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Effects Of Eggshell Powder And Curing Time On Compression Behaviour Of Fly Ash Stabilized Soft Clay

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Abstract:
In recent times, soft clay has become a commonly encountered soil type, known for its limited strength and pronounced compressibility, presenting significant challenges in the construction of geotechnical structures. Therefore, enhancing its properties before construction is imperative to prevent issues like settlement, instability, or structural damage. This experimental study aims to explore the impact of eggshell powder (ESP) content and curing times on the compression behaviour of fly ash (FA) stabilized soft clay, as there is limited research on the synergy of these two waste materials. A set of one-dimensional compression tests were conducted on soft clay samples treated with 20% FA and varying ESP levels (0%, 4%, 8%, and 12%) at different curing intervals (2 hours, 7 days, and 28 days). Four distinct mixtures were created by combining each ESP content with 20% FA. The results highlighted that the addition of fly ash significantly reduces the compressibility of soft clay soils. Meanwhile, an increased ESP content corresponds to a more pronounced reduction in compressibility, resulting in a smoother pattern at higher ESP levels. Additionally, higher ESP content, especially above 8%, leads to more pronounced yield stress. longer curing periods lead to decreased compressibility and increased yield stress in stabilized soil, emphasizing the ongoing improvement in its compressive strength over time. The e-logp curves for fly ash and eggshell powder modified clay soil show lower compressibility before yielding, which becomes significant after yielding. Furthermore, both eggshell powder and curing time lead to a subtle decrease in C_c before yielding, while significantly increasing C'_c after yielding. The current study reveals that 12% is the preferred ratio of eggshell powder in the fly ash blended soft clay, with relevance to future implementations.

Keywords: *Compressibility, Curing Time, Eggshell Powder, Fly Ash, Soft Clays, Soil Stabilization, Yielding Stress*

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I. Introduction

Recently, a substantial increase in the construction of structures on clay soils have been observed, driven by factors such as urbanization, infrastructure development, land scarcity, and the growing demand for land (Makusa, 2012). This trend presents a significant challenge in the fields of civil and geotechnical engineering, as clay-rich soils are recognized for their problematic nature (Indiramma et al., 2020). Building on these soils can result in issues such as slope instability, load-bearing failures, and considerable settling due to their limited shear strength and pronounced compressibility (Mohamad et al., 2016). Consequently, the construction of various types of structures on soft clays can result in damage to building foundations and the formation of fissures along roadways. Numerous approaches have been deployed to address the unfavourable characteristics of clay soils, reduce post-construction settlements, enhance soil bearing capacity, and improve the stability of dams and embankments (Bryson & El Naggar, 2013; Das, 2015; Gaafer et al., 2015). While there are various methods for enhancing the quality of subgrade soils, the use of stabilizing agents remains the most commonly employed approach, both in contemporary practice and in the present study. Many investigations have explored the stabilization of soft clays by incorporating stabilizing agents, such as cement, fly ash, lime, quarry dust, eggshell powder, plastic waste, rubber, marble dust, groundnuts, and others. The improvements achieved through these methods are extensively documented in the literature (Benny et al., 2017; Debnath et al., 2021; Gajera & Thanki, 2015; Ghadir & Ranjbar, 2018; Jassim et al., 2022; Javed & Chakraborty, 2020; Kamble et al., 2022; Keramatikerman et al., 2020; Krishna & Beebi, 2015; Sagar Mali, 2019; Roy, 2014; Wilson & Sudha, 2017; Zutting & Naktode, 2020)

Considered as a fine, powdery material that consists of tiny, spherical particles, fly ash is a by-product generated by the combustion of pulverized coal in coal-fired power plants. Its applications in construction are diverse, including uses in compacted fills, concrete mixes, bricks, liners, soil stabilization, and embankment construction (Takhelmayum et al., 2013). There are two main types of fly ash, designated as Class F and Class C based on their chemical composition as per ASTM C618 (Ghazali & Kaushal, 2015; Nizar et al., 2014). Class F fly ash results from the combustion of resilient anthracite and bituminous coal, displaying pozzolanic characteristics with a lime content of less than 10%. This type of fly ash requires a binder such as Portland cement, hydrated lime, or quicklime, combined with water, to produce cementitious substances. Alternatively, the addition of a chemical activator like Na_2SiO_3 may lead to geopolymer formation. On the other hand, Class C fly ash is typically derived from lignite coals and is highly resistant to expansion from chemical attack. Beyond its pozzolanic features, it exhibits self-cementing behaviour and gains strength over time when combined with water, eliminating the need for an activator (Dwivedi & Jain, 2014). Referred to as Calcareous fly ash, Class C fly ash contains over 20% lime, around 35% silica, and less than 2% carbon (Akhtar et al., 2019). It is commonly utilized in structural concrete, PCC pavements, as well as in the production of tiles, paving stones, bricks, and blocks (Akhtar & Akhtar, 2018; Jatale et al., 2013). Globally, approximately 500 million tonnes of coal fly ash are produced annually, with a significant portion often discarded in landfills (Ahmaruzzaman, 2010). Moreover, Improper disposal poses risks of air, surface water, and groundwater pollution due to the leaching of heavy metals into the surrounding environment, impacting both soil and aquatic ecosystems (Nawaz, 2013; Turan et al., 2019). However, Asokan et al. (2005) argued that using fly ash as a partial replacement of cement for soil stabilization can substantially reduce total CO_2 emissions. This is crucial considering that cement production globally contributes to around 5 to 7% of CO2 emissions, leading to environmental concerns (Liao et al., 2022; Yi et al., 2015). Therefore, using fly ash in soil engineering projects is more cost-effective than cement, reducing disposal expenses and mitigating environmental concerns (Kalita & Singh, 2009).

Eggshells sourced from various domestic outlets, including poultry farms, households, fast-food establishments, restaurants, hotels, and bakeries, are considered waste materials. They possess a coarse and granular texture and typically harbour as many as 17,000 small pores. They also function as a semi-permeable membrane, allowing the passage of air and water through their pores. Additionally, eggshell powder, primarily composed of calcium carbonate ($CaCO_3$) to the extent of up to 95%, undergoes decomposition into CO_2 and CaO after calcination (Hamada et al., 2020; Srinivasan et al., 2021). Due to its similar composition to industrial lime, eggshell powder can serve as a viable alternative (Diana et al., 2021; Anoop et al., 2017). However, the use of lime on sulfate-rich soils is not advised, as it can promote soil expansion by facilitating the formation of ettringite and thaumasite (Gao et al., 2021; Tariq & Yanful, 2013). Frequently discarding eggshell waste in landfills poses potential risks to human health and the environment (Faridi & Arabhosseini, 2018). Numerous studies have demonstrated the extensive utility of eggshell powder as an additive in soil treatment and concrete mixes, enhancing their engineering properties (Sathiparan, 2021). Furthermore, eggshell powder can also replace cement in the production of environmentally-friendly concrete, thus mitigating the environmental impact of eggshell disposal in landfills (Murthi et al., 2022). Therefore, the utilization of eggshells not only helps improve problematic soils but also addresses environmental concerns and reduces disposal costs.

II. Materials

The soil samples were collected from a depth of 2.5 meters from a project site in China. The fundamental physical properties of the soil were determined following ASTM D422-63, and the results can be found in Table 1. The soil sample has a liquid limit (LL) of 56.4%, a plastic limit (PL) of 28.6%, resulting in a plasticity index (PI) of 27.8. Additionally, particles smaller than 0.075mm make up more than 50% of the soil composition (Figure 1). Based on the Unified Soil Classification System (USCS), this soil is classed as high plasticity clay (CH). The chicken eggshell powder and Class C fly ash used for this experiment were both purchased online, and their chemical compositions are given in Table 2

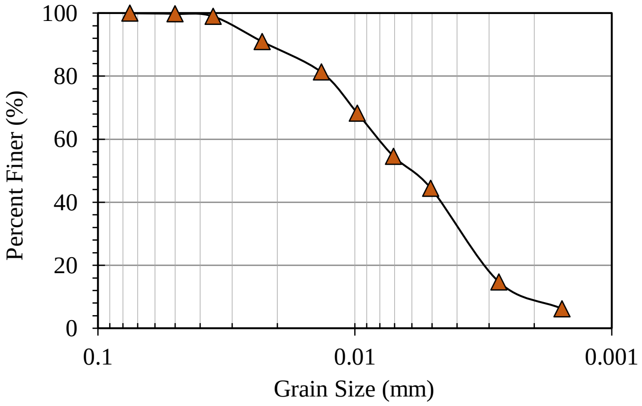

Figure 1: Particle Size Distribution of Soft Clay

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: Chemical Constitution 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

III. Methods

Untreated soil obtained from Jiangsu Province underwent one-dimensional compression tests with a mixture of fly ash and eggshell powder serving as stabilizing agents to evaluate its compression characteristics. Initially, the soft clay was dried in a laboratory oven for approximately 24 hours. Then, water was added to achieve the optimal moisture content. A consistent proportion of fly ash (20% by dry soil weight) and varying ESP concentrations (0%, 4%, 8%, and 12% by dry soil weight) were blended to create four distinct sample groups. This choice was based on a study conducted by Shirkhanloo et al. (2021), which suggested that the ideal fly ash content for soil stabilization range between 10% and 30%. Moreover, the ESP content options were referenced in previous research (Harikaran et al., 2023), highlighting the advantageous effects of ESP on clay soil properties. Each sample mixture (refer to Table 4) was thoroughly mixed for 10 minutes using a laboratory blender to achieve a fairly uniform paste (Wathiq et al., 2019). The moulds used for soil sample preparation were steel rings measuring 20mm in height and 61.8mm in diameter. The prepared samples were encased in plastic film, appropriately labelled, and stored in a plastic chamber equipped with a humidifier to maintain nearly constant temperature and relative humidity. Moreover, because of time limitations and prior research indicating improvements in soil properties at 0, 7 days, and 28 days of curing, all sample mixtures in the present study were specifically tested after curing for 2 hours, 7 days, and 28 days (Nur et al., 2022).

Table 3: Details of Mixing Proportion of Fly Ash and Eggshell Powder with Soil

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

Table 4: One-Dimensional Compression Testing Program

Tests Performed	Fly Ash Content (%)	Eggshell Powder Content (%)	Curing Time (days)	Consolidation Pressure (kPa)
One-Dimensional Consolidation	20	0, 4, 8, 12	2h, 7d, 28d	12.5, 25, 50, 100, 200, 400, 800

IV. Results and Discussions

Compression Curves (*e-logp*)

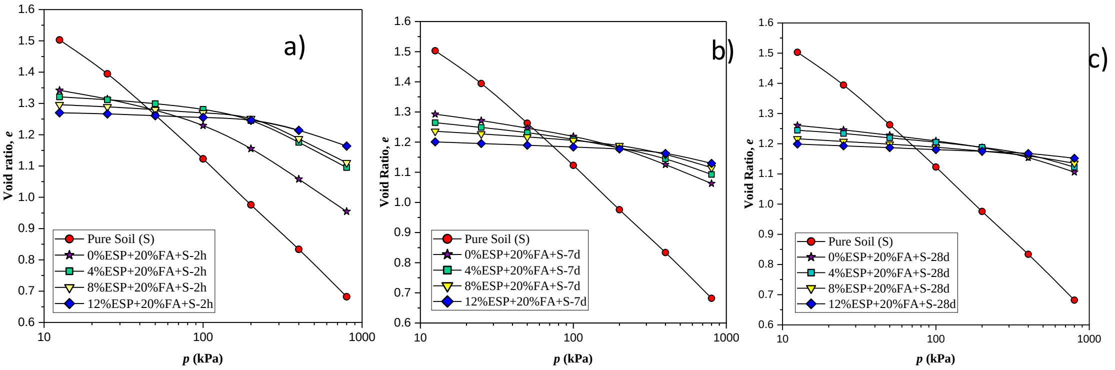

Figure 1: *e~logp* Compression Curves of Fly Ash Stabilized Samples with Different ESP Contents at Curing Time of (a) 2 hours, (b) 7 days, and (c) 28 days

The semi-logarithmic compression curve (*e−logp*) of fly ash fortified soft clay samples with varying ESP content at specific curing duration is illustrated in Figure 1. The plots depict the decrease in void ratio for samples with varying ESP contents as the applied loading pressure (*p*) increases. The curve associated with higher ESP content exhibits a smoother trend, indicating that an increase in ESP content correlates with a reduction in compressibility. In contrast to the linear trend observed in untreated soil, the stabilized soil samples exhibit two distinct straight lines. The slope of the linear curve for untreated soil represents the compression index, denoted as C_c. In the case of soil stabilized with fly ash and eggshell powder, the point where these two straight lines intersect is referred to as the compression yield stress, denoted as p'_y. During the pre-yield stage, when the consolidation pressure is below p'_y, the stabilized soil shows minimal compressibility. However, the compressibility significantly increases in the post-yield stage as the consolidation pressure exceeds p'_y. A similar result was recorded by Huang et al. (2012) in soil treated with cement. This phenomenon can be explained by the fact that during the pre-yield stage, the presence of fly ash and eggshell powder in the soil contributes to the formation of a stable and solidified structure that resists compression, resulting in minimal compressibility. However, in the post-yield stage, the external pressure becomes too great for the soil's internal structure to withstand, leading to its breakdown and a subsequent increase in compressibility (Pan et al., 2023).

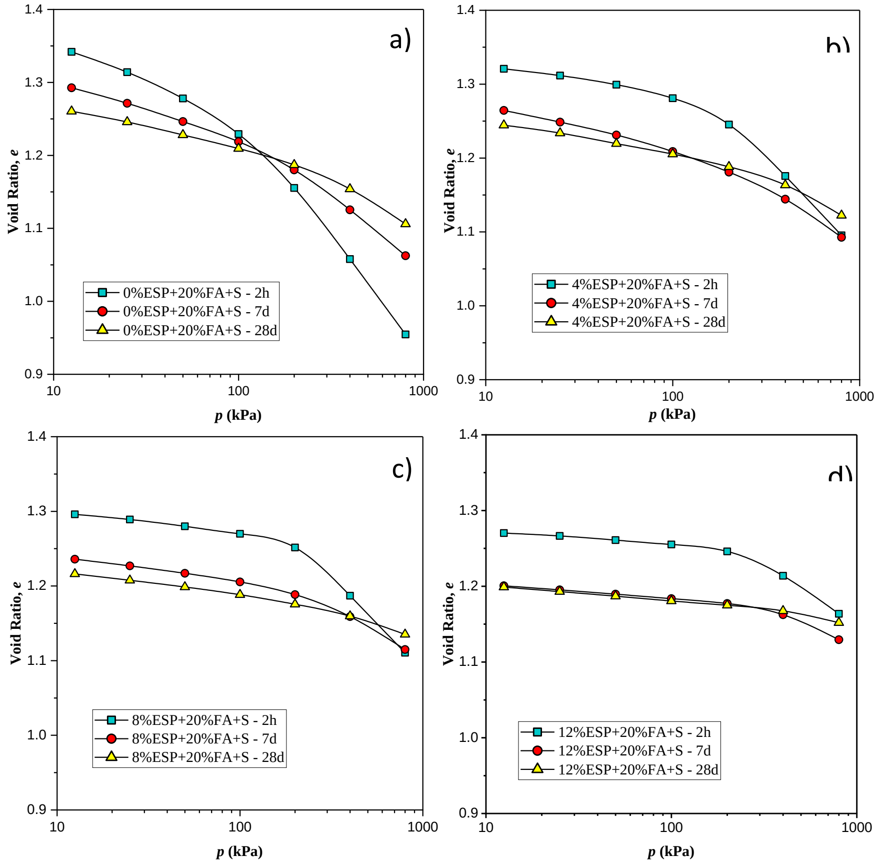

Figure 2: *e~logp* Compression Curves of Fly Ash Stabilized Samples with Various Curing Times under ESP Content of (a) 0%, (b) 4%, (c) 8%, and (d) 12%

The semi-logarithmic compression curve (*e−logp*) of stabilized soil samples are plotted in Figure 2 to provide insights into the relationship between void ratio and loading pressures. Typically, in the pressure range of 12.5kPa to 800kPa, the void ratio consistently decreases with rising loading pressure (p). All analysed samples exhibit a pattern of two straight lines, with the point of intersection denoted as the compression yield stress p'_y. The compression curve for samples undergoing a more extended curing duration is positioned below the curve of samples exposed to a shorter curing period. Irrespective of variations in ESP content, samples subjected to longer curing periods demonstrate diminished compressibility compared to those exposed to shorter curing times. This observation implies that an extended curing period leads to decreased compressibility in stabilized soil samples with fly ash and eggshell powder. This phenomenon arises from the time-dependent nature of hydration and chemical reactions involving water and the active components within fly ash and eggshell powder. As curing times lengthen, these reactions become more thorough, resulting in enhanced cementation and reduced compressibility (Hudu et al., 2022).

Effects of Eggshell Powder

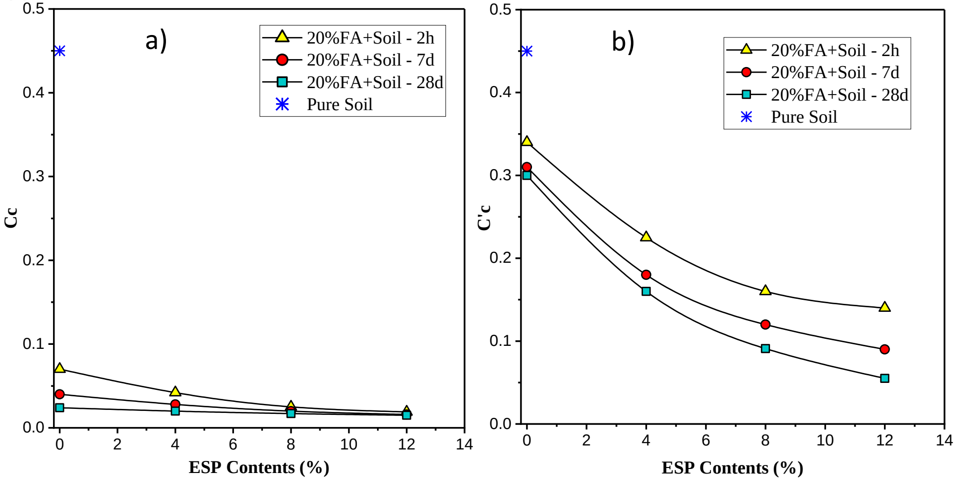

Figure 3: Variation of Compression Index with ESP Contents at (a) Pre-Yield Stage C_c and (b) Post-Yield Stage C'_c

From Figure 3, the alteration in the compression index with ESP contents at both stages is plotted. Overall, the compression index of fly ash and eggshell powder enhanced soil at varying ESP contents is smaller compared to that of untreated soil (C_c=0.45), highlighting a substantial reduction in the soil's compressibility, due to the solidified impact of fly ash and eggshell powder. The optimal C_c value in the pre-yield stage is 0.07, while the optimal C'_c value in the post-yield stage is 0.34. During the pre-yield stage, the trend lines for samples with different ESP contents tend to converge as ESP content increases, which is the opposite after yielding occurs. Moreover, as depicted in Figure 3(a), the C_c value shows minimal decrease (ranging from 0.07 to 0.015) as ESP content increases. This suggests that ESP content has a limited effect on soil compressibility during the pre-yield stage. In contrast, as shown in Figure 3(b), the decrease in C'_c (varying from 0.34 to 0.055) becomes more pronounced as ESP content increases. This substantial reduction in the post-yield compression index highlights the impact that eggshell powder has on fly ash modified soft clay. For instance, at 28 days of curing, increasing ESP content from 0% to 12% results in a 37.5% decrease in C_c (from 0.024 to 0.015). However, under similar duration, as the amount of ESP rises from 0% to 12%, the C'_c value drops from 0.34 to 0.055, representing an 81.67% reduction. It means that the active compounds SiO_2 and Al_2O_3 present in fly ash undergo a chemical reaction with water, forming compounds like calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). These compounds possess a binding and filling effect on the soft clay particles, reducing its ability to compress before reaching its yielding point. However, once the soil does yield, its structural integrity is quickly compromised, leading to a swift increase in compressibility (Pan et al., 2023).

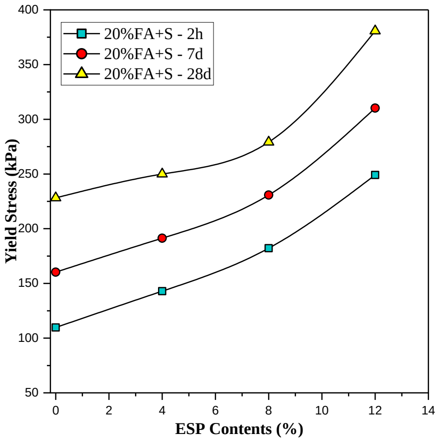

Figure 4: Variation of Yielding Stress with ESP Contents

Considering that the compression (*e-logp*) curve exhibits a two-straight-line pattern, the intersection point referred to as the compression yield stress p'_y can be determined. The variation in yield stress versus ESP contents is plotted in Figure 4. It is observed that the yield stress of stabilized soft clay samples increases as the ESP content increases. Furthermore, as the ESP content rises from 0% to 4% and from 4% to 8%, the increase in yield stress is less pronounced compared to its rapid growth when ESP content increase from 8% to 12%. This suggests that the effect of ESP content on yield stress is more significant within a higher range of ESP content, specifically above 8%. For instance, at a curing time of 2 hours, as the ESP content increases from 8% to 12%, the yield stress rises from 182.17kPa to 249.08kPa, marking an increment of 66.91kPa. However, when the ESP content increases from 0% to 4% and from 4% to 8%, the yield stress increases from 109.76kPa to 142.88kPa and from 142.88kPa to 182.17kPa, respectively, with smaller increments of 33.12kPa and 39.29kPa. This observation can be attributed to the fact that the pozzolanic reaction involving active SiO_2 and Al_2O_3 is more pronounced at higher ESP content (>8%). As the ESP content continues to rise, the pozzolanic reaction becomes more prominent.

Effects of Curing Time

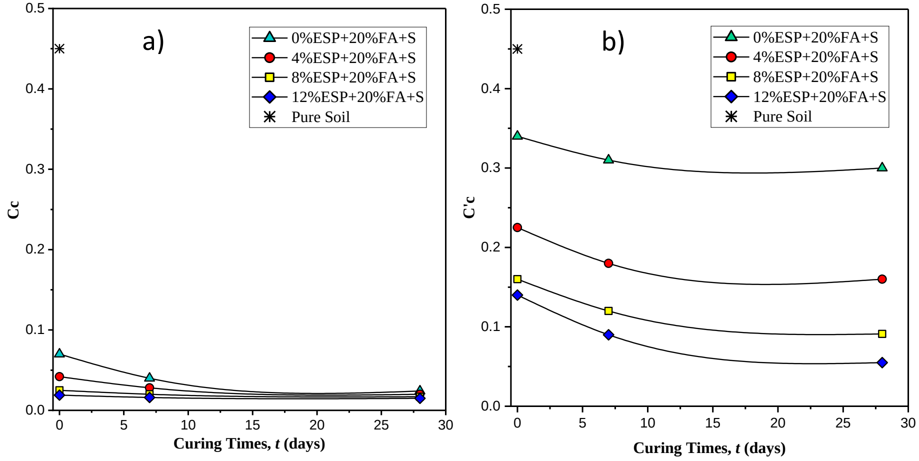

Figure 5: Effect of Curing Time on Compression Index at (a) Pre-Yield Stage; (b) Post-Yield Stage

Figure 5 illustrates the variation in compression index of stabilized samples with curing time at pre-yield and post-yield stages. It is evident that, irrespective of curing time, the compression indexes C_c and C'_c of all stabilized samples are lower than that of pure soil, suggesting that fly ash and eggshell powder effectively reduce the compressibility of soft clay. Furthermore, as shown in Figure 5(a), the variation in C_c value during the pre-yield stage exhibits minimal change with curing time, ranging from 0.07 to 0.015. However, in the post-yield stage, as depicted in Figure 5(b), the compression index C'_c for the stabilized soil samples is significantly higher compared to that of pre-yield stage. As the curing duration extends, the C'_c values for the modified samples show a diminishing trend, which tends to level off with further extension of the curing time. For ESP content of 0%, an increase in curing time from 2 hours to 7 days results in a reduction in C'_c value from 0.34 to 0.31, marking an 8.8% decrease. Similarly, when the curing time extends from 7 days to 28 days, the C'_c value reduces from 0.31 to 0.30, indicating a 3.2% decrease. This pattern indicates that, with an extended curing time, the C'_c value of the stabilized soil remains nearly constant, and compressibility undergoes minimal change. This stability arises from the time-dependent nature of the hydration reaction of fly ash and eggshell powder, with results suggesting that the hydration reaction is nearly reached within 7 days of curing, and gradual increases in curing time is irrelevant to the compressibility (Hudu et al., 2022).

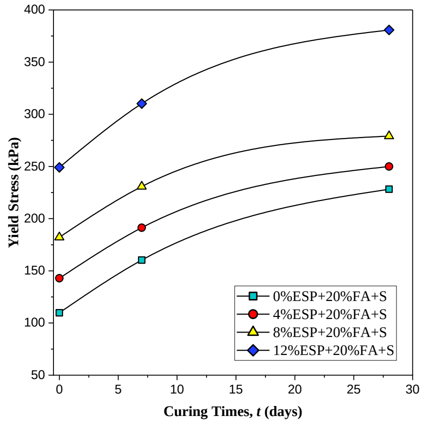

Figure 6: Variation of Yielding Stress of Stabilized Samples with Curing Times

The fluctuation in yielding stress of stabilized soft clay samples over curing time is depicted in Figure 6. The yield stress appears to steadily rises with prolonged curing time. For example, at an ESP content of 12%, the yield stress is 249.1kPa after 2 hours of curing. Subsequently, it elevates to 310.3kPa after 7 days, marking a substantial increase of 24.6%. Furthermore, after 28 days of curing time, it further climbs to 380.7kPa, reflecting a significant surge of 52.8%, which is more than half compared to the 2-hour sample. This trend signifies a notable augmentation in yield stress, particularly with the extension of curing time from 7 days to 28 days. This growth pattern of yield stress remains consistent across samples with varying ESP contents as the curing time progresses. This phenomenon can be elucidated by chemical reactions: fly ash and eggshell powder undergo chemical reactions with the clay minerals or water in the soil. These reactions may result in the formation of bonds and alterations in the soil structure. The rate of these reactions can impact the increment rate of yield stress, which may become more pronounced with the extension of curing time.

V. Conclusion

Through a series of one-dimensional consolidation trials, this paper explores the impact of various ESP contents and different curing periods on compression curves, variations in yield stress, and compression indexes for fly ash treated soft clay samples before and after yielding occurs. The following conclusions have been drawn:

(1) Unlike untreated soil, which exhibits heightened compressibility, the addition of fly ash to soft clay leads to a substantial reduction in compressibility. Furthermore, the curve associated with higher ESP content displays a smoother trend, indicating a correlation between increased ESP content and decreased compressibility. Additionally, under similar ESP content, samples subjected to varying curing durations demonstrate diminishing void ratios as the applied loading pressure increases.

(2) The $e-logp$ curves of the fly ash reinforced soil samples with eggshell powder exhibit two clearly defined straight lines, in contrast to the linear trend observed in untreated soil. These curves illustrate limited compressibility during the pre-yield stage, characterized by consolidation pressures below the compression yield stress ($p<p'_y$). However, a significant increase in compressibility is evident after yielding, when the compression stress surpasses the compression yield stress ($p>p'_y$).

(3) At both pre-yield and post-yield stages, variations in compression indexes with respect to ESP content reveal differences. The compression index of all stabilized samples proves to be smaller than that of the untreated soil, indicating a substantial reduction in compressibility. During the pre-yield stage, C_c exhibits a subtle declining pattern with increasing ESP content, suggesting minimal impact on soil compressibility. However, C'_c experiences a substantial decline with higher ESP content. Furthermore, the compression index values before yielding are significantly smaller than the compression index values after yielding.

(4) Concerning curing time, the change in the compression index at the pre-yield stage is less significant compared to the change in the compression index at the post-yield stage, which increases considerably. This implies that the soil's behaviour after yielding is more affected by changes in curing time compared to its behaviour before yielding. The compression index at the post-yield stage for fly ash modified soil samples with varying ESP content shows a declining pattern, which tends to stabilize as the curing age exceeds 7 days.

(5) The compression yield stress of fly ash and eggshell powder-stabilized soft clay samples increases significantly, particularly above 8% ESP content. Additionally, the yield stress consistently rises with longer curing times, especially after 7 days, as its subsequent increase becomes more prominent, suggesting that the soil strength continues to improve over time.

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