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EXPERIMENTAL STUDY ON STRENGTH BEHAVIOUR OF FLY ASH AND EGGSHELL POWDER STABILIZED SOFT CLAY

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ABSTRACT

Soil is one of the most vital building materials as it is the foundation of every construction project. Hence, constructing on sites with good soil conditions is a crucial engineering decision. This laboratory study aims to investigate the effects of eggshell powder contents and curing times on the strength behaviour of soft clays stabilized with fly ash (FA) and eggshell powder (ESP). To achieve this, direct shear and unconfined compressive strength (UCS) tests were conducted on soft clays samples mixed with a constant percentage of FA (20% by weight) and varying amounts of ESP (0%, 4%, 8%, and 12% by weight) at different curing times (2 hours, 7 days, and 28 days). By ensuring the presence of 20% fly ash in all samples, each proportion of eggshell powder was combined with fly ash to create four distinct sample mixes. The findings show that increasing ESP content significantly enhances the shear strength of the stabilized soil, with the improvement becoming more pronounced with longer curing times. Samples treated with higher ESP content exhibits greater shear strength parameters and unconfined compressive strength compared to those with lower ESP content. Furthermore, it is obvious that the increase in curing duration significantly improved the cohesion, the internal friction angle and the UCS of the stabilized samples. A similarity was observed in the pattern of the shear strength versus ESP content curves, indicating a relatively uniform relationship between them. In the present study, the optimal content of eggshell powder added to the soft clay-fly ash mixture was found to be 12%, which can be valuable for future applications.

Keywords: Curing Time, Eggshell Powder, Fly Ash, Soft Clays, Soil Stabilization, Strength Behaviour

I. INTRODUCTION

Due to industrialization, development of infrastructures, scarcity of lands and the rising demand for lands, the construction of structures on clay soils has dramatically increased nowadays (Makusa, 2012; AnoopS P et al., 2017). This has become a huge challenge in the field of civil and geotechnical engineering given that soils rich in clay minerals are known as problematic soils. Constructing on these soils causes several problems such as slope instability, bearing capacity failure and excessive settlement as a result of their low shear strength and high compressibility (Mohamad et al., 2016). Hence, the construction of any type of structures (buildings, roads, embankments, dams, slurry walls, airports, waste landfills etc.) on soft clays may result in damage to the foundation of buildings and cracks along the road pavement. Several methods have been implemented to improve undesirable properties of soft clay, reduce post construction settlements, enhance the shear strength of the soil and improve the stability of dams and embankments (Bryson & El Naggar, 2013; Das, 2015; Gaafer et al., 2015). According to (Chu et al., 2009), soil improvement techniques can be divided into four main categories as mentioned by (Gaafer et al., 2015): soil improvement without admixtures, soil improvement with admixtures, soil improvement using stabilization with additives and grouting methods, and soil improvement using thermal methods. Though, there are different ways of improving poor soils, stabilization with additives remains the most commonly used method nowadays as well as in the present research. Many investigations have been carried out to treat soft clays adding stabilizing agents or binders (e.g. cement, fly ash, lime, quarry dust, eggshell powder, plastic wastes, rubber, marble dust, groundnuts, etc…) and their improvements are widely documented (Benny et al., 2017; Debnath et al., 2021; Gajera et al., 2015; Ghadir & Ranjbar, 2018; Jassim et al., 2022; Javed & Chakraborty, 2020; Kamble et al., 2022; Keramatikerman et al., 2020; Krishna & Beebi, 2015; Mali et al., 2019; Roy, 2014; Wilson & Sudha, 2017; Zutting & Naktode, 2020).

In general, fly ash is a by-product waste material from thermal power plants utilized in soil stabilization by many because of its low cost, pozzolanic behaviour and ease of adaptability (Pavlik, 2018; Zimar et al., 2022). It has been used in a variety of construction applications such as compacted fills, concrete mixes, bricks, soil stabilization and construction of embankments (Kaniraj & Havanagi, 1999). Fly ash used in concrete mix improves the workability of plastic concrete, the strength and durability of hardened concrete (Longarini et al., 2014). For ordinary Portland cement, the soil is stabilized through wetting and pozzolanic reactions. Meanwhile, the excessive use of cement leads to environmental problems from the large quantity of CO_2 emissions generated (Lorenzo & Bergado, 2006; Yi et al., 2015). Cement is a common building material, widely used for construction works and its global production is responsible for about 5-7% of carbon dioxide emissions worldwide (Liao et al., 2022). However, it was mentioned by (Asokan et al., 2005) that the amount of CO_2 emitted could be greatly reduced if fly ash is used instead of cement to stabilize the soil. Up to 50% of fly ash can be used as a replacement of cement thus resulting in cost saving; that is because cement cannot be totally avoided. The important parameter of fly ash in soil stabilization is its unit weight, since it controls and improves the shear strength, permeability and compressibility (Santos et al., 2011).

In recent years, eggshell powder has extensively been used in the geotechnical field as a binder for soil treatment and also concrete mix. Bumpy and grainy in texture, an average eggshell contains up to 17000 small pores. It is a semipermeable membrane, which means that air and moisture can pass through its pores. In 2019, China was leading in global eggshell production with 24.8 billion kilograms of eggshell (Waheed et al., 2020). Eggshell is a bio-waste material obtained from domestic sources such as hotels, fast-food restaurants and bakeries. This waste material is frequently disposed in landfills, endangering human health and harming the environment (Faridi & Arabhosseini, 2018). Eggshell powder (ESP) has high amounts of calcium and can be combined with pozzolanic materials such as fly ash, which have low calcium content. Up to 95% of eggshell powder is made almost entirely of calcium carbonate $CaCO_3$, which decomposes into CO_2 and CaO after calcination (Hamada et al., 2020). Several researches have shown the potential of using ESP as a stabilizer for soil and brick to improve its mechanical properties (Sathiparan, 2021). Thanks to its identical-like chemical composition, eggshell powder can be used as a replacement of industrial lime (Diana et al., 2021; Anoop P et al., 2017). Moreover, lime is not suitable for soils that contain sulphates. The presence of sulphates can increase the swelling behaviour of soil due to the formation of swelling minerals such as ettringite and thaumasite (Brown & Hooton, 2002; Gao et al., 2021; Tariq & Yanful, 2013). Furthermore, eggshell powder also has the potential to replace cement in green concrete. This eliminates the environmental impact of disposing eggshells in landfills (Murthi et al., 2022). In comparison to other waste materials, eggshell powder is not only cost-effective but also a solution for sustainable projects.

Several studies have used either fly ash or eggshell powder or each of the two in conjunction with other materials for stabilization purposes. However, investigations on the effects of ESP contents mixed with FA on the engineering properties of soft clay are practically non-existent. Therefore, in this research, a series of tests on direct shear and unconfined compressive strength were conducted to analyse the strength behaviour of soft clay stabilized with a constant percentage of FA (20% by weight) and varying ESP contents (0%, 4%, 8% and 12% by weight) at different curing times (2 hours, 7 days and 28 days).

II. MATERIALS AND METHODS

1. Materials

The soil used in this research is sampled at a depth of 2.5m and a water table of 1.5m taken from a project site in China, Jiangsu province. According to ASTM D422-63, the determination of the test soil sample's fundamental physical properties is shown in Table 1. The content of each substance in the soil sample was determined by X-ray diffraction, and the results were shown in Table 2. The soil sample liquid limit (LL) and plastic limit (PL) are 56.4% and 28.6%, respectively. The corresponding plasticity index (PI) is 27.8, and particle size less than 0.075mm, particle content is more than 50%. According to the unified soil classification system (USCS), the soil is classified as high liquid limit clay (CH). In the current study, chicken eggshell powder and Class C fly ash were bought online; and their chemical composition are given in table 3.

Table 1: Physical Properties for Testing Soil

Natural moisture content, w/%	Liquid limit w_L/%	Plastic limit, w_p/%	Plasticity Index, I_p	Natural unit Weight, kN/m³	Specific Gravity, G_s
48.2~49.5	56.4	28.6	27.8	17.8	2.7

Table 2: Analysis Results of Clay Minerals

Mineral composition	Illite/smectite formation, (S/I)	Illite	Kaolinite	Chlorite	Ordered mixing ratio (S%)
Content (%)	59	31	5	4	53

Table 3: Chemical Composition of Fly Ash and Eggshell Powder (%)

Materials	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O+K_2O	SO_3	Others
Fly Ash	42.311	21.767	22.577	4.166	3.16	2.321	1.362	2.337
Eggshell Powder	0.069	97.819	0.031	0.084	0.469	0.495	0.436	0.597

2. Methods

Tests were performed on the virgin soil taken from Jiangsu Province using fly ash and eggshell powder as stabilizing agents to determine its strength characteristics. The soft clay was initially oven-dried in the laboratory for about 24 hours. Then, extra water was added to the soil to reach the optimum water content. A constant percentage of FA (20% by weight of dry soil) and different ESP contents (0%, 4%, 8% and 12% by weight of dry soil) were gradually poured into the soil-water mixture. We choose this based on a study by (Shirkhanloo et al., 2021), which showed that the optimal FA content for improving soil characteristics ranges from 10% to 30%. Also, the contents of ESP were selected due to their positive effects on soil, as reported in previous researches (Oluwatuyi et al., 2018; Veerabrahmam, 2021). The final mixture soil-water-fly ash with each concentration of ESP were thoroughly stirred for 10 minutes using a laboratory mixer. After a fairly homogeneous paste is obtained, all samples mixes (see Table 5) were prepared with a steel ring (61.8mm diameter and 20mm height) and a split mould (39mm diameter and 46mm height) for direct shear tests and UCS tests respectively. The prepared samples were wrapped with plastic film and placed in a plastic chamber equipped with a humidifier that maintained an almost constant temperature and relative humidity. All samples mixes were tested after curing durations of 2 hours, 7 days and 28 days.

Table 5: Details of Mixing Proportion of Fly Ash and Eggshell Powder with Soil

Samples Mixes	ESP Content, (%)	FA Content, (%)
Pure Soil (S)	0	0
S+FA+ESP0	0	20
S+FA+ESP4	4	20
S+FA+ESP8	8	20
S+FA+ESP12	12	20

Table 6: Direct Shear Strength and UCS Testing Program

Tests Performed	Fly Ash Content (%)	Eggshell Powder Content (%)	Curing Time (days)	Pressure (kPa)
Direct Shear Strength	20	0, 4, 8, 12	2h, 7d, 28d	50, 100, 200
Unconfined Compressive Strength	20	0, 4, 8, 12	2h, 7d, 28d	None

III. RESULTS AND DISCUSSIONS

1. Direct Shear Test

The direct shear test was conducted on soil samples with a constant percentage of fly ash (20% by weight) and various eggshell powder contents (0%, 4%, 8% and 12% by weight) at different curing times (2 hours, 7 days, 28 days). The test results are represented in the graphs below.

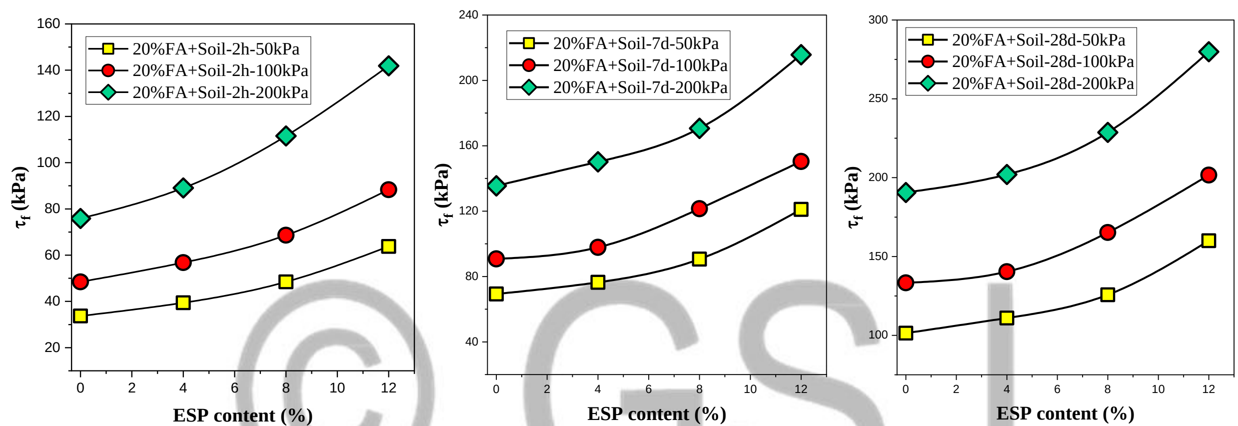

Figure 1: Variation of shear stress at failure τ_f with different ESP contents and vertical stresses at curing time of (a) 2 hours, (b) 7 days, and (c) 28 days;

Figure 1 plotted the variation of shear strength τ_f (defined as the shear stress at failure) with varying ESP contents at a given vertical stress for fly ash and eggshell powder stabilized soft clay. It can be observed that the shear strength of all tested samples gradually increase as the ESP content increases. For example, under a curing period of 7 days and a vertical stress of 200kPa, the shear strength values progressively increased to 135.5kPa, 150.2kPa, 170.7kPa, and 215.7kPa at ESP contents of 0%, 4%, 8%, and 12% respectively. This imply that the constant addition of eggshell powder content has a positive influence on the strength of fly ash stabilized soft clay. Additionally, for a given eggshell powder content, samples subjected to higher vertical stresses exhibit greater shear strength than those subjected to lower vertical stresses. For instance, under a curing time of 28 days and an ESP content of 8%, the shear strength value increases from 125.7kPa at a vertical stress of 50kPa to 165.2kPa at a vertical stress of 100kPa, and further rises to 228.7kPa at a vertical stress of 200kPa. The shear strength versus ESP contents curves, show a significant similarity in the pattern within a particular curing time. The almost parallel pattern implies that the relationship between eggshell powder content and shear strength is relatively uniform, with a predictable response. It suggests that increasing the eggshell powder content in soil stabilization consistently leads to a proportional increase in shear strength, providing engineers and construction professionals with a reliable method for controlling and optimizing the strength properties of the stabilized soil.

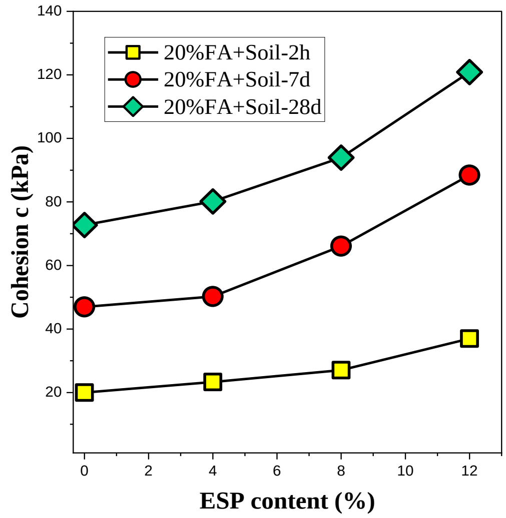

Figure 2: Variation of cohesion *c* with different ESP contents under various curing times

The variation of the cohesion *c* with ESP contents of soft clay stabilized with fly ash and eggshell powder at different curing times is plotted in figure 2. When ESP content is 0%. it can be observed that all soil samples stabilized with fly ash exhibit the smallest cohesion. However, as the ESP content increases, the cohesion value consistently and linearly rises, and the growth rate is also more prominent as the curing time increase. This suggests that incorporating eggshell powder can be beneficial for enhancing the cohesive properties of soil. The possible explanation is that the presence of eggshell powder alters the physical characteristics of soil and increases the content of fine-grained particles, leading to an elevated cohesion value. For instance, at 2 hours of curing time, the cohesion value is 20kPa when the ESP content is 0%. However, the increase of ESP to 4%, 8%, and 12% leads to cohesion values of 23.3kPa, 27kPa, and 37kPa, with percentage increments of 16.5%, 35%, and 85% respectively.

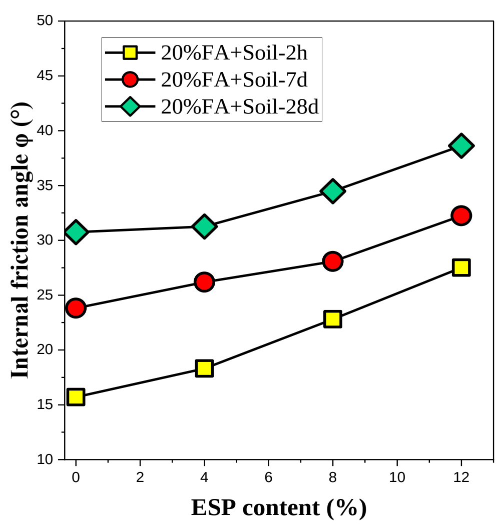

Figure 3: Variation of internal friction angle *φ* with different ESP contents under various curing times

The effect of ESP contents on internal friction angle φ of fly ash and eggshell powder stabilized soft clay is plotted in Figure 3. At a given curing time, the internal friction angle φ of stabilized soil samples shows a linear increase with the increase of ESP content. The presence of eggshell powder, composed mainly of calcium carbonate ($CaCO_3$), in the clay soil undergo chemical reactions with other soil components. These reactions produce calcium silicate hydrate (C-S-H) compounds which strengthens the bond between soil particles, resulting in an increase in the internal friction angle. For instance, at a 2-hour curing time, the increase in ESP content from 0% to 4% results in an increase in the internal friction angle from 15.7° to 18.3°. Further increasing the ESP content from 4% to 8% leads to a rise in the internal friction angle from 18.3° to 22.8°. Similarly, when the ESP content increase from 8% to 12%, the internal friction angle increases from 22.8° to 27.5°.

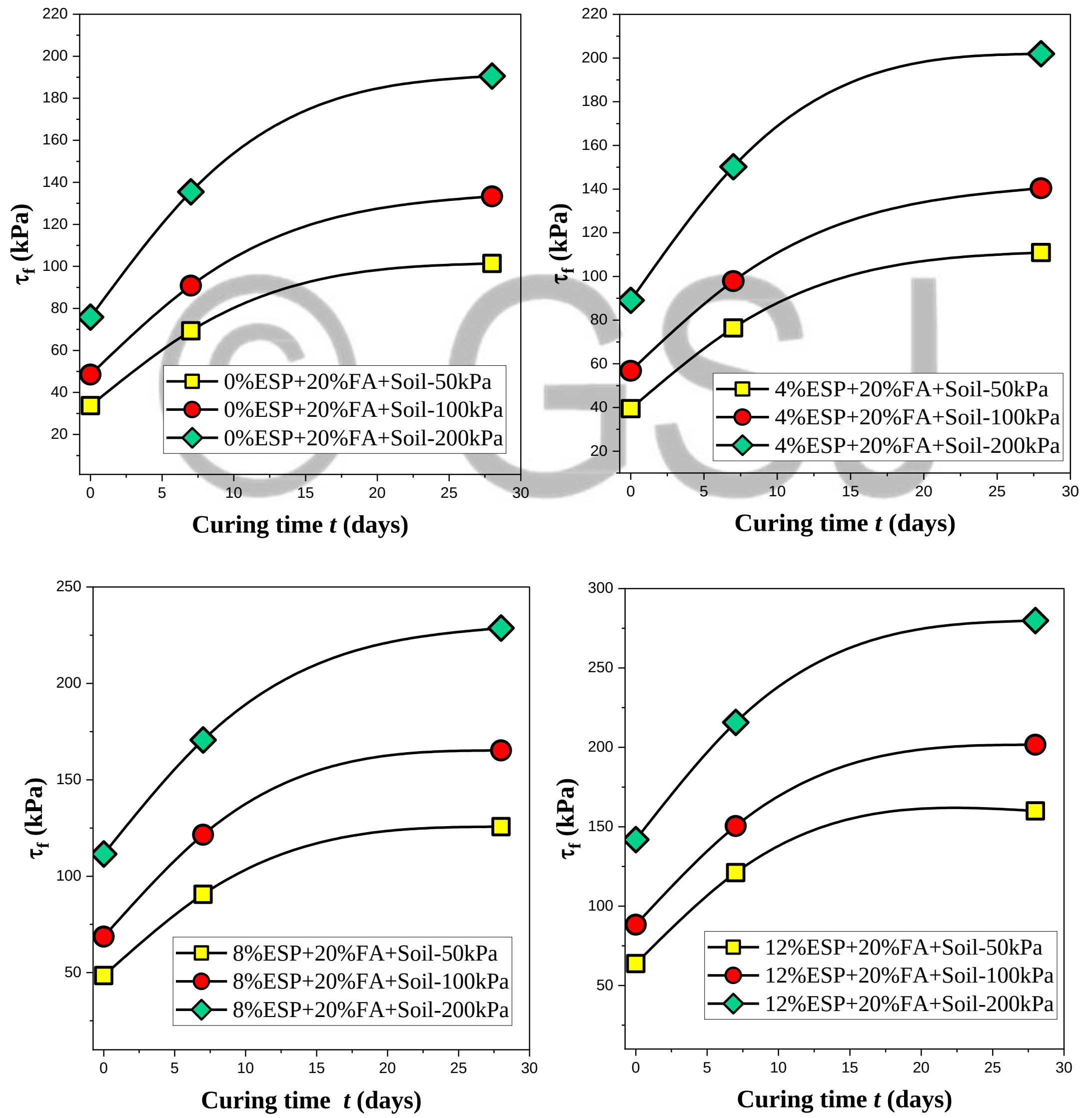

Figure 4: Variation of shear stress at failure τ_f with different curing time t and vertical stresses at ESP contents of (a) 0%, (b) 4%, (c) 8%, and (d) 12%

Figure 4 presents the effect of curing time on the shear strength τ_f (defined as the shear stress at failure) of soft clay stabilized with fly ash and eggshell powder under different vertical stresses. According to the general observation, the shear strength of the fly ash and eggshell powder stabilized soft clay increases significantly as the curing time also increases. The shear strength curves of soils samples stabilized with eggshell powder at 0%, 4%, 8%, and 12% in combination with fly ash exhibit a fast and parabolic increase over a period of 2 hours to 7 days to 28 days. For instance, at a vertical stress of 50kPa and an ESP content of 8%, the shear strength value increased from 48.5kPa to 90.6kPa as the curing time extended from 2 hours to 7 days. Moreover, with further curing from 7 days to 28 days, the shear strength increased from 90.6kPa to 125.7kPa. From the aforementioned discussion, it is evident that with 20% fly ash, the shear strength of soft clay reinforced with 0% eggshell powder exhibits great values, which significantly increase over time. This implies that for engineering projects, the use of fly ash in stabilizing soft clay is recommended for use. However, the inclusion of eggshell powder contents (4%, 8%, and 12%) has a more prominent influence on the shear strength of fly ash stabilized soil samples. The elevated strength observed after curing can be attributed to changes in the physical texture of the soil. Specifically, the presence of finer particles of eggshell powder and its greater effectiveness compared to the soil contribute to an increase in the uniaxial strength of the stabilized samples upon immediate curing.

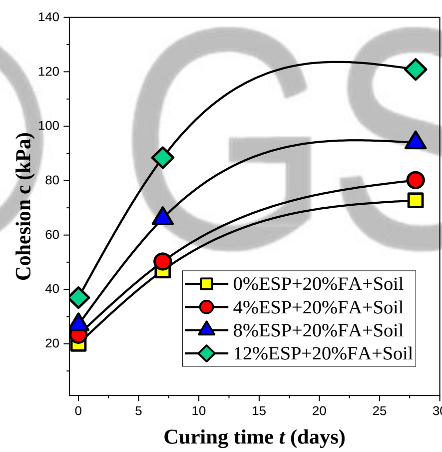

Figure 5: Variation of cohesion *c* with different curing times *t* at various ESP contents

The variation of cohesion *c* with curing times *t* under different ESP contents of fly ash and eggshell powder stabilized soft clay is given in Figure 5. It can be observed that with increasing curing time, the cohesion gradually increases. For instance, when the ESP content is 4%, the cohesion increases from 23.3kPa at 2 hours of curing time to 50.2kPa at 7 days of curing time. Similarly, when the eggshell powder content increases from 7 days to 28 days, the cohesion increases from 50.2kPa to 80.1kPa. As the duration of curing extends, the rate of cohesion growth also increases. Additionally, the curves representing soil samples with higher ESP content consistently lie above those with lower ESP content, indicating a significant growth in the cohesion, content. This imply that both the duration of curing and the amount of eggshell powder present in the stabilized samples have a combined effect on the cohesive characteristics of the soil.

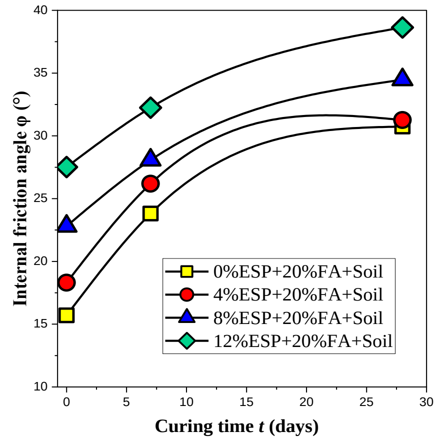

Figure 6: Variation of internal friction angle *φ* with different curing times *t* at various ESP contents

In figure 6, the effect of curing times on the internal friction angle at different ESP contents is illustrated. The general trend observed is that the internal friction angle tends to increase as the curing time prolongs. For fly ash stabilized soft clay containing 12% ESP, the internal friction angle increased from 27.5° to 32.2° when the curing time was extended from 2 hours to 7 days. Furthermore, when the curing time was increased from 7 days to 28 days, the internal friction angle further increased from 32.2° to 38.6°. In the case of soil samples without ESP, the effect of fly ash on the internal friction angle became more pronounced as the curing time progressed. The curing process of fly ash in the soil occurred at a faster rate with increasing curing time. Additionally, the presence of high contents of eggshell powder in the stabilized soft clay continued to promote water crystallization, resulting in soil compaction and a reduction in spacing between soil particles. This compression of the soil led to an increased frictional angle, indicating the positive impact of eggshell powder.

2. Unconfined Compressive Test

The Unconfined compressive strength test was conducted on soil samples with a constant percentage of fly ash (20% by weight) and various eggshell powder contents (0%, 4%, 8% and 12% by weight) at different curing times (2 hours, 7 days, 28 days). The test results are given in the graphs below.

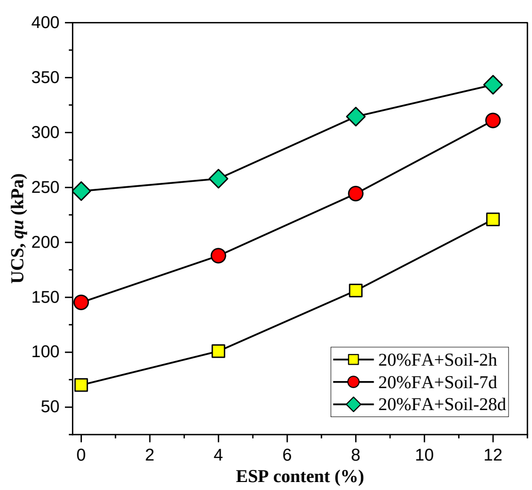

Figure 7: Variation of UCS with ESP contents under various curing times

The effect of ESP contents on the unconfined compressive strength under various curing periods is presented in Figure 7. The UCS increased gradually as the ESP content increased, and the ESP contents appeared to have a positive impact on the compressive strength of the stabilized soft clay by fly ash. For example, for a sample with an ESP content of 4%, the UCS for 28 days was 258kPa. And when the ESP content is increased to 12%, the UCS rose to 343.5kPa. It is concluded that the presence of eggshell powder in the soil has an aiding effect on the cementation process of soft clays cured by fly ash. The reason of this growth can be due to the mechanism of flocculation which refers to the aggregation or clumping together of individual soil particles to form larger units. The occurrence of flocculation contributes to improved soil structure and reduced water content within the soil mass. This, in turn, enhances the compressive strength of soil.

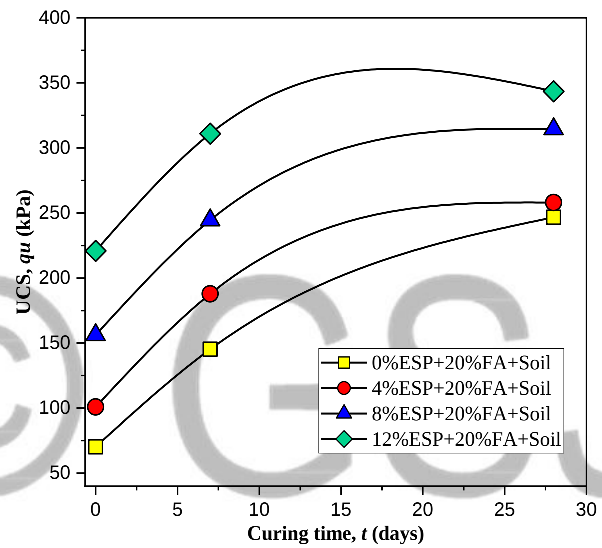

Figure 8: Variation of UCS with curing time *t* under various ESP contents

The effect of curing time on the unconfined compressive strength at different ESP contents is illustrated in Figure 8. The findings indicate that, with a specific ESP content, the unconfined compressive strength of the stabilized soft clay increases as the curing period lengthens. For instance, when the ESP content is 4%, the UCS rises from 100.9kPa to 187.8kPa as the curing time increases from 2 hours to 7 days. Moreover, with a further increase in curing time from 7 days to 28 days, the UCS elevates from 187.8kPa to 257.9kPa. This can be attributed to the presence of numerous small pores between fly ash and soil particles during the initial maintenance stage. Although the particles surfaces are initially coated with a cementitious material, it fails to form a cohesive structure. However, as the maintenance cycle progresses, the number of pores decreases compared to the initial stage, and they gradually become uniformly filled with cement. Consequently, this process leads to the formation of a well-connected and densified structure.

IV. CONCLUSION

The study provides valuable insights into the potential of fly ash and eggshell powder as stabilizing agents for soft clays, offering a cost-effective and a sustainable solution for improving the mechanical behaviour of such problematic soils in geotechnical applications. The curing times were found to further enhance the strength behaviour of the stabilized soil. The main conclusions are as follows:

(1) The addition of fly ash alone to soft clay resulted in a significant increase in shear strength and compressive strength over time compared to that of pure soil. However, the inclusion of the three different ESP contents had a more pronounced effect on shear strength, with 12% being the optimum content.

(2) Increasing both curing times and eggshell powder contents significantly enhanced the cohesion and internal friction angle of soft clay stabilized with fly ash and eggshell powder.

(3) For a specific ESP content, samples subjected to higher vertical stresses exhibited greater shear strength than those subjected to lower vertical stresses.

(4) The presence of eggshell powder aids the cementation process of soft clays cured with fly ash. This is attributed to the mechanism of flocculation, which promotes the aggregation of soil particles, leading to improved soil structure, reduced water content, and enhanced compressive strength.

(5) Across a specific curing time, the UCS of the stabilized soft clay increased as the ESP content increased. Similarly, at a given ESP content, the UCS values also improved as the curing time extended.

(6) The findings suggest that the combination of 20% fly ash and 12% eggshell powder after 28 days is more effective in improving the properties of soft clay compared to other mixture proportions investigated in this study. These results provide valuable references for future research endeavours.

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