

## Effect of Silica Fume as Industrial Byproduct on the Stabilization of Kaolin Clay Soil

Muhammad Syamsul Imran Zaini<sup>1\*</sup>, Muzamir Hasan<sup>1\*</sup>, Anang Rustanto Suwito<sup>1</sup>, Muhammad Farhan Zolkepli<sup>2</sup>, Norhidayah Mohamed<sup>1</sup>, Zaihasra Abu Talib<sup>3</sup>

<sup>1</sup> Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuhr Persiaran Tun Khalil Yaakob, 26300, Gambang, Pahang, MALAYSIA

<sup>2</sup> Department of Geotechnics and Transportation, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, 81310, MALAYSIA

<sup>3</sup> Faculty of Civil Engineering & Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, MALAYSIA

\*Corresponding Author: [muzamir@umpsa.edu.my](mailto:muzamir@umpsa.edu.my); [syamsulimran94@gmail.com](mailto:syamsulimran94@gmail.com)

DOI: <https://doi.org/10.30880/ijscet.2025.16.02.021>

### Article Info

Received: 16 January 2025  
Accepted: 9 November 2025  
Available online: 31 December 2025

### Keywords

Soil stabilisation, expansive soil, kaolin, silica fume, unconfined compressive strength

### Abstract

The utilization of chemical stabilizers for soil stabilization is a method by which the construction sector can minimize its negative effect on the environment. Stabilizing of soft clay remains challenging due to the requirement for costly and ecologically harmful materials such as lime and cement. This research investigates the viability of silica fume (SF), an industrial waste, as an eco-friendly soil stabilizer for kaolin clay soil (KCS). Laboratory tests were conducted to examine the impact of different SF concentrations (2%, 4%, 6%, and 8%) on the physical, mechanical, and strength properties of the soil. The addition of SF as soil stabilizers improved the KCS properties, which led to the increment of soil strength up to 87.02% when 6% of SF was utilized at 30 days of curing, reduction in OMC and increment MDD value, and reduction of liquid limit and plasticity index. After 30 days of curing with 6% SF, the KCS's unconfined compressive strength (UCS) markedly improved from 13.89 kPa to 25.94 kPa. The results demonstrate that industrial waste materials can enhance soil stabilization efficacy while simultaneously improving the environment, rendering them a viable alternative to traditional soil stabilizers.

## 1. Introduction

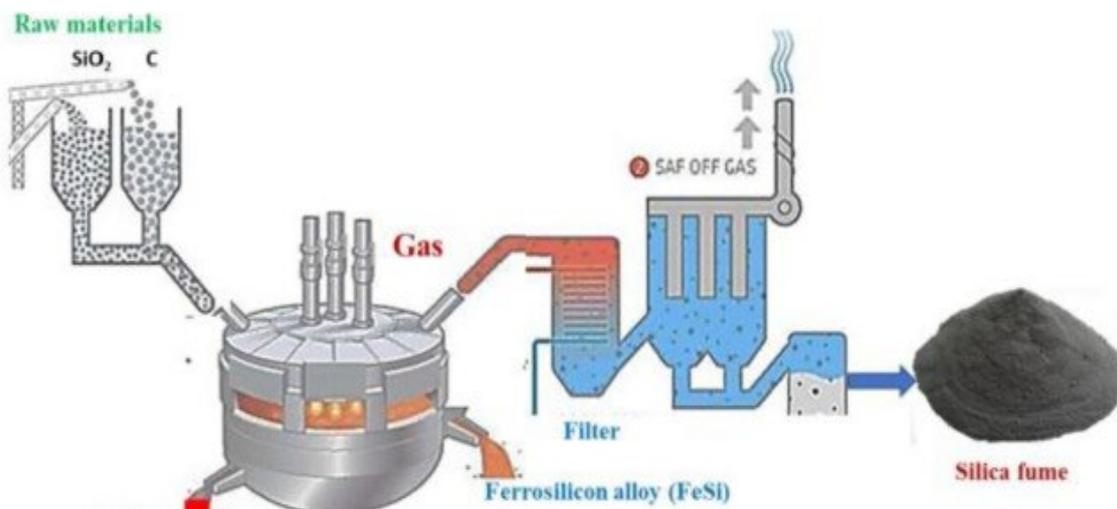
Geotechnical engineering, an essential branch of civil engineering, enhances infrastructure resilience, environmental conservation, and societal welfare [1-4]. One of the most difficult challenges in geotechnical engineering is stabilizing soils that threaten infrastructure safety and durability [5-8], such as expansive [9-12] and weak clays [13-16]. Kaolin clay soil (KCS), known for its weakness with a substantial compressibility, poses significant challenges in construction due to its suboptimal geotechnical properties [17-20]. For decades, the traditional methods of soil stabilization rely on the use of lime and cement [21-24]. Despite its effectiveness in improving soil characteristic, such approaches are linked to increased environmental challenges, excessive energy use, and elevated carbon emissions.

Recently, environmentally friendly soil-stabilizing methods have gained popularity. Silica fume (SF), a byproduct of silicon metal and ferrosilicon alloy manufacturing, can stabilize soil owing to its small particle size and significant pozzolanic activity [25-27]. Fig. 1 illustrates the phases necessary to produce SF. Silicon dioxide

(SiO<sub>2</sub>) constitutes the principal element of SF, generating cementitious compounds upon interaction with calcium hydroxide (Ca (OH)<sub>2</sub>) present in soil [28-30]. By recycling industrial residue that may otherwise harm the environment, SF enhances soil geotechnical qualities and tackles waste management challenges [31-35].

Several studies conducted by Ahmad et al. [36], Ahmad et al. [37], Bujang et al. [38], Ahmad et al. [39], Ahmad et al. [40], and Ahmad et al. [41] have highlighted the stabilizing effect of silica fumes in problematic soils. While much attention has been given to expansive clay, silica fume has also shown potential in improving the geotechnical properties of other difficult soils such as peat and marine soils. For instance, in peat soil, silica fume can improve compressive strength and reduce settlement due to its high pozzolanic activity and fine particle size, which enhance soil structure and reduces water content. Similarly, in marine clays, silica fume has been reported to enhance bearing capacity and reduce plasticity, especially when used in combination with lime or cement. In addition to silica fume, other industrial byproducts like palm oil fuel ash (POFA), ground granulated blast furnace slag (GGBS), and fly ash have been successfully employed as soil stabilizers. POFA, rich in silica and alumina, has demonstrated promise in improving the strength and durability of soft clays. GGBS, with its latent hydraulic properties, is effective when activated with lime or alkalis, particularly in sulphate-rich soils.

Although kaolin is often considered a relatively stable clay, its low strength and high permeability can limit its suitability in geotechnical applications. The use of silica fume as a stabilizing agent for kaolin has shown promise in enhancing strength parameters through pozzolanic reactions and microstructural refinement. However, literature remains limited in comparing the behaviours of silica fume-stabilized kaolin to other problematic soils, such as peat and marine clay, which exhibit more complex challenges like high organic content and salinity. Highlighting this comparison can underscore the versatility or limitations of silica fumes across different soil types. Therefore, exploring the comparative performance and hybrid binder systems in kaolin and other problematic soils represents a novel contribution to sustainable ground improvement practices.



**Fig. 1** Process of silica fume production

## 1.1 Literature Review

The stabilization of clay soils poses a critical challenge in geotechnical engineering due to their tendency for volumetric changes with moisture variations. The effects of such behaviours often lead to structural damage, inequitable settlements, and costly restorations. KCS needs stabilization for infrastructure applications due to its inadequate strength and excessive compressibility [42-45]. The extensive utilization of lime and cement, two conventional soil stabilizers, has adversely impacted the environment due to their significant energy consumption and CO<sub>2</sub> emissions. Annually, around 5–8% of global anthropogenic CO<sub>2</sub> emissions are attributed to cement manufacturing [46-48]. The use of industrial by-products has emerged as a viable alternative to address these challenges [49-53].

Studies demonstrate that SF can enhance soil performance. The enhancement is ascribed to the cementitious compounds produced by the pozzolanic interactions between silica fume and soil minerals [53-55]. In contrast to conventional stabilizers, SF is environmentally sustainable and economically advantageous since it improves the unconfined compressive strength (UCS) and durability of soils [56-58]. The strategy alleviates the negative environmental effects of building while simultaneously tackling waste management concerns by using industrial wastes.

The stabilisation of expansive soils has been well studied, however, the stabilisation of KCS using SF has garnered less focus. KCS, characterized by its little shrink-swell potential and limited flexibility, offers a distinctive opportunity to assess the efficacy of SF in improving the geotechnical features of the material. This research seeks to fill the gap by thoroughly investigating the influence of SF on KCS, hence clarifying its potential sustainable geotechnical uses.

## 1.2 Significance of Study

This study is important since it focuses on both vital geotechnical issues and the advancement of sustainable construction methods. This study enhances the understanding of sustainable soil development strategies by investigating KCS stabilization using SF. KCS, while often utilized in industrial applications, possesses poor strength and high compressibility, leading to substantial building difficulties [59-61]. Stabilizing this soil with SF is a unique solution that improves its technical features while reducing the environmental effect of traditional stabilizers such as lime and cement [62]. SF provides a sustainable solution that improves waste management by repurposing industrial waste, hence decreasing landfill trash and greenhouse gas emissions.

The study promotes the creation of sustainable urban settings by enhancing the durability and resilience of infrastructure. This research aims to clarify the effectiveness of SF as a soil stabiliser for kaolin clay through comprehensive laboratory testing and analysis. The findings have the potential to guide engineers, legislators, and the construction industry about sustainable soil stabilisation methods, thereby advancing durable and environmentally friendly infrastructure. This work promotes the incorporation of sustainable practices in geotechnical engineering by addressing both technical and environmental issues in soil stabilization.

## 2. Materials and Methods

In this section, a description of materials used such as kaolin clay soil (KCS) and silica fumes (SF), and experimental setup to determine the properties of the stabilized soil is explained in detail.

### 2.1 Materials

Kaolin powder was used as the main material in the research to produce reiteration homogenous soft clay samples. KCS is a white, soft powder consisting principally of the minuscule kaolinite particles (Fig. 2a). The KCS sample utilized in this study is sourced from Kaolin (M) Sdn Bhd. The KCS had a specific gravity of 2.63 and unconfined compressive strength (UCS) of 13.87 kPa. The liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the KCS were 42.5%, 35.1%, and 7.4%, respectively. The American Association of State Highway and Transportation (AASHTO) classified the KCS as A-5, a composition of clay and silt. The KCS was initially subjected to oven drying at 100°C for a duration of 1 day and was thereafter kept in an airtight container until the laboratory testing. Silica fume (SF) consists of extremely fine hyaline particles, approximately 100 times diminutive than typical cement particles, with a surface area of around 20,000 m<sup>2</sup>/kg, based upon nitrogen absorption measurement techniques [10]. The predominant component of SF is amorphous silicon dioxide, represented as (SiO<sub>2</sub>). SF in this research was sponsored by a company that sells chemical construction products situated in Malaysia. The type of SF used in this research was a densified SF for concrete (Fig. 2b). Table 1 shows the physicochemical properties of SF and KCS used in the study.

**Table 1** Physicochemical properties of KCS and SF

Properties	KCS	SF
Specific Gravity	2.63	2.35
Gravel (%)	0	-
Sand (%)	48	-
Silt & Clay (%)	52	-
Liquid Limit (%)	42.5	90.1
Plastic Limit (%)	32.1	80.2
Plasticity Index (%)	7.4	9.9
Maximum Dry Unit Weight (kN/m <sup>3</sup> )	1.509	-
Optimum Moisture Content (%)	19.77	-
Elemental Oxides (%)		
SiO <sub>2</sub>	65.01	76.05
Al <sub>2</sub> O <sub>3</sub>	19.37	0.45
Fe <sub>2</sub> O <sub>3</sub>	0.70	0.73
CaO	0.10	-
MgO	1.05	3.70
K <sub>2</sub> O	3.01	0.25
Na <sub>2</sub> O	-	0.44
SO <sub>3</sub>	-	0.90

## 2.2 Experimental Methods

The research study was designed to assess the effects of SF on KCS by analysing its physical, compaction, and strength properties. The KCS was subjected to treatments of 2%, 4%, 6%, and 8% SF based on the dry weight of the soil. Kaolin clay soil was treated with 2%, 4%, 6%, and 8% silica fume (SF) based on the dry weight of soil to systematically investigate the effect of incremental additions of silica fume on the geotechnical properties of the soil as highlighted by Zaini et al. [6] and Hasan et al. [3]. Table 2 presents the sample formulation employed during the study. The experimental method consists of three primary phases, which are determining critical physical features, compaction characteristics, and strength behaviour. The geotechnical characteristics of KCS and KCS-SF samples were evaluated using the procedures and standards listed in Table 3. In this study, the sample was cured for four (4) different curing periods which is 1, 7, 14, and 30 days of curing. In soil stabilization, like in concrete, 28 days is commonly used because research shows that treated soils typically achieve close to their maximum strength after 28 days. However, in engineering practice, an extra 2 days (moving from 28 to 30 days) acts as a safety margin to ensure quality before starting major loadings or construction on the stabilized soil. Field conditions such as moisture variations, temperature fluctuations, and soil variability can slow the stabilization reactions. Extending the curing period to 30 days ensures full reaction and strength gain.



**Fig. 2** Materials used in the study: (a) KCS; (b) SF

The physical parameters of KCS and KCS-SF samples were assessed by Atterberg limit test and specific gravity test. The Atterberg limit test was utilized to assess the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of untreated KCS and KCS stabilized with different quantities of SF (2%, 4%, 6%, and 8%). The tests followed the standard requirements outlined in BS 1377. The LL was evaluated using cone penetrometer method, while the PL was established by rolling soil samples into threads to a diameter of 3 mm. The PI was determined by deducting PL from LL. These leads critical data on the soil's workability and deformation properties. The specific gravity (Gs) of KCS and KCS-SF samples was determined using a small pycnometer. The objective of this test was to evaluate the soil's relative density, which directly affects its compaction and strength properties. The components underwent oven drying, were weighed, and mixed with water to guarantee precise Gs readings.

The standard Proctor test was utilized to evaluate compaction behaviour of samples. This evaluation identifies the soil's maximum dry density (MDD) and optimum moisture content (OMC). Each KCS and KCS-SF sample was combined with water at varying moisture levels and compacted into a standard Proctor mould using a rammer, as seen in Fig. 3. The soil sample was then compacted by the rammer released from a height of 305 mm. The correlation between dry density and water content was plotted to observe the MDD and OMC for each mix fraction. The compaction curve interprets the effect of SF on soil densification.

**Table 2** Sample formulation

Coding	Sample mixture	KCS-SF proportion
KCS	Kaolin clay soil	100:0
KCS2SF	Kaolin clay soil with 2% of Silica Fume	98:2
KCS4SF	Kaolin clay soil with 4% of Silica Fume	96:4
KCS6SF	Kaolin clay soil with 6% of Silica Fume	94:6
KCS8SF	Kaolin clay soil with 8% of Silica Fume	92:8

**Table 3** Laboratory tests and standards for sample

Sample	Type of testing	Number of Sample	Standard		
KCS	Atterberg limit test	3	BS 1377: Part 2: 1990 [57] BS 1377: Part 2: 1990 [57] BS 1377: Part 2: 1990 [57]		
SF		3			
KCS2SF		3			
KCS4SF		3			
KCS6SF		3			
KCS8SF		3			
KCS		3			
SF		3			
KCS2SF	Specific gravity test	3	BS 1377: Part 2: 1990 [57]		
KCS4SF		3			
KCS6SF		3			
KCS8SF		3			
KCS		5			
KCS2SF	Proctor compaction test	5	BS 1377: Part 4: 1990 [57]		
KCS4SF		5			
KCS6SF		5			
KCS8SF		5			
KCS		5			
KCS2SF		5			
KCS4SF		Unconfined compression test		5	ASTM D 2434 [58]
KCS6SF				5	
KCS8SF	5				

**Fig. 3** Standard proctor test equipment

The unconfined compressive strength traits of the KCS and KCS-SF samples were analysed using the unconfined compressive strength test (UCT). Cylindrical samples with 76mm height and 38 mm diameter were prepared and cured for 1, 7, 14, and 30 days under controlled moisture conditions. Table 4 shows the detail of the sample specimen tested for the test while Table 5 shows the specification of the UCS machine used. The UCT involved loading the specimens axially at a constant strain rate until failure. The maximum compressive stress sustained by each sample was recorded as the UCS value. The UCT results were used to assess the stabilization efficacy of SF over different curing periods. This test is particularly important for understanding the strength performance of the stabilized soil and its suitability for various geotechnical applications.

**Table 4** Detail of sample specimen tested for UCS

Coding	Volume (cm <sup>3</sup> )	Mass (g)	OMC (%)	MDD (g/cm <sup>3</sup> )
KCS	196.35	312	19.77	1.509
KCS2SF	196.35	312	20.71	1.602
KCS4SF	196.35	312	20.54	1.605
KCS6SF	196.35	312	20.48	1.610
KCS8SF	196.35	312	20.31	1.618

**Table 5** Detail of sample specimen tested for UCS

Specifications	Description
Product	TriPLEX Multitester 50 kN
Load Capacity	50 kN
Speed Range	0-50.8000 mm/mi
Fast Platen Adjustment Speed	50 mm/min
Vertical Clearance	1000 mm
Horizontal Clearance	380 mm
Platen Diameter	158 mm
Power Supply	90-240V, 50/60Hz, 1ph
Dimensions (W x D x H)	480mm x 445mm x 1490 mm
Weight	100 kg

### 3. Results and Discussions

#### 3.1 Atterberg Limit

The Atterberg limits, comprising the LL, PL, and PI, provide insight into the plasticity and workability of the stabilized soil. The experimental results show a consistent reduction in plasticity with increasing SF content, which directly influences the engineering behaviours of the soil. Fig. 4 shows Atterberg limits of each sample in this study. The LL, PL, and PI were reported at 42.5%, 35.1%, and 7.4%, respectively, for KCS that had not been prescribed any treatment. After stabilization, the inclusion of SF gradually decreased these values, which became less significant over time. Along with a PI of 7.3%, the LL and PL both reduced to 39.7% and 32.4%, respectively, when the SF was set at 2%. A partial substitution of clay particles with SF is responsible for the decline. These results align with Zaini et al. [6] and Türköz et al. [42], who reported decreasing trends in PI and LL in SF-treated clay soils, albeit with slightly higher reductions due to higher initial plasticity indices. The limited reduction in this study may be attributed to the inherently low plasticity of KCS compared to expansive clays.

Soil water absorption is reduced due to the reduction of the soil's active surface area caused by this replacement. The little decrease in PI suggests that there has been a minor improvement in the soil's workability that has occurred without a significant loss of cohesion. This resulted in a decrease in the LL to 40.4% and 40.9% at 4% and 6% SF, respectively, while the PL increased to 33.1% and 34.1% over the same time. The PI values of 7.1% and 6.8% indicate a continuous decrease in soil flexibility. Cementitious compounds are caused by pozzolanic interactions between SF and the KCS minerals found in the soil [20].

Soil particles are aggregated because of these interactions, which cause the creation of cementitious compounds. Through this reaction, the amount of free water that is available is reduced, which in turn helps to stabilize the soil matrix and increases its resilience to deformation. The LL increased to 41.3% with an 8% SF, while the PL increased to 34.6%, resulting in a PI of 6.6%. The LL was slightly higher than the PL. The little rise in LL that occurs when the concentration of SF is increased may indicate that there is a saturation limit, at which the presence of additional SF particles reduces the influence that they have on the decrease of plasticity and increases the formation of a denser matrix.

The gradual increase in plastic limit that occurs along with an increased sand fraction concentration is indicative of improved soil cohesion and stiffness, which has the effect of rendering the soil less susceptible to shrink-swell occurrences. The general drop in plasticity index across all sand-fines percentages demonstrates the effectiveness of sand-fines in reducing the flexibility of soil, which in turn improves the soil's suitability for use in construction applications [24]. The patterns that are observed in LL and PL are examples of the dual role of SF, which is to act as both a filler and a chemical stabilizer, so improving the functionality and longevity of the soil. This renders SF-stabilized KCS more controllable during construction and diminishes its susceptibility to deformation under load or environmental variations.

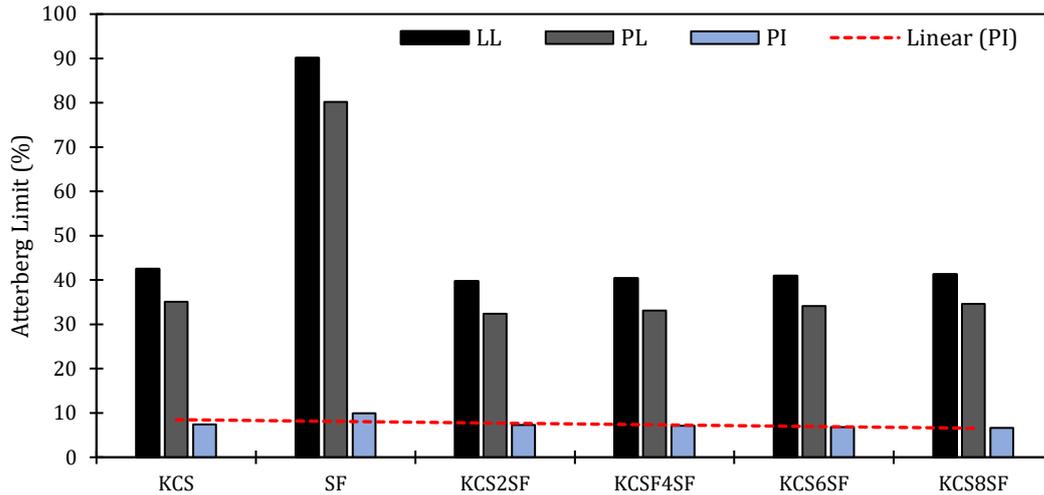


Fig. 4 Relationship between types of a sample with sample Atterberg limits (%)

### 3.2 Specific Gravity

The relative density of the KCS and KCS-SF samples can be determined by its specific gravity (Gs). The incorporation of SF caused variations in Gs values, signifying the interaction between the denser SF particles and the KCS matrix. Fig. 5 shows the Gs of the different type of samples in this study. The Gs of untreated KCS were measured at 2.63, whereas SF alone had a value of 2.35. Stabilized samples of 2%, 4%, 6%, and 8% SF exhibited Gs values of 2.54, 2.51, 2.48, and 2.47, respectively. The findings indicate that Gs first rises at 2% SF, then declines consistently as the SF level escalates. The increased voids caused by the micro-filler properties of SF at increasing concentrations impact the composite material's overall density, which is the reason behind the observed effect [25]. The slight decrease in Gs with increasing SF concentrations indicates an imbalance between particle packing efficiency and the dilutive effect of the lighter SF material. This research underlines the necessity of optimizing SF concentration to preserve soil density while enhancing engineering properties. The stabilizing mechanism indicates that moderate SF levels (6%) optimize soil growth while preserving compactness. These data illustrate SF's nuanced influence on soil stabilization, which extends little density enhancement to alter the entire structural matrix. This information is essential for tailoring SF stabilizing techniques to geotechnical applications that emphasize compaction or other mechanical properties. The decreasing Gs values with higher SF content mirror findings by Almuaythir et al. [14], though the magnitude of reduction in this study was more moderate, likely due to the finer gradation and higher mineral purity of the kaolin clay used here compared to the expansive clays in previous studies.

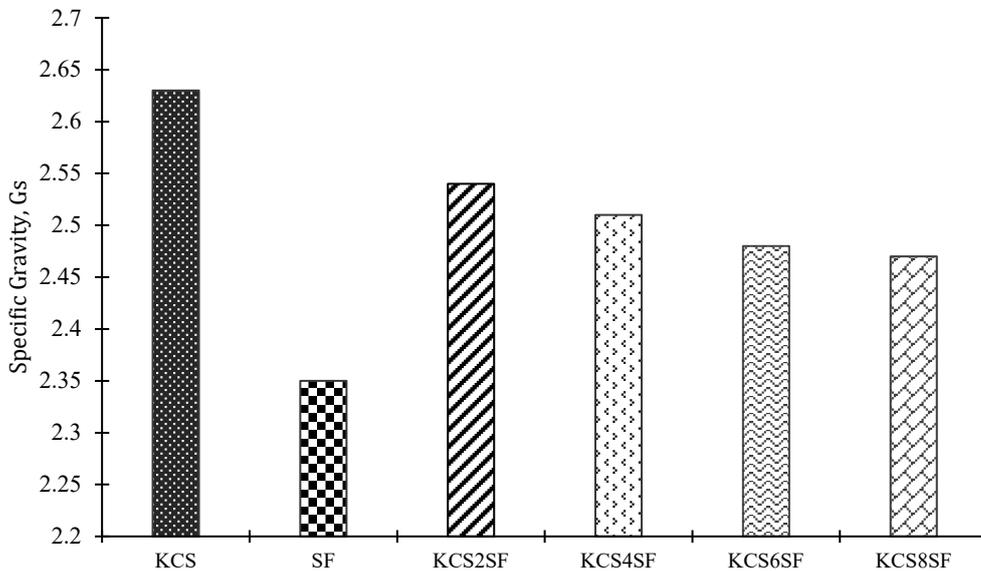


Fig. 5 Specific gravity of different type of samples

### 3.3 Proctor Compaction Test

The compaction properties, characterized by the maximum dry density (MDD) and optimum moisture content (OMC), were determined for KCS samples stabilized with varying percentages of SF. Fig. 6 illustrates the compaction curve of KCS and KCS-SF samples. The results show a gradual increase in MDD and a slight adjustment in OMC as the SF content increased. For untreated KCS, the MDD was recorded at  $1.509 \text{ g/cm}^3$  with an OMC of 19.77%. Upon the addition of 2%, 4%, 6%, and 8% SF, the MDD values increased to  $1.602 \text{ g/cm}^3$ ,  $1.605 \text{ g/cm}^3$ ,  $1.610 \text{ g/cm}^3$ , and  $1.618 \text{ g/cm}^3$  when 4, 6, and 8% of SF were used. While the OMC values adjusted to 20.70%, 20.50%, 20.40%, and 20.31%. These changes suggest that the finer particles of SF fill the voids between soil particles, leading to denser compaction. The decrease in OMC was appropriately supervised. It is predicted that the reduced specific gravity and larger particle sizes of the SF led to an increased void volume. As a result, the thickness of the duplex layer will decrease, and grain accumulation will transpire when sodium cations are substituted by silicon cations in the diffusive clay of KCS [14]. The gradual increase in MDD and relatively stable OMC suggests the filler effect of SF enhanced soil packing without significantly altering the water demand. This may be due to the low water absorption capacity of SF compared to clays and the presence of well-graded particles that reduce water film thickness around soil grains [42].

Nevertheless, the findings did not align well with the previous study regarding particle size, indicating that the incorporation of 2%, 4%, and 6% of SF diminishes the specific gravity of kaolinitic clay soil but does not significantly alter its particle size, leading to a marginal decrease in OMC across the different percentages of SF employed [14]. The condition arose from a little substitution of SF for kaolinitic clay particles during the stabilization process. Moreover, the common silty-type soil is found inside the KCS, leading to densely packed molecules that inhibit the formation of additional void volume. Consequently, the stabilization of the unstabilized KCS samples with 2%, 4%, 6%, and 8% SF decreased the OMC. The compaction curve demonstrates a more consistent dry density profile with higher SF percentages, signifying improved soil homogeneity. These findings underscore the importance of SF in enhancing soil density and stability, rendering it suitable for applications necessitating greater load-bearing capacities.

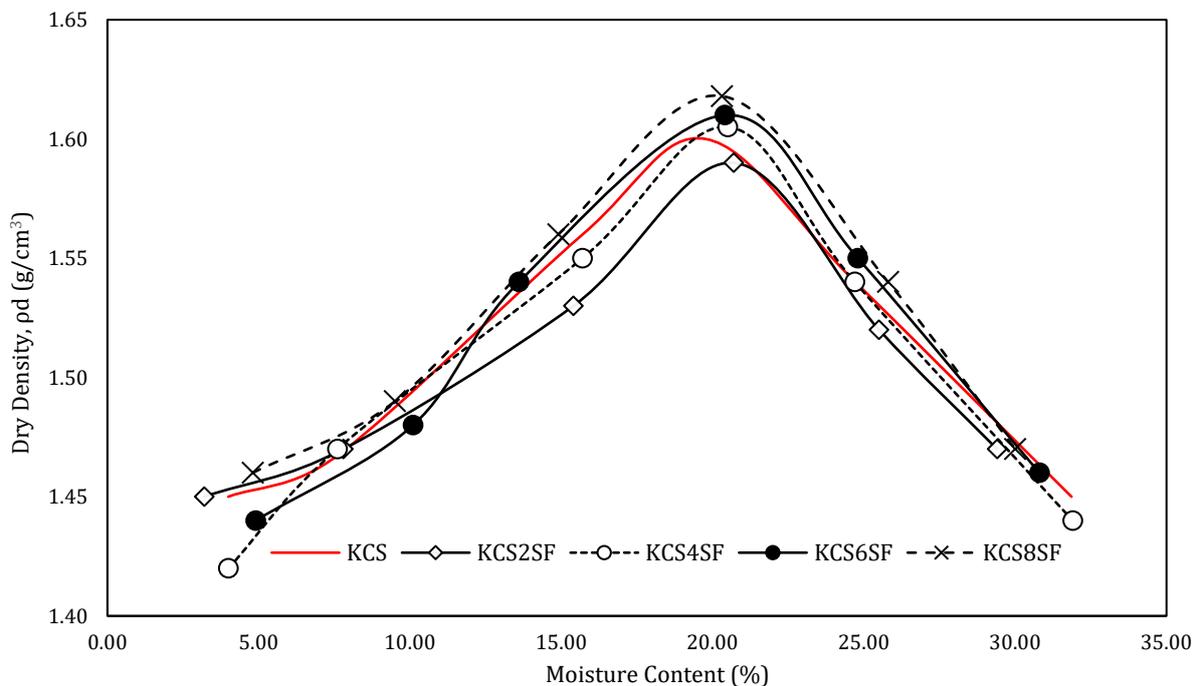


Fig. 6 Compaction curve of KCS and KCS-SF stabilised samples

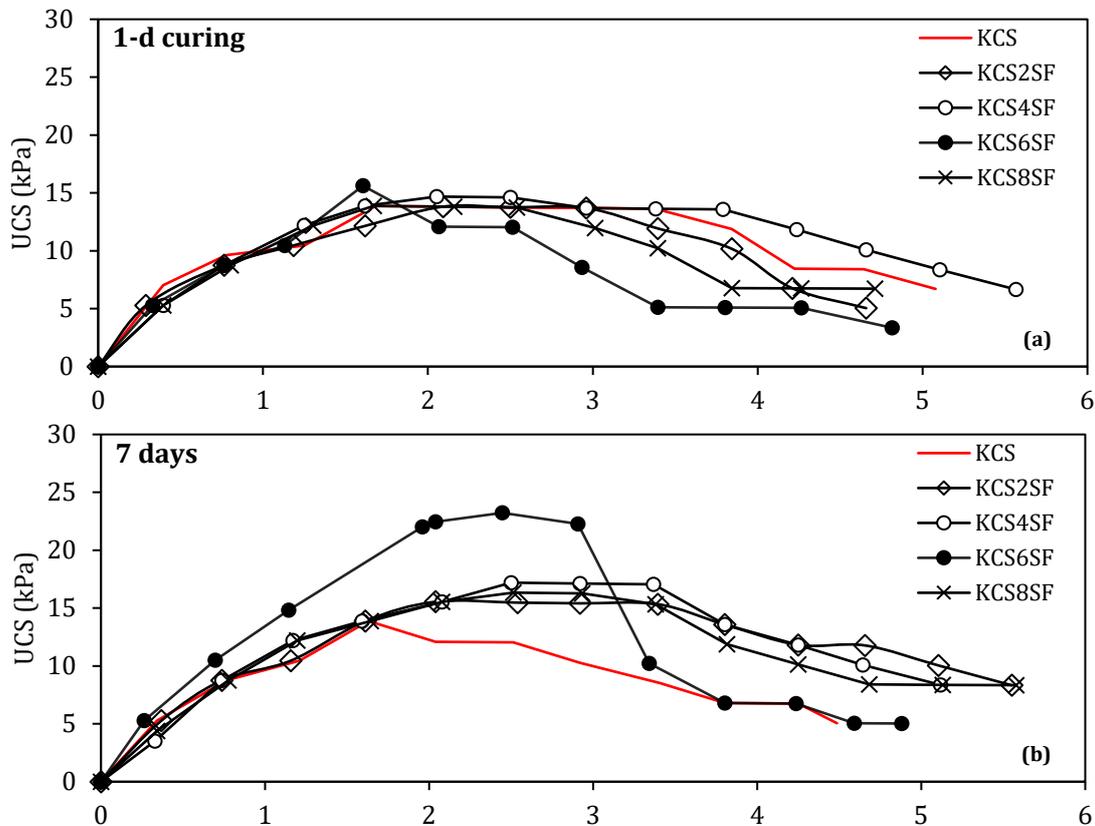
### 3.4 Strength Properties

The unconfined compression test (UCT) was conducted on KCS samples stabilized with varying percentages of SF revealed a clear trend of strength improvement with increasing SF content and curing time. After 1 day of curing, the unconfined compression strength (UCS) of untreated KCS was recorded at 13.87 kPa. Upon stabilization with 2%, 4%, 6%, and 8% SF, the UCS values increased to 13.91 kPa, 14.68 kPa, 15.62 kPa, and 13.89 kPa, respectively (Fig. 7a). The enhancement in strength is attributed to the initial pozzolanic reactions between SF and soil particles, leading to the formation of weak cementitious bonds. With an extended curing period (7 days of curing),

the UCS values further improved. The stabilized samples showed UCS values of 15.55 kPa (2% SF), 17.19 kPa (4% SF), 23.22 kPa (6% SF), and 16.33 kPa (8% SF) (Fig. 7b). This strength increment highlights the progressive development of cementitious compounds over time. This increase also reflects the ongoing hydration process and the gradual formation of stronger soil bonds. After 14 days of curing, the stabilized samples recorded UCS values of 17.27 kPa (2% SF), 19.00 kPa (4% SF), 24.09 kPa (6% SF), and 18.05 kPa (8% SF) (Fig. 7c). Although the peak UCS of 25.94 kPa appears modest, it represents a nearly 87% increase from the untreated sample and may suffice for low-load applications such as landscaping, footpaths, or slope surface stabilization. Similar applications were reported effective in work by Zaini et al. [6] for soils treated with comparable pozzolanic additives.

The results demonstrate the significant role of SF in enhancing soil strength by forming durable calcium silicate hydrates (CSH). The extended curing time allows additional pozzolanic reactions, leading to a denser soil matrix with enhanced mechanical properties. The final curing stage (30 days of curing) saw the most pronounced improvements. The UCS of samples with 2%, 4%, 6%, and 8% SF reached 19.03 kPa, 21.60 kPa, 25.94 kPa, and 20.66 kPa, respectively (Fig. 7d). The increased UCS at 30 days indicates the completion of pozzolanic reactions and the formation of a well-bonded soil matrix. These data underscore the peak pozzolanic and hydration responses of the stabilisation sample, resulting in a cohesive and durable soil structure.

The results verify that curing duration significantly influences the stabilization effectiveness of SF in KCS. The strength development observed across curing durations shows a dynamic process involving ongoing chemical interactions. During the initial days, the rapid reaction between SF and available  $Ca(OH)_2$  initiates bond formation, producing an immediate but moderate increase in strength [65,66]. This phase is critical for early stabilization in construction applications. As the curing progresses to Day 7 and beyond, the rate of strength gain slows but remains steady due to secondary hydration and pozzolanic activity within the soil matrix. These reactions fill voids and enhance particle bonding, transforming the soil structure into a dense, semi-rigid matrix. By Day 14, the soil achieves significant improvement in load-bearing capacity, suitable for heavier construction applications. The long-term curing effects observed at Day 30 are particularly significant. The improvement trends are consistent with findings from Hasan et al. [3] and Almuaythir et al. [14], who attributed similar strength increases to pozzolanic reaction products such as CSH.



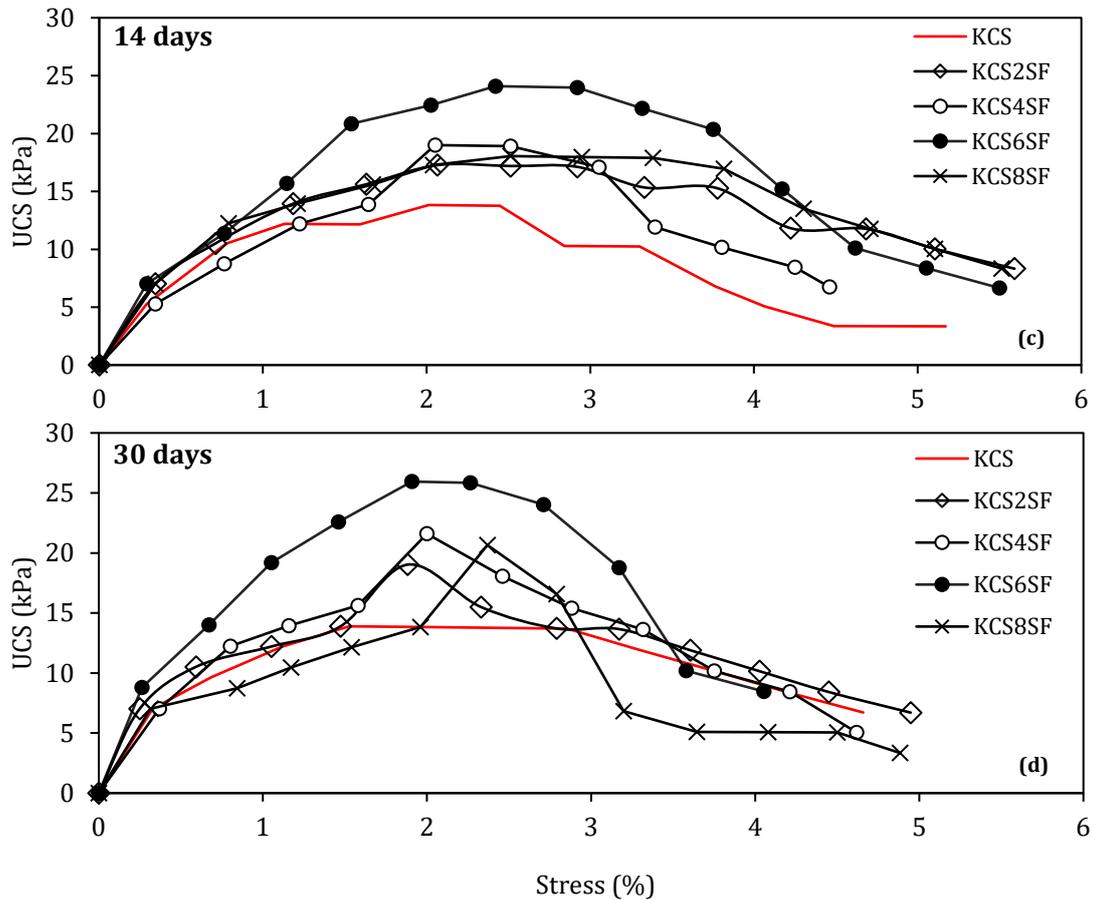


Fig. 7 Unconfined compressive strength of KCS and KCS-SF sample

The results reveal that even after primary reactions are complete, ongoing stabilization processes refine the soil microstructure. This leads to improved durability and resistance to environmental degradation. Such prolonged curing benefits indicate that SF stabilization can enhance soil resilience for applications requiring long service life. Fig. 8 depicts UCS evolution with the curing of the KCS and KCS-SF samples. The result reveals a strong dependency of KCS stabilization with SF on curing time. This highlights the need to consider appropriate curing durations in practical applications to maximize the performance benefits of SF stabilization. Future studies could explore accelerated curing techniques or complementary additives to further optimize this process. Although not directly measured, the deformation profile suggested by the UCS load-displacement curves indicates limited toughness and stiffness enhancement. Future work should include resilient modulus or stress-strain analysis to capture these parameters.

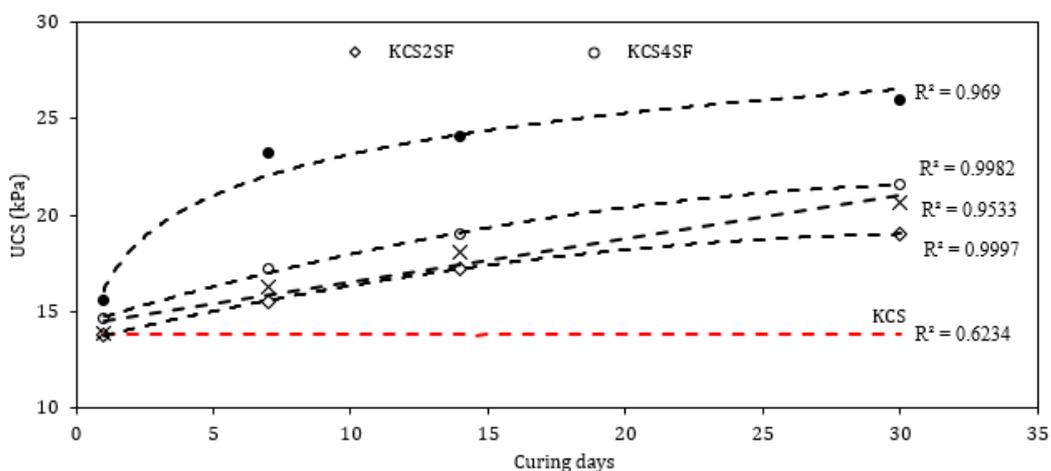


Fig. 8 UCS evolution with curing time, of the KCS and KCS-SF based soil stabilizers

## 4. Conclusion

This study demonstrates that SF is an effective sustainable stabilizer for KCS, significantly altering its physical and compaction attributes while increasing the strength properties. The optimum concentration was found to be 6% SF, which resulted in substantial improvements in all measures tested. The following findings were drawn:

- 1) Atterberg limit tests revealed that adding 6% SF reduced the PI from 7.4% to 6.8%, indicating better soil workability. Furthermore, the specific gravity increased significantly to 2.48 which indicates a more compact and denser soil matrix after the addition of SF.
- 2) The stabilized sample achieved MDD of 1.610 g/cm<sup>3</sup> and OMC of 20.40% at 6% SF. These findings suggest that SF improves particle packing in the soil matrix and reduces voids, resulting in enhanced soil compaction characteristics.
- 3) The UCS results demonstrates a significant improvement in soil strength, with the UCS reaching its peak value at 6% SF after 30 days of curing. The observed strength enhancement aligns with trends reported in studies attributing such gains to pozzolanic reactions by previous researchers, though microstructural analysis was not conducted in this study.

The results showed significant improvements in strength and plasticity characteristics, particularly at 6% SF, indicating the effectiveness of silica fume in enhancing soil performance. Beyond laboratory results, this research offers practical value by promoting the use of silica fume, an industrial by-product primarily from the silicon and ferrosilicon alloy industry — in geotechnical applications. The incorporation of silica fume in soil stabilization not only reduces reliance on conventional stabilizers like cement and lime, which have higher environmental footprints, but also contributes to more sustainable waste management practices. Utilizing this industrial by-product helps mitigate the environmental burden associated with its disposal, addressing growing concerns about solid waste accumulation in industrial sectors. Therefore, this method presents a dual benefit: improving the engineering properties of problematic soils while supporting circular economy goals by repurposing industrial waste in a value-added application.

## Acknowledgement

The authors would like to acknowledge Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA) and Hokoku Engineering for financing this research through the UMP Matching Grant (Project Number: RDU252702) and the Hokoku International Grant (Project Number: UIC251503). The cooperation of all parties involved in this research is also greatly acknowledged. The author would like to also thank Universiti Teknologi Malaysia for Grant UTM Encouragement Research (Q.J130000.3822.31J91- The Analysis of Slope Stability due to Tree Water Uptake on Tropical Residual Soil) and the Department of Geotechnics and Transportation, Universiti Teknologi Malaysia for the guidance and support given for this work.

## Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows: **Data collection, analysis, draft manuscript:** Muhammad Syamsul Imran Zaini, Anang Rustanto Suwito; **Supervision:** Muzamir Hasan; **Interpretation of results:** Muhammad Syamsul Imran Zaini, Norhidayah Mohamed; **Reviewing of manuscript:** Muhammad Farhan Zolkepli, Zaihasra Abu Talib.*

## References

- [1] Sorooshian, S. (2024). The sustainable development goals of the United Nations : A comparative midterm research review. *Journal of Cleaner Production*, 453(March), 142272. <https://doi.org/10.1016/j.jclepro.2024.142272>
- [2] Zaini, M. S. I., Hasan, M. & Zolkepli, M. F. (2022). Urban landfills investigation for leachate assessment using electrical resistivity imaging in Johor, Malaysia. *Environmental Challenges*, 6, 100415. <https://doi.org/10.1016/j.envc.2021.100415>
- [3] Hasan, M., Zaini, M. S. I., Yie, L. S., Masri, K. A., Putra Jaya, R., Hyodo, M., & Winter, M. J. (2021). Effect of optimum utilization of silica fume and eggshell ash to the engineering properties of expansive soil. *Journal of Materials Research and Technology*, 14, 1401-1418. <https://doi.org/10.1016/j.jmrt.2021.07.023>

- [4] Zolkepli, M. F., Ishak, M. F., & Zaini, M. S. I. (2019). Slope stability analysis using modified Fellenius's and Bishop's method. *IOP Conference Series: Materials Science and Engineering*, 527, 012004. <https://doi.org/10.1088/1757-899X/527/1/012004>
- [5] Zaini, M. S. I., Ishak, M. F., Zolkepli, M. F., Wahap, M. S., Sidek, J. I. J., Yasin, A. M., Zolkepli, M. N., Sidik, M. H. M., Arof, K. Z. M. & Talib, Z.A. (2020). Granite Exploration by using Electrical Resistivity Imaging (ERI): A Case Study in Johor. *International Journal of Integrated Engineering*, 12(8), 328-347. <https://doi.org/10.30880/ijie.2020.12.08.032>
- [6] Zaini, M. S. I., Hasan, M., Yie, L. S., Masri, K. A., Jaya, R. P., Hyodo, M. & Winter, M.J. (2022). The Effect of Utilizing Silica Fume and Eggshell Ash on the Geotechnical Properties of Soft Kaolin Clay. *Jurnal Teknologi*, 84(1), 159-170. <https://doi.org/10.11113/jurnalteknologi.v84.17115>
- [7] Shayan, N. F., Mohabbati-kalejahi, N., & Alavi, S. (2022). Sustainable Development Goals ( SDGs ) as a Framework for Corporate Social Responsibility ( CSR ). *Sustainability*, 1-27. <https://doi.org/https://doi.org/10.3390/su14031222>
- [8] Fei, W., Opoku, A., Agyekum, K., Oppon, J. A., Ahmed, V., Chen, C., & Lok, K. L. (2021). The Critical Role of the Construction Industry in Achieving the Sustainable Development Goals ( SDGs ): Delivering Projects for the Common Good sustainability. August. <https://doi.org/10.3390/su13169112>
- [9] Zaini, M. S. I., Hasan, M. & Jusoh, W. N. B. W. (2023). Utilization of bottom ash waste as a granular column to enhance the lateral load capacity of soft kaolin clay soil. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-023-25966-x>
- [10] Hasan, M., Zaini, M. S. I., Hong, N. A. W., Wahab, A., Masri, K. A., Jaya, R. P., Hyodo, M., Winter, M. J., Sholichin, M. & Haribowo, R. (2021). Sustainable ground improvement method using encapsulated polypropylene (PP) column reinforcement. *IOP Conference Series: Earth and Environmental Science*, 930, 012016. <https://doi.org/10.1088/1755-1315/930/1/012016>
- [11] Ishak, M. F., Zolkepli, M. F., Yunus, M. Y. M., Ali, N., Kassim, A. & Zaini, M. S. I. (2021). Verification of tree induced suction with numerical model. *Physics and Chemistry of the Earth*, 121, 102980. <https://doi.org/10.1016/j.pce.2021.102980>
- [12] Zaini, M. S. I., Ishak, M. F. & Zolkepli, M. F. (2020). Monitoring soil slope of tropical residual soil by using tree water uptake method. *IOP Conference Series: Materials Science and Engineering*, 736, 072018. <https://doi.org/10.1088/1757-899X/736/7/072018>
- [13] Afrin, H. (2017). A Review on Different Types Soil Stabilization Techniques. *International Journal of Transportation Engineering and Technology*, 3(2), 19. <https://doi.org/10.11648/j.ijtet.20170302.12>
- [14] Almuaythir, S., Zaini, M. S. I., Hasan, M., & Hoque, M. I. (2024). Sustainable Soil Stabilization Using Industrial Waste Ash: Enhancing Expansive Clay Properties. *Heliyon*, 10(20), e39124. <https://doi.org/10.1016/j.heliyon.2024.e39124>
- [15] Zaini, M. S. I., Ishak, M. F. & Zolkepli, M. F. (2019). Forensic assessment on landfills leachate through electrical resistivity imaging at Simpang Renggam in Johor, Malaysia. *IOP Conference Series: Materials Science and Engineering*, 669, 012005. <https://doi.org/10.1088/1757-899X/669/1/012005>
- [16] Ishak, M. F., Zolkepli, M. F., Yunus, M. Y. M., Ali, N., Kassim, A. & Zaini, M. S. I. (2021). The effect of tree water uptake on suction distribution in tropical residual soil slope. *Physics and Chemistry of the Earth*, 121, 102984. <https://doi.org/10.1016/j.pce.2021.102984>
- [17] Ishak, M. F. & Zaini, M. S. I. (2018). Physical Analysis Work for Slope Stability at Shah Alam, Selangor. *Journal of Physics: Conference Series*, 995(1), 012064. <https://doi.org/10.1088/1742-6596/995/1/012064>
- [18] Ibrahim, H. H., Alshkane, Y. M., Mawlood, Y. I., Noori, K. M. G., & Hasan, A. M. (2020). Improving the geotechnical properties of high expansive clay using limestone powder. *Innovative Infrastructure Solutions*, 5(3). <https://doi.org/10.1007/s41062-020-00366-z>
- [19] Mohammed Al-Bared, M. A., & Marto, A. (2017). A review on the geotechnical and engineering characteristics of marine clay and the modern methods of improvements. *Malaysian Journal of Fundamental and Applied Sciences*, 13(4), 825-831. <https://doi.org/10.11113/mjfas.v13n4.921>
- [20] Awang, H., Salmanfarsi, A. F., Zaini, M. S. I., Mohamad Yazid, M. A. F. & Ali, M. I. (2021). Investigation of groundwater table under rock slope by using electrical resistivity imaging at Sri Jaya, Pahang, Malaysia. *IOP Conference Series: Earth and Environmental Science*, 682, 012017, <https://doi.org/10.1088/1755-1315/682/1/012017>

- [21] Wahab, A., Hasan, M., Kusin, F. M., Embong, Z., Zaman, Q. U., Babar, Z. U. & Imran, M. S. (2022). Physical Properties of Undisturbed Tropical Peat Soil at Pekan District, Pahang, West Malaysia. *International Journal of Integrated Engineering*, 14(4), 403-414. <https://doi.org/10.30880/ijie.2022.14.04.031>.
- [22] Ishak, M. F., B. K. K., Zaini, M. S. I. & Zolkepli, M. F. (2018). Investigation and Monitoring of Groundwater Level: Building Crack Near to IIUM Kuantan. *International Journal of Engineering Technology and Sciences*, 5(3), 51-56. <http://dx.doi.org/10.15282/ijets.5.3.2018.1.1004>
- [23] Zaini, M. S. I. & Hasan, M. (2023). Effectiveness of Silica Fume Eggshell Ash and Lime Use on the Properties of Kaolinitic Clay. *International Journal of Engineering & Technology Innovation* 13(4), 337-352, <https://doi.org/10.46604/ijeti.2023.11936>
- [24] Yamada, Y., Tsuchida, T., Kyaw, N. M., Aoyama, T., Akasaki, T., Hlaing, M. M. S., & Hashimoto, R. (2023). Geotechnical properties of soft clays along Yangon River – Characteristics of soft clays in Thilawa Port area. *Soils and Foundations*, 63(4), 101331. <https://doi.org/10.1016/j.sandf.2023.101331>
- [25] Zaini, M. S. I., & Masri, K. A. (2023). Stabilization of Kaolinitic Soil Using Crushed Tile Column. *Magazine of Civil Engineering*, November. <https://doi.org/10.34910/MCE.123.4>
- [26] Zaini, M. S. I., Hasan, M., Almuaythir, S., & Hyodo, M. (2024). Experimental investigations on physico-mechanical properties of kaolinite clay soil stabilized at optimum silica fume content using clamshell ash and lime. *Scientific Reports*, 0123456789, 1–20. <https://doi.org/10.1038/s41598-024-61854-1>
- [27] Suwito, A. R., Hasan, M., & Zaini, M. S. I. (2024). Basic Geotechnical Characteristic of Soft Clay Stabilised with Cockle Shell Ash and Silica Fume. *Construction*, 4(2), 255–260. <https://doi.org/10.15282/construction.v4i2.11110>
- [28] Zaini, M. S. I., & Hasan, M. (2023). Effects of Industrial and Agricultural Recycled Waste Enhanced with Lime Utilisation in Stabilising Kaolinitic Soil. *International Journal of Sustainable Construction Engineering And Technology*, December. <https://doi.org/10.30880/ijscet.2023.14.04.025>
- [29] Khaiyum, M. Z., & Sarker, S. (2023). Evaluation of Carbon Emission Factors in the Cement Industry : An Emerging Economy Context. *Sustainability*, 15(21). <https://doi.org/https://doi.org/10.3390/>
- [30] Liao, Y., Wang, S., Wang, K., Qunaynah, S. Al, Wan, S., Yuan, Z., Xu, P., & Tang, S. (2023). A study on the hydration of calcium aluminate cement pastes containing silica fume using non-contact electrical resistivity measurement. *Journal of Materials Research and Technology*, 24, 8135–8149. <https://doi.org/10.1016/j.jmrt.2023.05.080>
- [31] Zaini, M. S. I., Hasan, M. & Zolkepli, M. F. (2023). Influence of Alstonia Angustiloba tree water uptake on slope stability: A case study at the unsaturated slope, Pahang, Malaysia. *Bulletin of the Geological Society of Malaysia*, 75, 37 – 55. <https://doi.org/10.7186/bgsm75202305>
- [32] Zolkepli, M. F., Mohamad Rozar, N., Ishak, M. F., Sidik, M. H., Ibrahim, N. A. S. & Zaini, M. S. I. (2021). Slope mapping using unmanned aerial vehicle (UAV). *Turkish Journal of Computer and Mathematics Education (TURCOMAT)*, 12(3), 1781-1789. <https://turcomat.org/index.php/turkbilmat/article/view/1005>
- [33] Zaini, M. S. I. & Hasan, M. (2024). Effect of Alstonia Angustiloba tree moisture absorption on the stabilization of unsaturated residual soil slope. *International Journal of Environmental Science and Technology*, 21, 8487- 8506. <https://doi.org/10.1007/s13762-024-05550-7>
- [34] Zaini, M. S. I. & Hasan, M. (2024). Application of Electrical Resistivity Tomography in Landfill Leachate Detection Assessment. In: Anouzla, A., Souabi, S. (eds) *A Review of Landfill Leachate*, Springer Water, Springer, Cham, [https://doi.org/10.1007/978-3-031-55513-8\\_1](https://doi.org/10.1007/978-3-031-55513-8_1)
- [35] Zaini, M. S. I., Hasan, M. & Md Jariman, W. (2024). Strength of Kaolinitic Clay Soil Stabilized with Lime and Palm Oil Fuel Ash. *CONSTRUCTION*, 4(1), 77–84. <https://doi.org/10.15282/construction.v4i1.10517>
- [36] Ahmad, A., Sutanto, M. H., Ahmad, N. R., Bujang, M., & Mohamad, M. E. (2021). The Implementation of Industrial Byproduct in Malaysian Peat Improvement: A Sustainable Soil Stabilization Approach. *Materials*, 14(23), 7315. <https://doi.org/10.3390/ma14237315>
- [37] Ahmad, A., Karunatilaka, D. S., Anggraini, V., & Raghunandan, M. E. (2024). Mechanical, microstructural, and environmental performance of industrial byproducts in peat reinforcement. *Construction and Building Materials*, 451(15), 138780. <https://doi.org/10.1016/j.conbuildmat.2024.138780>
- [38] Bujang, M., Mohamad, M. E., Ahmad, A., Sutanto, M. H., Zainudin, K., & Ali Mohamad, S. N. (2024). Performance of silica waste as a stabilizing agent in peat. *AIP Conference Proceedings*, 2838(1), 060031. <https://doi.org/10.1063/5.0181227>

- [39] Ahmad, A., Karunatilaka, D. S., Anggraini, V., & Raghunandan, M. E. (2021). Physio-Chemical Properties, Consolidation, and Stabilization of Tropical Peat Soil Using Traditional Soil Additives — A State of the Art Literature Review. *KSCE Journal of Civil Engineering*, 25(10), 3662-3678. <https://doi.org/10.1007/s12205-021-1247-7>
- [40] Ahmad, A., Sutanto, M. H., Ahmad, N. R., Mohamad, M.E., & Bujang, M. (2023). Microstructural Characterization of Fibric Peat Stabilized with Portland Cement and Silica Fume. *Materials*, 16 (1), 18. <https://doi.org/10.3390/ma16010018>
- [41] Ahmad, A., Sutanto, M. H., Ahmad, N. R., Ali Khan, M., Wahab, A., Sapar, N. I. F., & Hashir, M. (2023). Feasibility of bituminous stabilizer in the stabilization of problematic soil: An overview on the non-traditional soil additive. *AIP Conference Proceedings*, 2688(1), 040012. <https://doi.org/10.1063/5.0113900>
- [42] Türköz, M., Umu, S. U., & Öztürk, O. (2021). Effect of silica fume as a waste material for sustainable environment on the stabilization and dynamic behavior of dispersive soil. *Sustainability (Switzerland)*, 13(8). <https://doi.org/10.3390/su13084321>
- [43] Zaini, M. S. I. & Hasan, M. (2024). Shear Strength of Soft Soil Reinforced with Singular Bottom Ash Column. *CONSTRUCTION*, 4(1), 85–93. <https://doi.org/10.15282/construction.v4i1.10448>
- [44] Zaini, M. S. I., Hasan, M. & Jamal, M. K. F. (2024). Strength of Problematic Soil Stabilised with Gypsum and Palm Oil Fuel Ash. *CONSTRUCTION*, 4(2), 170–175. <https://doi.org/10.15282/construction.v4i2.10735>
- [45] Goh, J. R., Ishak, M. F., Zaini, M. S. I. & Zolkepli, M. F. (2020). Stability Analysis and Improvement Evaluation on Residual Soil Slope: Building Cracked and Slope Failure. *IOP Conference Series: Materials Science and Engineering*, 736, 072017. <https://doi.org/10.1088/1757-899X/736/7/072017>
- [46] Zolkepli, M. F., Ishak, M. F. & Zaini, M. S. I. (2018). Analysis of Slope Stability on Tropical Residual Soil. *International Journal of Civil Engineering and Technology (IJCIET)*, 9(2), 402-416. <http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=2>
- [47] Dwiatmoko, M. U., Saismana, U., & Maulanai, R. (2019). Characteristics of Kaolin Clay on Alluvial Formation Subdistrict Mataraman Based on Physical Properties and Chemical Properties. *International Conference on Sustainable Built Environment*, 09, 0–4. <https://doi.org/https://doi.org/10.1051/mateconf/201928003009>
- [48] Hasan, M., Zaini, M. S. I., Hong, N. A. W., Wahab, A., Masri, K. A., Jaya, R. P., Hyodo, M., Winter, M. J., Sholichin, M., & Haribowo, R. (2021). Stabilization of Kaolin Clay Soil Reinforced with Single Encapsulated 20mm Diameter Bottom Ash Column. *IOP Conference Series: Earth and Environmental Science*. <https://doi.org/10.1088/1755-1315/930/1/012099>
- [49] Yue, L. J., Ishak, M. F., Zaini, M. S. I. & Zolkepli, M. F. (2019). Rainfall Induced Residual Soil Slope Instability: Building Cracked and Slope Failure. *IOP Conference Series: Materials Science and Engineering*, 669, 012004. <https://doi.org/10.1088/1757-899X/669/1/012004>
- [50] Zaini, M. S. I., Hasan, M. & Zulkafli, A. S. (2024). Basic and Morphological Properties of Bukit Goh Bauxite. *CONSTRUCTION*, 4(2), 135–139. <https://doi.org/10.15282/construction.v4i2.10736>
- [51] Zolkepli, M. F., Ishak, M. F., Yunus, M. Y. M., Zaini, M. S. I., Wahap, M. S., Yasin, A. M., Sidik, M. H. & Hezmi, M. A. (2021). Application of unmanned aerial vehicle (UAV) for slope mapping at Pahang Matriculation College, Malaysia. *Physics and Chemistry of the Earth*, 123, 103003. <https://doi.org/10.1016/j.pce.2021.103003>
- [52] Shan, Y., Liu, Y., Tao, S., & Guan, D. (2023). Projecting future carbon emissions from cement production in developing countries. *Nature Communications*. <https://doi.org/10.1038/s41467-023-43660-x>
- [53] Phanikumar, B. R., & Nagaraju, T. V. (2018). Engineering behaviour of expansive clays blended with cement and GGBS. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, 171(3), 167–173. <https://doi.org/10.1680/jgrim.17.00054>
- [54] Zaini, M. S. I. & Hasan, M. (2024). Stabilization of Expansive Soil using Silica Fume and Lime. *CONSTRUCTION*, 4(1), 45–51. <https://doi.org/10.15282/construction.v4i1.10484>
- [55] Zaini, M. S. I., Hasan, M. & Y. Nuraini. (2024). Strength and Compressibility of Soft Clay Reinforced with Group Crushed Polypropylene (PP) Columns. *CONSTRUCTION*, 4(2), 186–192. <https://doi.org/10.15282/construction.v4i2.10737>
- [56] Hasan, M., Zaini, M. S. I., Zulkafli, A. S., Wahab, A., Hokabi, A. A., Masri, K. A., Jaya, R. P., Hyodo, M., Winter, M. J., Sholichin, M., Haribowo, R. & Zulkafli, M. S. (2021). Geotechnical Properties of Bauxite: A Case Study in Bukit Goh, Kuantan, Malaysia. *IOP Conference Series: Earth and Environmental Science*, 930, 012098. <https://doi.org/10.1088/1755-1315/930/1/012098>

- [57] Mohamed, N., Zolkepli, M. F., A. Rashid., A. S., Kassim, A., Zaini, M. S. I., Shahrin, M. I., Ishak, M. F., & Abu Talib, Z. (2024). Analysis of Residual Soil Properties on Slope: A Study in Dusun, Universiti Teknologi Malaysia, Johor. *International Journal of Integrated Engineering*, 16(9), 96-107. <https://doi.org/10.30880/ijie.2024.16.09.007>
- [58] Barman, D., & Dash, S. K. (2022). Stabilization of expansive soils using chemical additives: A review. *Journal of Rock Mechanics and Geotechnical Engineering*, 14(4), 1319–1342. <https://doi.org/10.1016/j.jrmge.2022.02.011>
- [59] Harun, G. M., Rahman, M. F., & Siddique, A. B. (2019). A Comparative Study on Fly Ash and Bagasse Ash Using as a Sub-Grade A Comparative Study on Fly Ash and Bagasse Ash Using as a Sub-Grade Material. August. <https://doi.org/10.11648/j.ajce.20190704.11>
- [60] Al-Khafaji, R., Dulaimi, A., Jafer, H., & Mashaan, N. S. (2023). Stabilization of Soft Soil by a Sustainable Binder Comprises Ground Granulated Blast Slag ( GGBS ) and Cement Kiln. *Recycling MDPI*. <https://doi.org/https://doi.org/10.3390/recycling8010010>
- [61] Zaini, M. S. I., & Hasan, M. (2023). Effect of Optimum Utilization of Silica Fume and Lime On the Stabilization of Problematic Soils. *The International Journal of Integrated Engineering*, 1, 352–366. <https://doi.org/10.30880/ijie.2023.15.01.032>
- [62] Zaini, M. S. I., Hasan, M. & Almuaythir, S. (2024). Experimental study on the use of polyoxymethylene plastic waste as a granular column to improve the strength of soft clay soil. *Scientific Reports*, 14, 22558. <https://doi.org/10.1038/s41598-024-73224-y>
- [63] BS. (1990). Methods of Tests for Soils for Civil Engineering Purposes, (BS 1377: Part 1-9). London: British Standard Institution.
- [64] ASTM. D2434-68: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM Int 2011.
- [65] Mohamed, N., Zolkepli, M. F., A. Rashid., A. S., Zaini, M. S. I., & Ishak, M. F. (2024). Characterization of Residual Soil Properties on Slope in Dusun UTM, Johor. *Journal of Advanced Research in Applied Mechanics*, 132(1), 11-25. <https://doi.org/10.37934/aram.132.1.1125>.
- [66] Almuaythir, S., Zaini, M. S. I., Hasan, M., & Hoque, M. I. (2025). Stabilization of expansive clay soil using shells based agricultural waste ash. *Scientific Reports*, 15, 10186. <https://doi.org/10.1038/s41598-025-94980-5>.