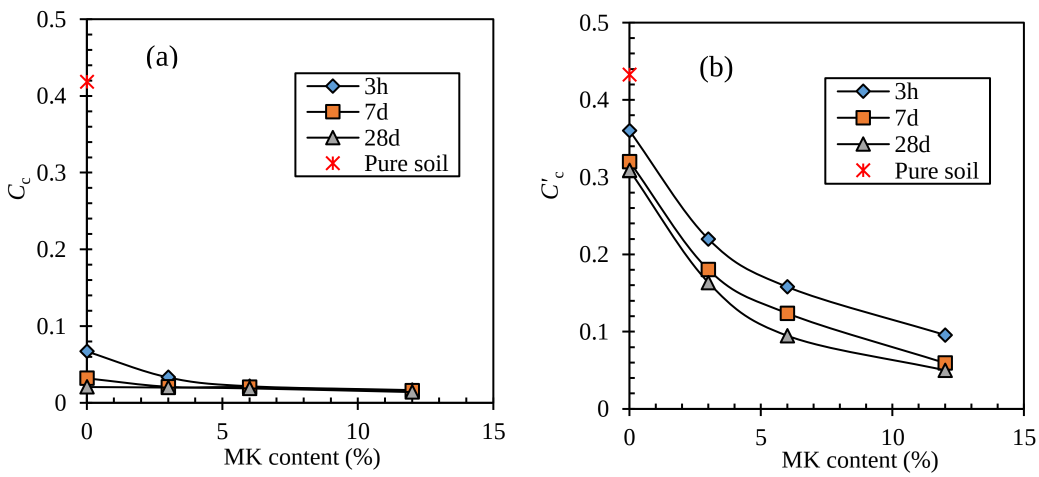

Fig. 2 Variation of compression index (a) C_c at the pre-yield stage and (b) C'_c at the post-yield stage with MK content

It can be seen from Fig. 2 that the change of compression index with metakaolin content in the pre-yield and post-yield stage is different. On the whole, the compression index of fly ash and metakaolin solidified soil samples under different metakaolin contents is lower than that of pure soil (C_c=0.42), indicating that the compressibility of solidified soil has been significantly reduced. This reflects the solidifying effect of the addition of fly ash and metakaolin. In addition, in the pre-yield stage, as shown in Fig. 2(a), soil samples with different metakaolin contents showed the same variation laws, that is, the C_c value showed a slightly decreasing trend with the increase of metakaolin content, which indicates that the metakaolin content has little effect on the compressibility of soil in the pre yield stage. In the post-yield stage, as shown in Fig. 2(b), however, the compression index C'_c showed a significant decreasing trend with the increase of metakaolin content. The C_c value of the pre-yield stage is significantly

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lower than the C'_c value of the post-yield stage. For example, the maximum C_c value in the pre-yield stage is 0.067 and the maximum C'_c value in the post-yield stage is 0.360.

Besides, as shown in Fig. 2(a), the C_c value of the pre-yield stage is unsusceptible to metakaolin content, varying in the range between 0.014 and 0.067, which is much lower than the slope C'_c in the post-yield stage. The variation curves of samples with different metakaolin contents tend to overlap. For example, for the specimen at the curing time of 28d, as the metakaolin increases from 0% to 12%, the C_c value decreases from 0.021 to 0.014 with a reduction of 33.3%. In contrast, in the post-yield stage, for the specimen at the curing time of 28d, when the metakaolin increased from 0% to 12%, the C'_c value decreased from 0.309 to 0.050 with a reduction of 83.8%, which indicates a significant decrease in soil compressibility of fly ash and metakaolin stabilized sample in the post-yield stage. The possible reason is that the active components SiO_2 and Al_2O_3 in fly ash react with water to produce calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) and other hydraulic compounds (Horpibulsuk et al. 2013), which have cementation and filling effect on soft soil particles, resulting in low compressibility of the solidified soil before yielding. When the yielding is reached, the structure of the solidified soil is rapidly damaged, resulting in a rapid increase in compressibility.

Since the compression e-lg$p$ curve for fly ash-metakaolin-treated soft soil samples shows the two-straight-line type, the intersection point termed as the compression yield stress can be obtained. Fig. 3 shows the variation of yield stress with the metakaolin content. It can be seen from Fig. 3 that the yield stress of fly ash-metakaolin-treated soft soil samples shows an increasing trend with the increase of metakaolin content. Moreover, as the metakaolin content is increased from 0% to 6%, the yield stress rapidly increases, while a less increment can be found when the metakaolin content is increased from 6% to 12%. This indicates that the effect of metakaolin content on the yield stress is more significant in the lower range of metakaolin content within 6%. For example, the specimen at curing time of 7d, as the metakaolin is increased from 6% to 12%, and the yield stress increased from 320 kPa to 350 kPa with an increment of 30 kPa, while when the metakaolin is increased from 3% to 6%, the yield stress was increased from 270 kPa to 320 kPa with an increment of 5kPa. The possible reason is that the pozzolanic reaction of active SiO_2 and Al_2O_3 is more obvious at the lower content of metakaolin (<6%). When the metakaolin content continues to increase, the pozzolanic reaction becomes less significant.

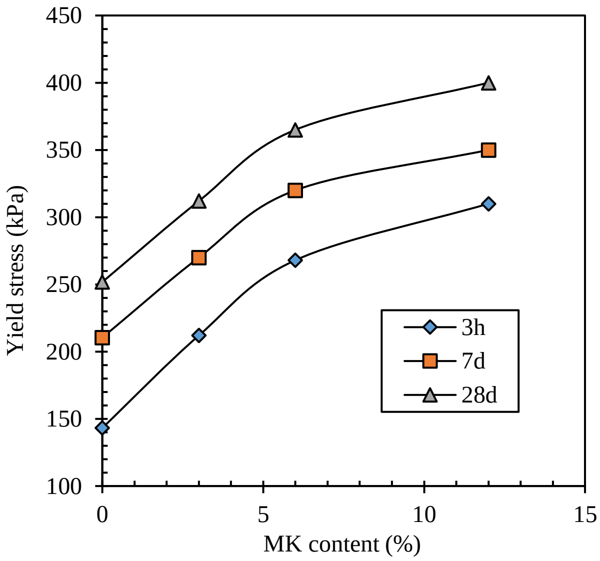

Fig. 3 Variation of yielding stress with MK content

3.3 Effect of curing time

For further analyzing the influence of curing time on compression index in the pre-yield and post-yield stage of fly ash and metakaolin stabilized soft soil, Fig. 4 shows the variation of the compression index in the pre-yield and post-yield stage with curing time. It can be seen from Fig. 4 that the values of compression indexes C_c and C'_c are smaller than that of pure soil regardless of the curing time, indicating that adding fly ash and metakaolin can well reduce the compression characteristics of soft soil.

In addition, it can be seen from Fig. 4 (a) that the change of C_c value in the pre-yield stage with the curing time is not obvious, ranging from 0.014 to 0.067, which is much lower than the compression index C'_c value in the post-yield stage. However, in the post-yield stage, as shown in Fig. 4(b), the compression index C'_c of the solidified soil sample has significantly increased compared with that in the pre-yield stage, indicating that the structure of the soil is damaged and the compressibility increases significantly. With the increase of curing time, the compression index C'_c value of solidified soil samples with different metakaolin contents shows a downward trend, and with the increase in curing time, the C'_c value tends to be stable. For example, for the sample with metakaolin content of 0%, the curing time increases from 3h to 7d, the C'_c value decreases from 0.36 to 0.32 by 11.1%, and when the curing time increases from 7d to 28d, the C'_c value decreases from 0.32 to 0.31 by 3.4%, indicating that with the increase of curing time, the C'_c value of the solidified soil sample tends to be stable, and the compressibility of the stabilized soil sample does not change significantly. The main reason is that the hydration reaction of fly ash is time-dependent. The longer the curing time is, the more sufficient the reaction and the lower the compressibility (Syed et al. 2020). Test results show that the hydration reaction is almost done within 7d curing time, and the increase in subsequent curing time has no significant impact on its compressibility.

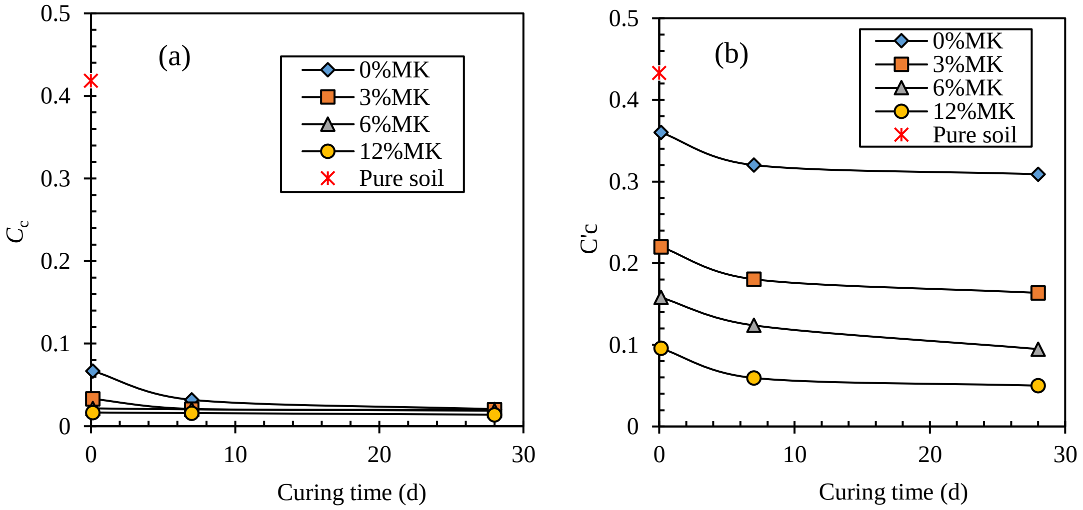

Fig. 4 Effect of curing time on compression index in (a) pre-yield; (b) post-yield stage

Fig. 5 shows the variation of the yield stress with curing time. It can be seen that the yield stress of the fly ash and metakaolin solidified soft soil sample consistently increases with the increase of the curing time. For example, for the solidified soil sample with a metakaolin content of 0%, as the curing time increases from 3h to 7d, the yield stress increases from 143.2 kPa to 210.4 kPa by 46.9%, while from 7d to 28d, the yield stress increases from 210.4 kPa to 251.8 kPa by 109.7%. This indicates that the yield stress of the sample increases significantly within the 7d curing time, and as the curing time continues to increase, the corresponding increase in yield stress is relatively small. Moreover, it can be seen from Fig. 5 that the yield stress of samples under different metakaolin contents shows a similar growth law with the increase in curing time. This may be because the hydration of fly ash and metakaolin is almost completed within 7d of the curing time. As the curing time continues to increase, the pozzolanic products produced by the hydration reaction become less, resulting in a small increase in the yield stress for the solidified soil samples.

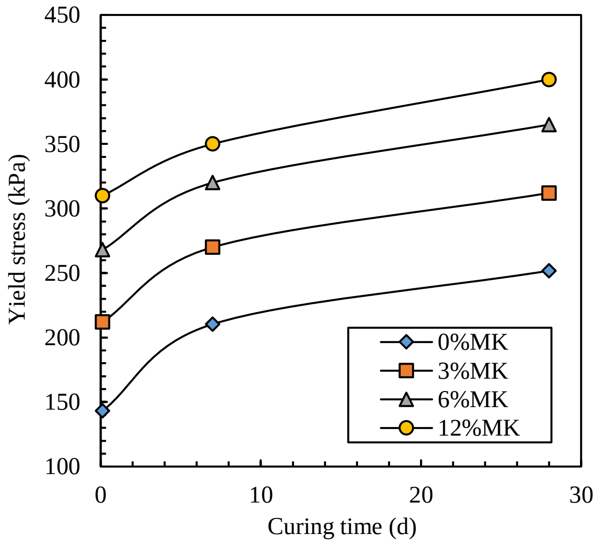

Fig. 5 Variation of yielding stress with curing time

4. CONCLUSIONS

(1) Compared with the higher compressibility of pure soil, the compressibility of fly ash-metakaolin-treated soft soil is significantly reduced. At the same curing time, the compressibility decreases with the increase of metakaolin content. At the same metakaolin content, the longer the curing time, the lower the compressibility of the fly ash-metakaolin-treated soft soil samples.

(2) Compared with the straight line of pure soil, fly ash-metakaolin-treated soil specimens shows two straight-line compression e-lg$p$ curves. The compressibility of the soil sample is very small in the pre-yield stage, while it increases significantly in the post-yield stage.

(3) The compression index in the pre-yield stage showed a slightly decreasing trend with the increase of metakaolin content and curing time. However, the compression index in the post-yield stage showed a significant decreasing trend with the increase of metakaolin content and curing time.

(4) The yield stress of fly ash-metakaolin-treated soft soil samples shows an increasing trend with the increase of metakaolin content and curing time. The effect of metakaolin content on the yield stress is more significant at a lower range of metakaolin content within 6%. The effect of curing time on the yield stress is more significant within the 7d curing time.

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