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Strength Development of Soil Stabilised with POFA-RCT Binder

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ABSTRACT

Soil stabilisation is a critical facet of civil engineering, involving the modification of soil properties for enhanced engineering characteristics. Traditional binders commonly used for soil stabilisation, such as cement and lime, have well-known adverse environmental impacts. Their production process consumes substantial energy and release greenhouse gases that contribute to air pollution and climate change. Ordinary Portland Cement, responsible for over 4.1 billion tonnes annually, contributes to 8% of global CO_2 emissions. This study delved into formulating an innovative soil binder utilising 80% palm oil fuel ash (POFA) and 20% recycled ceramic tile (RCT) to optimise soil stabilisation. The integration of by-products in soil stabilisation gains prominence due to cost-effectiveness, resource conservation, improved performance and environmental benefits. This study also assessed the effectiveness and performance of soil stabilised with various dosages of POFA-RCT binder (3, 6, 9, 12 and 15%) cured for 1, 7, 14 and 28 days, focusing on strength development. The chemical composition of the stabilised soil was analysed through x-ray fluorescence (XRF). POFA was found to consist primarily of silica, while RCT contained calcium and silica, where both exhibited pozzolanic characteristics. Unconfined compression strength (UCS) test was conducted to assess the strength development of stabilised soil with POFA-RCT binder. The results of this study revealed that the optimum blend of POFA-RCT ratio was 80:20, with the ideal dosage of 15% at 28 days of curing. These findings underscored the potential of POFA-RCT binder in enhancing soil strength and durability, emphasising its applicability in sustainable construction practices. By employing by-product materials as an alternative soil binder, this study aligns with Sustainable Development Goals 9, 12, 13 and 15, promoting economically and environmentally sustainable practices in the construction industry through the utilisation of local resources and waste materials.

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1. Introduction

The rapid population growth in Malaysia as well as various other global regions has spurred an accelerated pace of infrastructure development to meet societal demands and facilitate economic transformation [1]. Soil, a fundamental element in the construction industry, plays a crucial role in building slopes, foundations and roads. However, natural soil found on construction sites is not always suitable for engineered structures, particularly when dealing with clay and peat soil. These soil types present significant challenges due to their problematic geotechnical properties, including high moisture content, low bearing capacity and poor shear strength. James *et al.,* [2] reported widespread damage to lightly loaded structures constructed on soft soils in multiple countries, including Australia, China, India, Israel, South Africa, the United Kingdom and the United States of America. These soil types require enhancement for the stability and safety of such constructions.

Traditional soil binder materials, such as cement and lime, are widely utilised for soil stabilisation, but they pose adverse environmental effects [3]. Their production process consumes substantial energy and emits greenhouse gases, contributing to air pollution and climate change. Ordinary Portland Cement alone accounts for over 4.1 billion tons of annual output and is responsible for 8% of global CO_2 emissions [4,5]. Research efforts are directed towards exploring alternative materials that can reduce both energy consumption and CO_2 emissions [6].

The adoption of by-products as viable and sustainable soil binders has received recent prominence due to their remarkable capacity to enhance soil performance while significantly reducing solid waste sent to landfills [7]. Furthermore, the use of by-products in soil stabilisation is favourable due to cost-effectiveness [6], resource conservation [8], improved performance in soil stabilisation, availability of by-products [9] and reduction of environmental impact by promoting beneficial reuse and minimising waste [10,11]. Various by-products have been employed for chemical soil stabilisation, such as fly ash and bottom ash [12-14], eggshell [15], silica fume [16,17], gypsum [12], ceramic powder [12,17] and palm oil fuel ash [12,18]. Palm oil fuel ash (POFA) and recycled ceramic tile (RCT), as highlighted by Claisse [19], exhibit promising material qualities to replace cement. They possess pozzolanic properties, with POFA primarily composed of silica and alumina and RCT containing calcium, silica, iron and alumina. These inherent characteristics enable a reaction with calcium hydroxide in the presence of moisture, leading to the formation of cementitious compounds.

This study investigated the effectiveness of utilising a mixture of POFA and RCT as an alternative soil binder for soil stabilisation. The primary focus was to evaluate the effect of different dosage levels of the POFA-RCT mixture, ranging from 3% to 15%, on soil stabilisation. Additionally, this study explored the influence of various curing periods on soil strength development, specifically at 1, 7, 14 and 28 days (approximately 4 weeks). The idea of combining these two by-products to create a new material with both outstanding features originated from the gap in the existing literature on soil stabilisation using POFA and RCT. Based on the XRF analysis, the POFA-RCT mixture exhibited pozzolanic elements, with POFA containing silica and alumina and RCT containing calcium, silica, iron and alumina. The elements facilitate reactions with calcium hydroxide in the presence of moisture to form cementitious compounds.

2. Materials and Method
2.1 Materials

The main materials used in this study were kaolin clay, POFA and RCT.

2.1.1 Kaolin clay soil

In this study, the effect of POFA-RT binder on the engineering properties of kaolin clay soil was evaluated. The kaolin utilised in this study was supplied by Kaolin Malaysia Sdn. Bhd. and the soil were screened using a 75-µm sieve (No. 200). Prior to mixing with soil by-products and additives, the kaolin clay soil underwent initial oven drying at 105°C for 24 hours to eliminate moisture content, which could affect its properties. The basic properties of the untreated kaolin are delineated in Table 1 and Table 2 presents its chemical composition as analysed by XRF.

Table 1
Basic properties of untreated kaolin

Properties	Mir *et al.,* [20]	Afrasiabian *et al.,* [21]	Abbey *et al.,* [22]	Average value
Specific gravity	2.64	2.69	2.6	2.64
Liquid Limit, LL (%)	49	38.2	56	47.7
Plastic Limit, PL (%)	23	-	26	24.5
Plastic Index, PI (%)	-	19	30	24.5
Maximum dry density, MDD Mg/m^3	-	1.56	1.43	1.5
Optimum moisture content, OMC (%)	27.5	28.5	27	27.6
Unconfined compressive strength, UCS (kPa)	-	180	-	180
pH	7.7	8.82	-	6.3

Table 2
Chemical composition of kaolin based on XRF analysis (in weight percentage)

Oxides (% Weight)	SiO_2	Al_2O_3	Fe_2O_3	K_2O	CaO	TiO_2
Kaolin	44.08	33.85	17.20	4.12	0.47	0.27

2.1.2 POFA-RCT binder

The binder employed in this study consisted of 80% POFA and 20% RCT as aluminosilicate sources. POFA was sourced from Classic Segamat Palm Oil Mill Sdn Bhd, Segamat, Johor, while the RCT was obtained from KSL Ceramic Tile & Renovation (M) Sdn. Bhd., Kemaman, Terengganu.

The POFA was oven-dried at 105 ± 5°C for 24 hours to eliminate coarse particles, such as fibre and unburned kernels and then followed by sieving through No. 0.425 sieve. Subsequently, the POFA was finely ground to obtain additional fine particles and any remaining unburned carbon was removed by further heating the POFA in the oven at 105 -110°C for another 24 hours.

On the other hand, RCT was manually crushed into smaller pieces using hammer. Then, the small pieces of RCT were ground into powder using an industrial grinder. Finally, the RCT powder was sieved through a No. 0.425 sieve to obtain uniform particle size before mixing with kaolin and POFA.

2.2 X-Ray Fluorescence (XRF) Analysis

XRF is a non-destructive method for assessing the chemical composition of materials [23]. In this study, XRF was performed to examine the chemical composition of POFA and RCT as crucial elements in determining their suitability as cementitious material. The analysis conformed to ASTM E1621-21 standard guidelines, specifically utilising the Analytical Epsilon 3 range and applying the standardless OMNIAN method on pressed powders. In addition, the initial step involved sieving the materials through a No. 200 (75 µm) sieve to eliminate unknown substances and determine the powder size. Subsequently, the XRF scanned the multipoint area to obtain the average value of the sample.

2.3 Unconfined Compression Strength (UCS) Test

Sample preparation for the UCS test was divided into two stages, as shown in Table 3. The first stage investigated the effect of POFA-RCT binder on soil strength development at a mixture ratio of 80:20 with various dosages of 3, 6, 9, 12 and 15% relative to 450 g dry mass of soil. The selection of 80:20 as the optimum ratio was based on the highest and peak UCS value obtained at the ratio from the pilot test conducted, with a slight decrease observed afterward.

Table 3
Mix design of POFA-RCT binder

Stage	Parameter	POFA-RCT ratio	POFA-RCT Dosage (%)	Curing time (days)
1	POFA-RCT dosage mixed into the soil	80:20	3, 6, 9, 12, 15	28
2	Curing time	80:20	15 (maximum performance from stage 1)	1, 7, 14, 28

The second stage assessed the effect of different curing periods of 1, 7, 14 and 28 days for POFA-RCT binder at 80:20 ratio and the optimum dosage determined from the first stage. The samples for this test were prepared according to the control density method (Figure 1), a technique employed to ensure consistency and uniformity in the compaction process, thereby yielding precise and accurate testing results. Crucial parameters in the soil control density approach included optimum moisture content (OMC) of 27% and maximum dry density (MDD) of 1.5 mg/m^3 obtained from standard proctor compaction test, which is critical for achieving the desired compaction level and density [18].

The homogenised mixed samples (450 g) were divided into three equal portions, resulting in three samples for each proportion. About 150 g sample was further divided into three equal portions, with each portion containing 50 g of sample and placed into UCS cylindrical mould measuring 38 mm in diameter and 76 mm in height in accordance with BS 1924:1990 (Part 2).

Figure 1 illustrates the step-by-step process of sample preparation for the UCS test in this study. This systematic procedure ensured the clarity and precision of the test conducted. In the initial stage of sample preparation, meticulous sieving of dry materials was conducted to meet the specified requirements. Then, 150 g of kaolin was accurately measured and manually mixed with the binder materials, with appropriate adjustments made to achieve the desired mixture and dosage. Distilled water was meticulously added to the mixture to control the moisture content for optimum mixture consistency. Subsequently, the prepared sample was divided into three portions, each weighing 50 g, which were placed in the UCS mould. The sample surface was manually pressed three times to ensure a uniform flat surface. This process continued with the utilisation of hydraulic compactor machine to systematically compact the sample to achieve uniform density and strength. This compaction process was repeated, with intermittent scratching of the sample surface to enhance the bonding between the layers. The samples were extracted using a motorised sample extruder to ensure the preservation of sample integrity. Upon extraction, precise sample dimensions were recorded and the sample was securely wrapped in plastic. It was then placed inside a curing box in compliance with specific curing times for subsequent analysis. This comprehensive procedure guaranteed meticulous preparation and handling of UCS samples for robust and reliable testing.

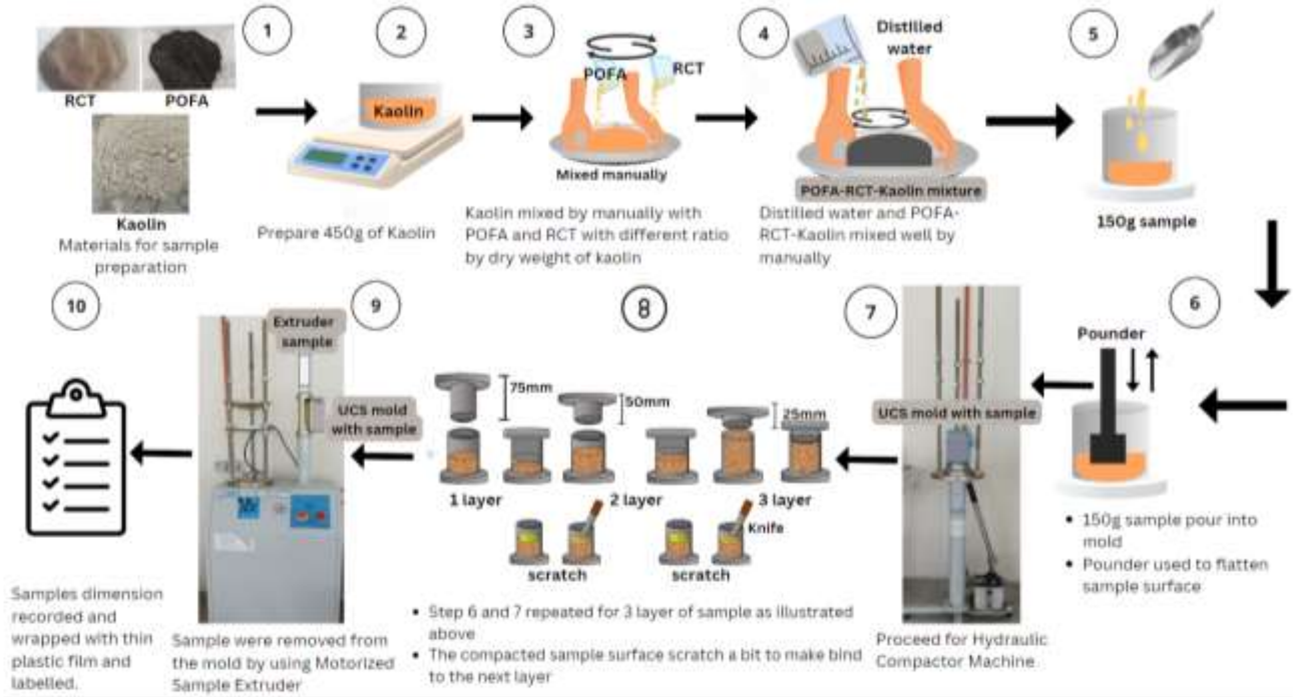

Fig. 1. Illustration of sample preparations steps for UCS test

3. Results

3.1 Chemical Composition of POFA and RCT

Table 4 presents the chemical compositions of POFA and RCT. The findings indicated that POFA exhibited a significant presence of potassium, iron and silica, whereas RCT contained iron, calcium and silica. Cementitious pozzolanic material comprises aluminosilicate compounds with silicon and aluminium elements. These materials react with calcium hydroxide produced during cement hydration, forming a robust cementitious matrix [24,25]. Potassium functions as an alkali activator when present with silica and alumina, forming calcium silicate hydrate (C-S-H) gel. It contributes to the strength and durability of the material [26]. In addition, iron oxide can affect the colour of cementitious material and, in the presence of silica and alumina, participate in the formation of C-S-H gel, like potassium [26]. Moreover, calcium, in the form of calcium oxide or calcium silicate, plays a crucial role in the strength and durability of cementitious material. It reacts with silica to form C-S-H gel, the primary binding agent in concrete, enhancing its strength and durability [27]. Silica, typically in the form of silicon dioxide, is also a vital component of cementitious materials. Its reaction with calcium forms C-S-H gel, which is also essential for the strength and durability of the material. Silica also contributes to the chemical resistance and overall durability of the material [27-29]. When the material hydrates, a reaction occurs, leading to the formation of calcium aluminate hydrates (C-A-H) and C-S-H. It is believed that the significant amount of non-crystalline silica in POFA greatly contributes to C-S-H production, improving the engineering quality of soil over time as the reaction continues [30]. However, potassium and iron have less effect on cement like materials compared to calcium and silica. Cement has only small amounts of potassium oxide (K_2O) and iron oxide (Fe_2O_3) originated from clay, iron ore, recycled iron and fly ash [31,32]. These elements are crucial for influencing how the materials behave in cement-like applications.

Table 4
Chemical compositions (weight percentages) of POFA and RCT from XRF analysis

Oxides (% Weight)	K_2O	Fe_2O_3	SiO_2	CaO
POFA	39.05	18.98	17.47	12.70
RCT	-	42.26	15.75	27.32

3.2 Effect of POFA-RCT Dosage on Soil Strength Development

Figure 2 depicts the relationship between UCS and the dosage of the POFA-RCT mixture, along with the influence of curing time. It was found that the UCS values increased with increasing POFA-RCT binder dosage up to 15%. When the dosage increased from 3% to 6%, the UCS value indicated 2.44% increment from 205 kPa to 210 kPa. Subsequently, a more substantial increase of about 19.05% was observed when the dosage was elevated from 6% to 9%, achieving 250 kPa. The transition from 9% to 12% dosage indicated a 2% increment, resulting in a UCS value of 255 kPa. Finally, 5.88% increment was observed when the dosage was shifted from 12% to 15% resulting in UCS value of 270 kPa.

A higher dosage of POFA-RCT mixture applied to the kaolin clay soils resulted in maximum compressive strength. Specifically, kaolin clay soil with 15% dosage of POFA-RCT mixture exhibited maximum strength at 28 days of curing time due to the formation of CAH and C-S-H. This was also reported by Dadsetan *et al.,* [26]. A substantial amount of non-crystalline silica in POFA significantly contributes to the formation of C-S-H; thereby, improving the engineering quality of the soil over time as the reaction continues [30]. However, a minimum strength of 0.8 MPa for stabilised subgrade soil should be achieved as specified by the Malaysian Public Works Department (PWD) [40,41]. Therefore, most of the soil samples stabilised with POFA-RCT mixture in this study did not meet the requirement after 28 days of curing time. Nevertheless, further studies should explore the potential of achieving desired strength levels with an increased dosage of POFA-RCT mixture of more than 15%.

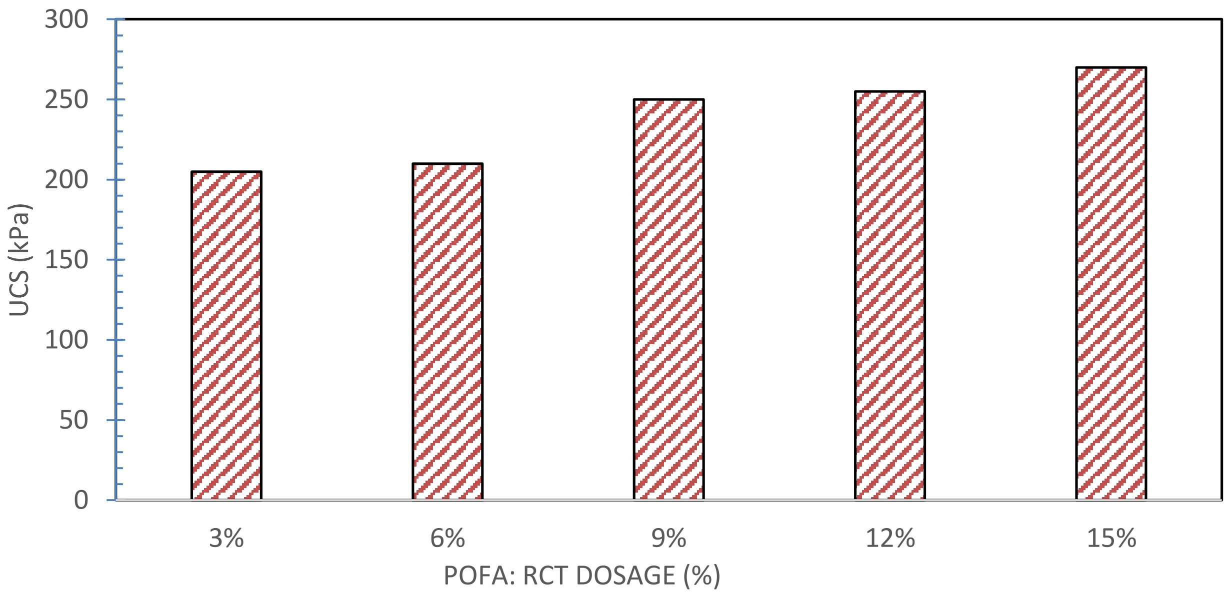

Fig. 2. UCS values against POFA-RCT binder dosages

3.3 Effect of POFA-RCT Curing Time on Soil Strength Development

The effect of curing time on soil strength was evaluated by determining the optimum curing period to achieve the desired strength development of the stabilised soil. In this stage, POFA-RCT ratio of 80:20 and dosage level of 15% were selected based on prior research findings. To observe the short-and long-term effects of POFA-RCT on soil strength development, different curing periods of 1, 7, 14 and 28 days were selected [33,37].

Based on Figure 3, curing time of 28 days resulted in the highest UCS value. It was found that as the curing time of POFA-RCT sample increased, there was a corresponding increase in the maximum compressive strength. It was also evident that during the initial 7-day curing period, there was an increment of approximately 2.05%, progressing from 230 kPa to 247 kPa. In the 7 to 14-day interval, the UCS values continued to increase by 1.77%, reaching 258 kPa on the 14th day. Meanwhile, from day 14 to day 28, the UCS exhibited a more gradual yet still noticeable improvement, with an average increase of about 0.91%, ultimately reaching a strength of 270 kPa on day 28.

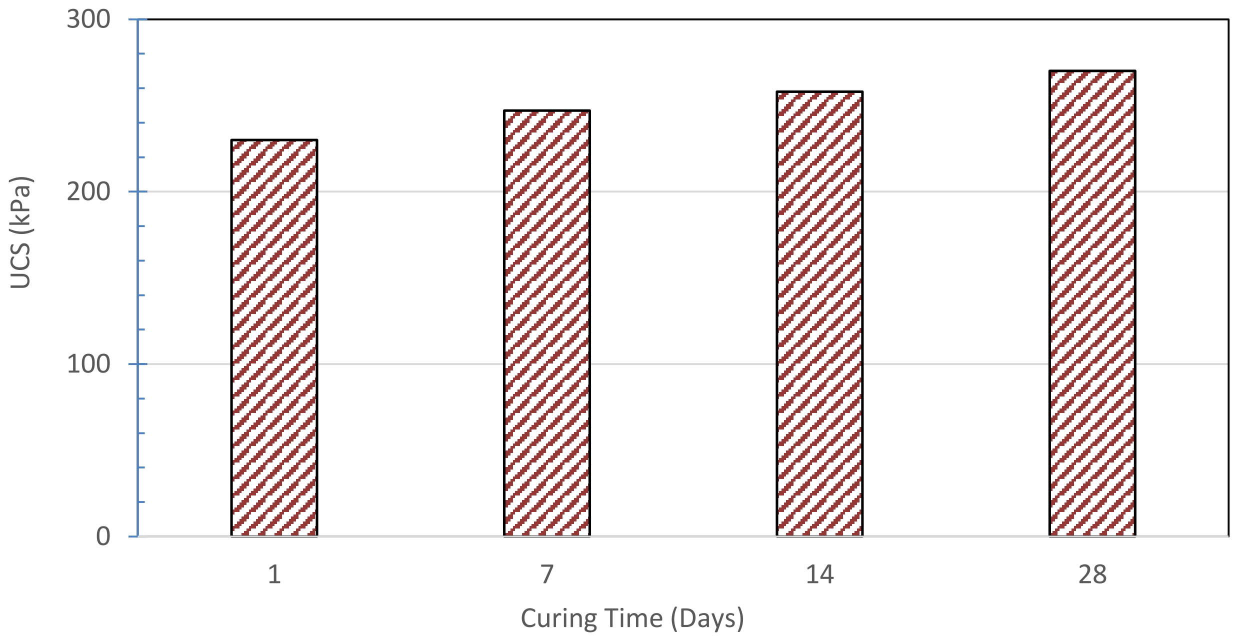

Fig. 3. UCS values against curing time (days)

The strength development of POFA-RCT binder mixed with kaolin increased slightly with respect to curing periods due to the differences in the rate of formation of cementitious products, such as C-S-H and C-A-H, providing strength and stability to the stabilised soil [34]. Based on the XRF analysis summarized in Table 4, significant chemical composition of RCT was iron oxide, calcium oxide and silica oxide. When RCT was incorporated with POFA, it promoted pozzolanic reactions in cementitious materials due to its high silica content. According to Daud *et al.,* [35], the pozzolanic reaction and cementitious material hydration that coats and binds the soil particles to produce stronger matrices will increase as the curing time increases until it reaches the optimal curing period.

Moreover, Kumar [36] stated that for longer curing periods, strength gain is dominated by the effect of pozzolanic reaction, while effect of density is dominant for shorter curing periods. The strength and stability of soil is significantly influenced by its density. The soil has less time to settle and compress over shorter curing period; therefore, the initial compaction process has a greater impact on soil density. Longer curing period provides soil more time to settle and compress, which reduces the importance of density in determining strength gains [37,41].

Furthermore, Horpibulsuk [38] explained that during 7 days of curing, cementitious products filled pores smaller than 0.1 micron, leading to an increase in the volume of small pores and a decrease in total pore volume. Thus, the strength development over time is achieved. Activated alumina and silica derived from waste ceramic powder dissolve in the pore solution, forming new C-A-S-H with active Ca^{2+} and OH^- ions [34].

Variations in the gradient of the time-strength curves are of significant concern. The hardening process of POFA-RCT binder was characterised by high initial strength increment, followed by a gradual reaction period with a lower rate. Table 5 presents the classification of soil according to the unconfined compression test. It was revealed that the range of UCS values between 230 kPa and 247 kPa for 7 to 24 days of curing time indicated the typical of very stiff clayey soils [39].

Table 5
Classification of soil according to the unconfined compression test [39]

Unconfined Compressive Strength (kPa or kN/ sqm)	Consistency
< 25	Very Soft
25-50	Soft
50-100	Medium
100-200	Stiff
200-400	Very Stiff
> 400	Hard

For various traffic classifications, Public Works Department (PWD) Malaysia [40] established minimum UCS criteria for stabilised subgrade materials. The minimum UCS value for roads with less traffic is 0.4 MPa (408 kPa), whereas the minimum UCS value for medium-volume traffic roads is 0.6 MPa (609 kPa). In addition, the minimum UCS value recommended for roads with heavy traffic is 0.8 MPa (816 kPa). The range of UCS value between 230 kPa and 247 kPa for POFA-RCT binder was relatively low, indicating typical of very stiff clayey soils and it did not satisfy the suitability criteria for subgrade soils for road construction applications. The POFA-RCT binder may be suitable for non-structural fill materials, temporary road surfaces or other applications, where the strength of soil is not vital to withstand heavy loads or stresses.

4. Conclusions

In conclusion, the POFA-RCT binder demonstrated potential as a binding material due to its rich cementitious elements. POFA has substantial contents of potassium, iron and silica, while RCT features iron, calcium and silica. The presence of calcium, either in the form of calcium oxide or calcium silicate, plays a pivotal role in fortifying the strength and durability of cementitious materials. Its interaction with silica prompts the formation of C-S-H gel, the primary binding agent, amplifying the overall strength and durability of the binder. Additionally, silica also contributes to the chemical resistance and overall durability of cementitious materials.

However, the UCS results revealed that the POFA-RCT binder with 15% dosage did not meet the standards set by PWD Malaysia. The UCS value of POFA-RCT binder was 270 kPa at 28 days, which was lower than the minimum UCS value of 0.4 MPa (408 kPa) for roads with lower traffic. Therefore, it is recommended to elevate the dosage up to 40%. This is supported by Khasib *et al.,* [42] that the highest strength was achieved by mixing 40% POFA with the soil, emphasising the potential of increasing the dosage to enhance the UCS value significantly.

In terms of curing time, POFA-RCT binder with 15% dosage necessitated an extended period to reach optimum strength. Although the 28-day UCS value did not meet the minimum requirement, significant improvement was observed after curing for 52 days, with UCS value exceeding 600 kPa. It surpassed the minimum UCS value for medium-volume traffic roads (0.6 MPa or 609 kPa). Thus, the binder is considered suitable for medium-volume traffic road applications. This highlights the potential advantages of a prolonged curing period.

In summary, the utilisation of by-product materials, such as POFA and RCT, for soil stabilisation offers several benefits to the industry by enhancing various engineering properties of stabilised soil and creating a superior construction material. The incorporation of by-products as soil stabilisers can boost soil strength, durability and stiffness by improving the chemical composition of the material with the appropriate dosage. Notably, the presence of pozzolanic elements in the materials facilitates effective pozzolanic reactions in cementitious products.

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References
[1] Malaysia, Jabatan Perangkaan. "Buku Tahunan Perangkaan Malaysia." (2012).
[2] James, Jijo and P. Kasinatha Pandian. "Soil stabilization as an avenue for reuse of solid wastes: a review." *Acta Technica Napocensis: Civil Engineering & Architecture* 58, no. 1 (2015): 50-76.
[3] Singh, Manpreet, Kailash Choudhary, Anshuman Srivastava, Kuldip Singh Sangwan and Dipendu Bhunia. "A study on environmental and economic impacts of using waste marble powder in concrete." *Journal of Building Engineering* 13 (2017): 87-95. https://doi.org/10.1016/j.jobe.2017.07.009
[4] Cloete, Schalk, Antonio Giuffrida, Matteo C. Romano and Abdelghafour Zaabout. "Economic assessment of the swing adsorption reactor cluster for CO2 capture from cement production." *Journal of Cleaner Production* 275 (2020): 123024. https://doi.org/10.1016/j.jclepro.2020.123024
[5] Harrison, Edward, Aydin Berenjian and Mostafa Seifan. "Recycling of waste glass as aggregate in cement-based materials." *Environmental Science and Ecotechnology* 4 (2020): 100064. https://doi.org/10.1016/j.ese.2020.100064
[6] Türker, Hakan Tacettin, Müzeyyen Balçikanli, İbrahim Halil Durmuş, Erdoğan Özbay and Mustafa Erdemir. "Microstructural alteration of alkali activated slag mortars depend on exposed high temperature level." *Construction and Building Materials* 104 (2016): 169-180. https://doi.org/10.1016/j.conbuildmat.2015.12.070
[7] Wu, Jun, Yongfeng Deng, Guoping Zhang, Annan Zhou, Yunzhi Tan, Henglin Xiao and Qingsong Zheng. "A generic framework of unifying industrial by-products for soil stabilization." *Journal of Cleaner Production* 321 (2021): 128920. https://doi.org/10.1016/j.jclepro.2021.128920
[8] Pedro, D., J. De Brito and L. Evangelista. "Evaluation of high-performance concrete with recycled aggregates: Use of densified silica fume as cement replacement." *Construction and Building Materials* 147 (2017): 803-814. https://doi.org/10.1016/j.conbuildmat.2017.05.007
[9] Pushpakumara, B. H. J. and T. T. D. Silva. "Evaluation of mechanical properties of steel slag as replacement for fine and coarse aggregate in concrete." *Australian Journal of Structural Engineering* 24, no. 3 (2023): 254-263. https://doi.org/10.1080/13287982.2023.2167644
[10] Sherwood, P. *Soil stabilization with cement and lime*. 1993.
[11] Khashi'Ie, Najiyah Safwa and Khairum Hamzah. "Mechanical properties of jute fiber polyester hybrid composite filled with eggshell." *Semarak Eng J* 6, no. 1 (2024): 20-8. https://doi.org/10.37934/sej.6.1.2028
[12] Onaizi, Ali M., Nor Hasanah Abdul Shukor Lim, Ghasan F. Huseien, Mugahed Amran and Chau Khun Ma. "Effect of the addition of nano glass powder on the compressive strength of high volume fly ash modified concrete." *Materials Today: Proceedings* 48 (2022): 1789-1795. https://doi.org/10.1016/j.matpr.2021.08.347
[13] Amran, Mugahed, Solomon Debbarma and Togay Ozbakkaloglu. "Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties." *Construction and Building Materials* 270 (2021): 121857. https://doi.org/10.1016/j.conbuildmat.2020.121857

[14] Amran, YH Mugahed, Mariantonieta Gutierrez Soto, Rayed Alyousef, Mohamed El-Zeadani, Hisham Alabduljabbar and Vegard Aune. "Performance investigation of high-proportion Saudi-fly-ash-based concrete." *Results in Engineering* 6 (2020): 100118. https://doi.org/10.1016/j.rineng.2020.100118
[15] Avudaiappan, Siva, Supriya Prakatanoju, Mugahed Amran, Radhamanohar Aepuru, Erick I. Saavedra Flores, Raj Das, Rishi Gupta, Roman Fediuk and Nikolai Vatin. "Experimental investigation and image processing to predict the properties of concrete with the addition of nano silica and rice husk ash." *Crystals* 11, no. 10 (2021): 1230. https://doi.org/10.3390/cryst11101230
[16] Mosaberpanah, Mohammad A., Y. H. Amran and Abdulrahman Akoush. "Performance investigation of palm kernel shell ash in high strength concrete production." *Computers and Concrete* 26, no. 6 (2020): 577-585.
[17] Muthalvan, Renuka Senthil, Suraj Ravikumar, Siva Avudaiappan, Mugahed Amran, Radhamanohar Aepuru, Nikolai Vatin and Roman Fediuk. "The effect of superabsorbent polymer and nano-silica on the properties of blended cement." *Crystals* 11, no. 11 (2021): 1394. https://doi.org/10.3390/cryst11111394
[18] Al-Hokabi, Abdulmajeed, Muzamir Hasan, Mugahed Amran, Roman Fediuk, Nikolai Ivanovich Vatin and Sergey Klyuev. "Improving the early properties of treated soft kaolin clay with palm oil fuel ash and gypsum." *Sustainability* 13, no. 19 (2021): 10910. https://doi.org/10.3390/su131910910
[19] Claisse, P. A. "Measurement of porosity as a predictor of the transport properties of concrete." In *Woodhead publishing series in civil and structural engineering, transport properties of concrete*, pp. 115-147. Sawston: Woodhead Publishing, 2021.
[20] Mir, B. A. and A. Juneja. "Some mechanical properties of reconstituted kaolin clay." In *Proc. of the the 17th Southeast Asian Geotechnical Conf. Taipei, Taiwan*, vol. 1, pp. 145-148. 2010.
[21] Afrasiabian, Armin, Mahdi Salimi, Mehran Movahedrad and Amir Hossein Vakili. "Assessing the impact of GBFS on mechanical behaviour and microstructure of soft clay." *International Journal of Geotechnical Engineering* 15, no. 3 (2021): 327-337. https://doi.org/10.1080/19386362.2019.1565393
[22] Abbey, Samuel J., Eyo U. Eyo, Jonathan Oti, Samuel Y. Amakye and Samson Ngambi. "Mechanical properties and microstructure of fibre-reinforced clay blended with by-product cementitious materials." *Geosciences* 10, no. 6 (2020): 241. https://doi.org/10.3390/geosciences10060241
[23] Brown, Oyeleke Raifu, Mohd Badruddin Bin Mohd Yusof, Mohd Razman Bin Salim and Kamaruddin Ahmed. "Physico-chemical properties of palm oil fuel ash as composite sorbent in kaolin clay landfill liner system." In *2011 IEEE Conference on Clean Energy and Technology (CET)*, pp. 269-274. IEEE, 2011. https://doi.org/10.1109/CET.2011.6041495
[24] McCarthy, Michael John and Thomas Daniel Dyer. "Pozzolanas and pozzolanic materials." *Lea's Chemistry of Cement and Concrete* 5 (2019): 363-467. https://doi.org/10.1016/B978-0-08-100773-0.00009-5
[25] Massazza, Franco. "Pozzolana and pozzolanic cements." In *Lea's chemistry of cement and concrete*, pp. 471-635. Butterworth-Heinemann, 1998. https://doi.org/10.1016/B978-075066256-7/50022-9
[26] Dadsetan, Sina, Hocine Siad, Mohamed Lachemi, Obaid Mahmoodi and Mustafa Şahmaran. "Geopolymer binders containing construction and demolition waste." In *Handbook of Sustainable Concrete and Industrial Waste Management*, pp. 437-474. Woodhead Publishing, 2022. https://doi.org/10.1016/B978-0-12-821730-6.00002-4
[27] Young, J. F. "Portland cements." *Encyclopedia of Materials: Science and Technology* (2001): 7768-7773. https://doi.org/10.1016/B0-08-043152-6/01398-X
[28] Siddique, Rafat. "Utilization of silica fume in concrete: Review of hardened properties." *Resources, conservation and recycling* 55, no. 11 (2011): 923-932. https://doi.org/10.1016/j.resconrec.2011.06.012
[29] Etim, Roland Kufre, David Ufot Ekpo, Imoh Christopher Attah and Kennedy Chibuzor Onyelowe. "Effect of micro sized quarry dust particle on the compaction and strength properties of cement stabilized lateritic soil." *Cleaner Materials* 2 (2021): 100023. https://doi.org/10.1016/j.clema.2021.100023
[30] Luo, Yunlong, Xintao Zhou, Zhongqiu Luo, Hongyan Ma, Yu Wei and Qin Liu. "A novel iron phosphate cement derived from copper smelting slag and its early age hydration mechanism." *Cement and Concrete Composites* 133 (2022): 104653. https://doi.org/10.1016/j.cemconcomp.2022.104653
[31] Gadayev, Anatoly and Boris Kodess. "By-product materials in cement clinker manufacturing." *Cement and Concrete Research* 29, no. 2 (1999): 187-191. https://doi.org/10.1016/S0008-8846(98)00094-5
[32] Sharma, Prateek Kumar, Jitendra Prasad Singh and Anil Kumar. "Effect of particle size on physical and mechanical properties of fly ash based geopolymers." *Transactions of the Indian Institute of Metals* 72, no. 5 (2019): 1323-1337. https://doi.org/10.1007/s12666-019-01628-w
[33] Keskin, İnan, İbrahim Şentürk, Halil İbrahim Yumrutaş, Ermedin Totiç and Ali Ateş. "An environmentally friendly approach to soil improvement with by-product of the manufacture of iron." *BioResources* 18, no. 1 (2023): 2045. https://doi.org/10.15376/biores.18.1.2045-2063

[34] Zhang, Xiwei, Maria Mavroulidou and M. J. Gunn. "Mechanical properties and behaviour of a partially saturated lime-treated, high plasticity clay." *Engineering Geology* 193 (2015): 320-336. https://doi.org/10.1016/j.enggeo.2015.05.007

[35] Daud, Nik Norsyahariati Nik, Abubakar Sadiq Muhammed and Zainuddin Md Yusoff. "Geotechnical assessment of palm oil fuel ash (POFA) mixed with granite residual soil for hydraulic barrier purposes." *Malaysian Journal of Civil Engineering* 28 (2016).

[36] Kumar, SM Prasanna. "Cementitious compounds formation using pozzolans and their effect on stabilization of soils of varying engineering properties." In *International conference on environment science and engineering, IPCBEE*, vol. 8. 2011.

[37] Athanasopoulou, Antonia. "The role of curing period on the engineering characteristics of a cement-stabilized soil." *Rom. J. Transp. Infrastruct* 5 (2016): 38-52. https://doi.org/10.1515/rjti-2016-0041

[38] Horpibulsuk, Suksun. "Strength and microstructure of cement stabilized clay." In *Scanning electron microscopy*. IntechOpen, 2012. https://doi.org/10.5772/35225

[39] Hastuty, Ika Puji. "Comparison of the use of cement, gypsum and limestone on the improvement of clay through unconfined compression test." In *Journal of the Civil Engineering Forum*, vol. 5, no. 2, pp. 131-138. 2019. https://doi.org/10.22146/jcef.43792

[40] Malaysia, P. W. D. "Design Guide for Alternative Pavement Structures: Low-Volume Roads (JKR 21300-0025-12)." *PWD Malaysia, Kuala Lumpur* (2013).

[41] Amadi, A. A. and A. S. Osu. "Effect of curing time on strength development in black cotton soil–Quarry fines composite stabilized with cement kiln dust (CKD)." *Journal of King Saud University-Engineering Sciences* 30, no. 4 (2018): 305-312. https://doi.org/10.1016/j.jksues.2016.04.001

[42] Khasib, Isam Adnan, Nik Norsyahariati Nik Daud and Noor Azline Mohd Nasir. "Strength development and microstructural behavior of soils stabilized with palm oil fuel ash (POFA)-based geopolymer." *Applied Sciences* 11, no. 8 (2021): 3572. https://doi.org/10.3390/app11083572