

A Review of Advances in Peat Soil Stabilisation Technology: Exploring the Potential of Palm Oil Fuel Ash Geopolymer as a Soil Stabiliser Material

Adriana Erica Amaludin ¹, Hidayati Asrah ^{1, 2*}, Habib M. Mohamad ^{1, 2}

¹ Civil Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, Kota Kinabalu, 88400, Sabah, Malaysia.

² Green Materials and Advanced Construction Technology (GMACT) Research Unit, Faculty of Engineering, Universiti Malaysia Sabah, 88400 UMS Road, Kota Kinabalu, Sabah, Malaysia.

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Abstract

This study aims to highlight the latest developments in the field of peat soil stabilisation technology via chemical stabilisation. The review examines the use of traditional stabilisers such as OPC and various non-traditional stabiliser materials, i.e., Palm Oil Fuel Ash (POFA)-OPC blends, chemical solutions, and geopolymer materials, to enhance the Unconfined Compressive Strength (UCS) characteristics of peat soils based on the ASTM D 4609 requirements. OPC, POFA-OPC blends, and alkaline solutions mostly produced stabilised soil samples that fell short of the ASTM requirements. Existing studies on the use of waste-derived geopolymers to treat peat soils are limited, while the use of POFA geopolymer materials has mostly focused on the improvement of clayey and silty soils. The results of soil stabilisation with geopolymer were very encouraging, as the strength gains were in line with the ASTM soil strength requirements. As a result of this review, it can be concluded that POFA geopolymer is a viable soil stabiliser material with the addition of Ground Granulated Blast Furnace Slag, and that the use of POFA-GGBFS geopolymer to enhance the strength properties of peat soils should be investigated.

Keywords: Peat Soil; Ordinary Portland Cement; Palm Oil Fuel Ash; Geopolymer; Soil Stabilisation; Unconfined Compressive Strength.

1. Introduction

Peat soils are defined as highly heterogeneous materials as they are derived from decomposing organic matter, i.e., plant leaves and roots, and are typically brown or black in colour [1, 2]. From a geotechnical engineering standpoint, the ASTM D 4427 standard defines peat soil as soil with >75% organic content [3]. Peat soil is deemed geotechnically problematic since it has high natural moisture content, high water-holding capacity, low shear strength, and high compressibility, hence making it one of the most difficult soils to construct roads and buildings on [4–6]. In general, peat soils can be classified based on several methods, such as Particle Size Distribution, Degree of Humification, Fibre Content, Ash Content or Acidity level [4]. The most commonly used classification system for peat soils is based on the Fibre Content and Degree of Humification. As mentioned previously, soils with more than 75% organic content are classified as peat soil (per ASTM D 4427), while ASTM D 1997 further classifies the highly organic soil into three types according to its fibre content, namely sapric peat (< 33%), hemic peat (between 33–67%) and fibrous peat (>67% content).

* Corresponding author: hidayati@ums.edu.my

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Subsequently, the degree of humification can also be used to categorise peat soils, as proposed by Lennart von Post, a renowned Swedish geologist and botanist [7]. More specifically, there are 10 degrees of humification, which can be identified based on the appearance of peat soil observed after it is squeezed by hand. H1 corresponds to soil with easily recognisable plant structure and no soil decomposition, while H10 indicates peat soil that has completely decomposed and has no distinguishable plant structure.

Shear strength is a crucial parameter to be considered for any engineering design associated with soils because adequate soil shear strength is required during construction (to support construction activities) and during post-construction (to support the built structure) [4]. Moreover, peat soil shear strength values are also highly anisotropic [8], where their characteristics depend on various factors, namely the soil origin, moisture content, organic content, degree of humification, and the soil sampling type (undisturbed or disturbed) [9]. As stated previously, peat soils are difficult to work with on site since they have low shear strength and are highly compressible. Therefore, these problems associated with peat soils should be resolved by means of soil stabilisation. The soil compressive strength is considered effective when there is an increase of 345 kPa from the natural soil's Unconfined Compressive Strength (UCS) value, as stated by ASTM D 4609 [10]. More specifically, the target stabilised soil UCS value should be 345 kPa or more compared to the original UCS value, and not 345 kPa as the end result.

Chemical stabilisation is defined as a cost-effective technique employed to enhance the engineering characteristics of problematic soils, i.e., to reduce the soil compressibility, increase the soil shear strength, and increase the durability of weak soils [11]. This method uses chemical stabilising binders, which are mixed with weak soils encountered on site and can be done either at shallow levels or deeper levels of soil strata. As the name suggests, the former is called shallow stabilisation, while the latter is termed deep stabilisation, and it concerns the stabilisation of thick soil deposits [12]. For this research work, the literature review is focused on shallow stabilisation, and in the interest of scope, the aspects of deep soil stabilisation will not be discussed. In the following sections, the use of traditional stabilisers (with special emphasis on OPC) and non-traditional stabilisers such as polymers, alkaline solutions, and pozzolanic mixes for the purposes of shallow chemical stabilisation of weak soils are reviewed in detail.

It is important to note that the prolonged use of traditional soil stabilisers is not in line with the United Nations Sustainable Development Goals, which require nations to comply with the SDG targets by 2030. Omer and Noguchi [13] had written extensively regarding the contribution of building materials to achieve the SDGs, where various terminologies of sustainable materials were introduced, e.g., low embodied energy building materials (stabilised earth brick) and alternative building materials (geopolymer material). More specifically, alternative building materials are defined as the combination of materials that use available resources (agricultural and industrial wastes) such as Eco Processed Pozzolan (EPP) [14], Coffee Husk Ash (CHA) [15], and Palm Oil Fuel Ash (POFA) [16] instead of traditional non-green resources to improve the inefficient consumption of energy and achieve sustainability in buildings [13]. Chang et al. [17] stated that around 5% of the global carbon dioxide emissions are attributed to cement production, making it one of the highest contributors to the annual carbon dioxide emissions. As such, researchers have started to focus on the use of alternative or non-traditional soil stabilising materials to achieve the SDG goals.

In this review paper, the use of traditional stabilisers, i.e., Ordinary Portland Cement (OPC), and non-traditional stabilisers, e.g., Palm Oil Fuel Ash (POFA), OPC-POFA blends, and alkaline solutions to remediate the strength of peat soils, are examined in depth. Subsequently, the application of Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBS) geopolymer to improve peat soils, and POFA-based geopolymer to improve the shear strength of clayey soils are also discussed in detail.

2. Research Gap in Malaysia

In Malaysia, it is estimated that about 8% of the total land is covered with peat (equivalent to 3 million hectares), with about 86,000 hectares of peatlands in Sabah, North Borneo, Malaysia [9, 18]. With research undertaken by the researchers in this region, the results on the basic and engineering soil properties of peat soils in Sabah, North Borneo, have been established, with particular emphasis on the peat classification, microstructural characteristics, strength, and compressibility characteristics [19–23]. In addition, studies on the dynamic properties of North Borneo peat soil were also ascertained in comprehensive research works [24–26]. Meanwhile, limited attempts at studies pertaining to the stabilisation of peat soil were carried out by researchers in Malaysia. Some notable studies include the stabilisation of peat soil with Ordinary Portland Cement (OPC) by Malaysian researchers from the previous decade [27, 28]. More recent studies on the use of OPC for stabilisation purposes were conducted by previous researchers [29–31]. In these aforementioned peat stabilisation studies, only the study by Ahmad et al. [31] produced acceptable stabilised samples based on ASTM D 4609. Research works using various non-traditional stabilisers to improve the Unconfined Compressive Strength (UCS) of peat soil were also attempted by Malaysian researchers, with POFA-OPC blends [30, 32, 33], Magnesium Chloride solution [34, 35], SS299 liquid polymer [36], and Vinyl Acetate Acrylic Copolymer (VAAC) [37]. With the exception of the study conducted using VAAC (which recorded a stabilised peat UCS value of 2000 kPa), the results of UCS for peat soils stabilised using non-traditional stabilisers were deemed unacceptable since

the stabilised soils registered UCS values lower than 345 kPa. Encouraging results were reported by researchers in India [38, 39], where the studies on the use of RHA Geopolymer and GGBS Geopolymer to remediate fibric, hemic, and sapric Indian soils produced stabilised peat UCS values ranging between 558–2344 kPa. However, the natural moisture content of Indian peat soils (198–600%) [39, 40] is generally lower compared to Malaysian peat soils, where West Malaysian peat soils possess moisture contents ranging from 150–814.6% [41, 42], while values ranging from 448.32–985.3% were recorded for North Borneo peat soils [2, 19, 20]. Since the North Borneo peat soils possess a higher moisture content, peat stabilisation with geopolymers might present a different outcome. Therefore, an attempt to use geopolymers to remediate North Borneo peat soils should be made to examine the effect of elevated natural moisture content on the strength characteristics of the stabilised soil.

Meanwhile, the use of POFA-based geopolymers has also been studied by Malaysian researchers in recent years, but these studies focused on the stabilisation of silt and clay soils. For example, Zainuddin et al. [43] produced POFA geopolymers to stabilise very silty soil, while Abdeldjouad et al. [44] focused on the improvement of residual soil and marine clay using POFA geopolymers, and lastly, [45] conducted a study on the use of POFA geopolymers to enhance the shear strength of silts and clays. The studies carried out by Yusof [42] and Zainuddin et al. [43] showed promising results, with stabilised soil UCS ranging from 900–4180 kPa. At the time of writing, there are no known studies conducted on the improvement of tropical peat soils with POFA-based geopolymers. As such, the current review paper is part of ongoing research that focuses on the use of POFA geopolymer to remediate North Borneo peat soil. Figure 1 shows the planned experimental programme to be conducted for this study.

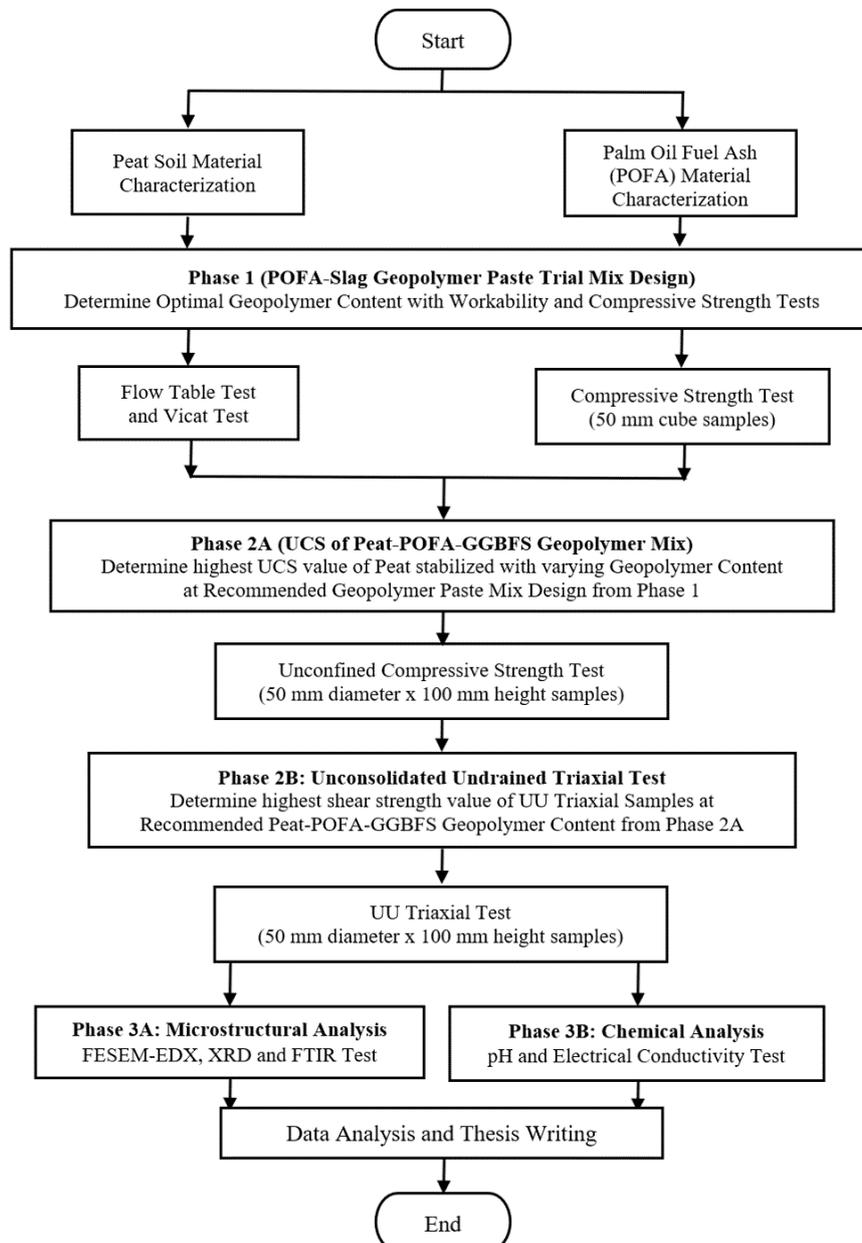


Figure 1. Planned experimental research program

3. Traditional Peat Soil Stabiliser

3.1. Ordinary Portland Cement (OPC)

In the context of chemical stabiliser materials, traditional stabilisers are defined as conventional binder materials that are known to provide adequate cementitious reactions when mixed with weak soils, such as lime and Ordinary Portland Cement (OPC) [46]. However, in the case of peat soil with elevated levels of organic content, the use of lime has been proven to be counterproductive, as reported in the European Design Guide for Soft Soil Stabilisation [47].

The presence of organic content adversely affects the OPC cementation process in the soil due to the humic acid contained in peat soils, which causes the soil to possess a low pH, hindering the hydration process of OPC [48] when it is added to the soil. Additionally, Tremblay et al. [49] stated that humic acids act as strong retarding agents in the process of hydration. The hydration process of OPC in peat soil is also affected due to the tendency of organic matter in peat to exhaust the supply of calcium ions obtained from the OPC, which reduces the amount of calcium ions available for cementation [50, 51], and its ability to change the structure of the cement hydration products such as Calcium-Silicate-Hydrate (CSH) gel and ettringite [48]. As such, the European Design Guide for Soft Soil Stabilisation recommends the use of OPC-gypsum and OPC-furnace slag blends in an effort to increase the alkalinity of the stabilised peat soil mix.

In order to ascertain the effectiveness of the soil stabilisation method, the minimum UCS requirement shall be based on the value recommended by ASTM D 4609 [10], which sets the target of 345 kPa UCS value improvement, as mentioned in the previous section. Section 3.2 shall discuss the findings of recent research that focused on the outcome of peat soil remediation with OPC.

3.2. Unconfined Compressive Strength of Peat Soils treated with Traditional Stabilisers

Recent studies have been conducted to investigate and confirm the effectiveness of using OPC as a stabilising material to remediate peat soils. A summary of recent peat soil stabilisation studies conducted with OPC is shown in Table 1. The salient findings of these studies are discussed in this section.

Table 1. Summary of recent studies on peat soils stabilised with Ordinary Portland Cement (OPC)

Peat Origin	Peat Classification	Moisture Content (%)	OPC dosage (kg/m ³)	Peat UCS (kPa)	Stabilised Peat UCS at 28 days curing (kPa)	Percentage of Strength Improvement (%)	Remarks
Teluk Intan, Perak, Malaysia [31]	Fibric (H ₃)	224	170	42.9	393.5	817	The UCS of 393.5 kPa was achieved with the specified OPC dosage at 28 days curing, which fulfils the ASTM D 4609 requirement.
Pontian, Johor, Malaysia [30]	Fibric (H ₃)	938	300	8.7	82	842	The 28 day UCS improvement of 73.3 kPa falls short of the ASTM D 4609 requirement (at least 345 kPa increase should be recorded). Higher dosage of OPC should be used.
Highway 39, Assam, India [19, 20]	Sapric (H ₈ -H ₁₀)	268	187	11	700	6,263	The UCS value of OPC treated peat shows noticeable improvement with OPC dosages > 10% of dry peat weight. Rapid increase in the UCS value is seen within the first 14 days of treatment.
Kalinagar Estate, Assam, India [19, 20]	Fibric (H ₁ -H ₄)	600	187	10	600	5,900	Presence of organic matter and natural moisture adversely affects the stabilisation with OPC, Hemic peat produced the lowest OPC treated peat UCS value (500 kPa), since it has an organic content of 76% and moisture content of 600%. All treated peat specimens fulfilled the ASTM D 4609 requirement.
Manipur, India [19, 20]	Hemic (H ₅ -H ₇)	404	187	8	500	6,150	
Ireland [52]	Hemic (H ₆)	165	100	–	44	–	UCS value of natural Irish Moss peat was not disclosed. All reported UCS value of OPC stabilized peat (fell short of the ASTM requirement due to very high moisture content of the reconstituted peat samples (1000%), with a pH value of 3.6. The reconstituted peat moisture content should be lowered, and OPC dosage should be increased to meet the ASTM requirement. [52] opted to use biochar to improve peat soil strength values.
			150	–	118	–	
			200	–	197	–	
Pontian, Johor, Malaysia [29]	Fibric (H ₃)	495	300	10	164	1,540	The UCS value of OPC treated Pontian peat showed an increase of 153.7 kPa, which does not fulfil the ASTM D 4609 requirement of 345 kPa improvement in the stabilized soil. Higher OPC dosages should be used to achieve the ASTM strength requirement.
Matang, Sarawak, Malaysia [53]	Fibric (H ₃)	587	144	14.23	115	72	The UCS value of OPC treated Matang peat showed an increase of 100.77 kPa, and therefore falls short of the ASTM D 4609 requirement for the acceptable attempt of soil stabilisation. OPC dosages must be increased in order to meet the 345 kPa requirement stated in the ASTM standard.

The study conducted by Ahmad et al. [31] focused on the effects of adding OPC to Teluk Intan fibrous peat. More specifically, adding 15% of OPC (dry weight of peat soil) to the peat managed to increase the Unconfined Compressive Strength (UCS) value from 42.94 kPa to 393.5 kPa after curing for 28 days, which represents an increase of 817% compared to its natural state. It was also observed that a longer curing period (28 days) yielded higher strength values of the treated soil compared to shorter curing periods (7 and 14 days), since the pozzolanic reactions of the peat soil and the OPC are less than ideal due to the high acidity of peat soils. Based on the ASTM D 4609 requirement, the UCS increase of 350.56 kPa observed in this study suggests that the soil stabilisation is indeed effective.

Meanwhile, the research performed by Wahab et al. [30] explored the use of OPC to improve the strength properties of Medan Sari (Pontian) fibrous peat. This peat possessed a high moisture content of 938% and was treated with a 300 kg/m³ dosage of OPC, with the soil-stabiliser mix prepared as stipulated in EuroSoilStab [47]. At the given OPC dosage, the Medan Sari peat had improved from 8.7 kPa to 82 kPa within 28 days of curing, a rise of 842% from the original UCS value. However, the improvement of 73.3 kPa with the addition of OPC does not comply with the effective soil stabilisation requirement as stated in ASTM D 4609. As mentioned previously, the presence of humic acid hinders the cement hydration process and is likely the cause of the sub-par outcome of the soil stabilisation. The researchers also investigated the effect of adding POFA to OPC in order to improve the cement hydration process during the curing period, and this will be discussed further in Section 4.3.

In an investigation carried out by Zainorabidin et al. [19] and Sapar [20], the researchers attempted to improve the strength characteristics of three types of peat (fibric, hemic, and sapric) originating from the North East region of India. The fibric, hemic, and sapric peats had UCS values of 10 kPa, 8 kPa, and 11 kPa, respectively. After treatment with a 187 kg/m³ dosage of OPC and 28 days of curing, the final UCS values of the peats are 600 kPa (fibric), 500 kPa (hemic), and 700 kPa (sapric), corresponding to an increase of 5900%, 6150%, and 6263% from their natural strength values, respectively. According to ASTM D 4609, the soil stabilisation attempt is deemed effective since an increase of more than 345 kPa was observed for each type of peat soil examined in this study.

Lau et al. [52] carried out a study that aimed at improving the strength of Irish moss peat, which was classified as hemic peat. Since the peat used in this study was obtained from a local supplier, the researchers were only able to determine the air-dried moisture content of the soil, valued at 165%. To simulate the on-site conditions, Lau et al. [52] increased the water content to 1000% for the reconstituted peat samples prior to the addition of OPC treatment. Three dosages of OPC were used for the peat stabilisation attempt: 100, 150, and 200 kg/m³, which yielded the treated peat UCS value (28 days of curing) of 44 kPa, 118 kPa, and 197 kPa, respectively. In reference to the ASTM D 4609 standard, these final UCS values fall short of the 345 kPa requirement for effective soil stabilisation. This is largely due to the fact that the reconstituted peat moisture content was very high (1000%) and that the original pH value of the peat was very acidic, with a pH level of 3.6, contributing to the less than ideal conditions for cement hydration to take place. As such, the researchers had incorporated biochar powder (from commercially available pyrolyzed wooden chips) to increase the alkalinity of the peat soil-stabiliser mix. With the blend of 200 kg/m³ OPC and 200 kg/m³ biochar, the UCS value (28 days of curing) of 500 kPa was achieved and met the ASTM D 4609 effective soil stabilisation requirement.

An investigation by Dehghanbanadaki et al. [29] also studied the effect of OPC treatment on the strength characteristics of fibrous peat from Pontian, Johor. The UCS samples for stabilised peat were prepared at the average natural moisture content, which was valued at 495%. At 300 kg/m³ OPC dosage, the 28-day curing UCS value of the Pontian peat was 163.7 kPa, an improvement from 10 kPa (natural peat) and representing a strength improvement of 1540%. However, this improvement does not fulfil the ASTM D 4609 requirement of 345 kPa. As stated previously, it is imperative to increase the alkalinity of the soil-stabiliser mix to facilitate the cement hydration process and yield an effective result in soil stabilisation.

The research conducted by Kolay et al. [53] to enhance the strength of Matang fibrous peat also concentrated on the soil strength of OPC-treated peat. The range of OPC dosage used to treat the Matang peat soil was 5, 10, 15, and 20% of OPC (as a percentage of peat soil dry weight). The natural peat and OPC-treated peat soils were prepared at their Maximum Dry Density (MDD) and Optimum Moisture Content (OMC), where the UCS value of the natural peat is 14.23 kPa. At 28 days of curing, the highest UCS value of OPC-treated peat was obtained with 115 kPa at a 20% OPC dosage. The trend shows that higher UCS values are achieved with higher OPC dosage, but the resultant UCS value of 115 kPa at 20% OPC dosage is still inadequate according to the 345 kPa strength increase requirement of the ASTM. A more conducive alkaline environment is recommended to boost the soil strength gain using OPC, where an addition of alkaline solution or cementitious materials can reduce the acidity of the soil-stabiliser mix and enable the formation of more cementitious compounds to strengthen the stabilised soil matrix.

The use of traditional stabilisers to stabilise peat soils largely revolves around the use of Ordinary Portland Cement (OPC) as recommended by the European Design Guide for Soft Soil Stabilisation, where it was found that an OPC dosage of at least 10% of the dry soil weight is required for marked improvement of the soil strength [54]. From the reviewed studies in this section, it can be observed that the alkalinity of OPC is used to reduce the acidity of peat soil, which is caused by the presence of humic acid in the organic matter [55]. The inherent existence of humic acid within the peat soil impedes the cementation process, which inhibits the creation of calcium crystals (which are responsible for soil strength enhancement) [25, 26]. As seen in the "Remarks" column in Table 1, in order to improve the OPC hydration

process, it is recommended to increase the alkalinity of the soil-stabiliser mix by increasing the OPC dosages and adding supplementary cementitious materials (SCMs) such as coal fly ash or biochar material, as suggested by Lau et al. [52]. As such, it can be said that peat soils with very high moisture content, especially those originating from tropical countries, require a reduction in moisture content and the formation of hydration products during the stabilisation process to produce a stabilised soil mix with acceptable strength characteristics. Despite the less-than-ideal conditions for the hydration of OPC for the stabilisation of peat soils due to its naturally acidic nature, OPC remains a popular choice for peat soil treatment on site due to the ease of obtaining OPC on most development sites.

4. Non-Traditional Peat Soil Stabilisers

4.1. Palm Oil Fuel Ash (POFA)

Palm Oil Fuel Ash, otherwise known as Palm Oil Boiler Ash, is an agricultural waste material that is currently gaining attention in countries with sizeable palm oil industries. It is the material obtained after burning the palm oil waste materials, i.e., palm oil bunches, husks, shells, and fibres, in a boiler machine that produces energy to power the palm oil mill [56, 57]. POFA is typically used as landfill material, although this practice is frowned upon as POFA has a negative impact on the ecosystem [32].

However, the use of POFA as a sustainable pozzolanic material yields more encouraging results, as explored by Southeast Asian researchers. This is because POFA is an environmentally friendly compound if it is incorporated with cementitious materials. Table 2 shows a comparison between the characteristics of treated (sieved, oven dried, and ground) POFA material from Lumadan, Beaufort, and Johor (all regions of Malaysia) with the ASTM C618 standard that shows POFA is typically classified as a Class F (low calcium fly ash) material [58]. Some applications of POFA include its use as a supplementary cementitious material (SCM) to produce green mortar [59–62], green concrete [63, 64], and interlocking brick material [65, 66]. More recently, the use of POFA as a viable geopolymer precursor material was studied by [67–71], with the promising findings from these studies adopted for the application of POFA geopolymer for soil stabilisation purposes. The use of POFA geopolymer as a soil stabiliser will be discussed further in Section 4.4 of this paper.

Table 2. Chemical Composition of Treated Lumadan, Beaufort and Johor POFA compared to ASTM C618 [58]

Fly Ash/ POFA Type	CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	SO ₃ (%)	SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃ (%)	Moisture Content (%)	LOI (%)
Class F Fly Ash [58]	18 max.	–	–	–	5 max.	50 min.	3 max.	6 max.
Lumadan POFA [65]	10.5	59.77	1.8	3.2	0.55	64.77	2.23	8.74
Beaufort POFA [59]	17.04	47.44	1.63	10.02	–	59.09	–	–
Johor POFA [71]	11.83	47.37	3.53	6.19	1.22	57.09	–	1.84

4.2. Geopolymers

Since the introduction of the use of geopolymers as a cementitious binder to the engineering research community by Davidovits [72] and Duxson et al. [73], the use of geopolymers for soil stabilisation purposes has also gained attention in recent years. The emergence of geopolymer applications to enhance the engineering properties of weak soils has proven its benefits to the geotechnical research community [74–76]. Abdullah [77] summarised the engineering benefits of using geopolymers to remediate the inherent weaknesses in problematic soils: (1) enhanced soil structure due to the synthesis of cementitious gels created in the soil voids; (2) increased strength of the soil matrix as the presence of geopolymer material improves the shear stress resistance of the stabilised soil.

Geopolymerization involves the use of two precursor materials: (1) industrial waste materials, which are inherently rich in aluminosilicate contents (such as slag and fly ash), and (2) alkali solutions used to activate the pozzolanic materials in order to synthesise the stabilisation compound. Abdullah [77] stated that the base liquid (a highly alkaline solution) is required to dissolve the alumina and silica contents in the soil-industrial waste mix, and the formation of cementitious products ensues. In the work of Garcia-Lodeiro et al. [78], as highlighted by Abdullah et al. [79] in their comprehensive review on geopolymers, there are three types of geopolymer alkaline reaction models that exist, as shown in Table 3.

Table 3. Geopolymer Reaction Model III

Model	Precursor Material	Alkaline Activator	Curing Conditions	Reaction Product
I	Low CaO Content, High Al ₂ O ₃ and SiO ₂ (Class F coal fly ash)	High Molarity	High Temperature (> 60°C)	N-A-S-H (Sodium Aluminate Silicate Hydrate gel)
II	High CaO and SiO ₂ content (> 70%) (Blast Furnace Slag)	Moderate Molarity	Moderate Temperature	C-A-S-H (Calcium Silicate Hydrate gel)
III	High CaO, Al ₂ O ₃ and SiO ₂ (> 20%) (Mixture of Agricultural Waste Ash, Blast Furnace Slag, Coal Fly Ash or Ordinary Portland Cement)	Low to High Molarity	Moderate Temperature (Ambient)	Sodium Aluminate Silicate Hydrate (N-A-S-H) and Calcium Aluminate Silicate Hydrate (C-A-S-H) gel

Model I geopolymers typically consist of pozzolanic materials with high aluminosilicate content and low calcium oxide content, i.e., low calcium (Class F) coal fly ash [80, 81], which are activated with alkaline solutions with high molarity. Moreover, an elevated temperature condition is another requirement to produce the Model I geopolymer product, which is Sodium Aluminate Silicate Hydrate (N-A-S-H) gel. To better illustrate the Model I geopolymerization mechanism, the conceptual model proposed by Duxson et al. [73] is presented in Figure 2. In general, the geopolymerization process involves six steps, namely (1) dissolution of the Class F fly ash with the alkaline solution, producing hydroxyl ions; (2) diffusion of the aluminate and silicate compounds; (3) condensation of the alkali cations; and the subsequent (4) gelation, followed by (5) reorganisation; and lastly, (6) polymerisation and hardening of the gels to produce the N-A-S-H compound.

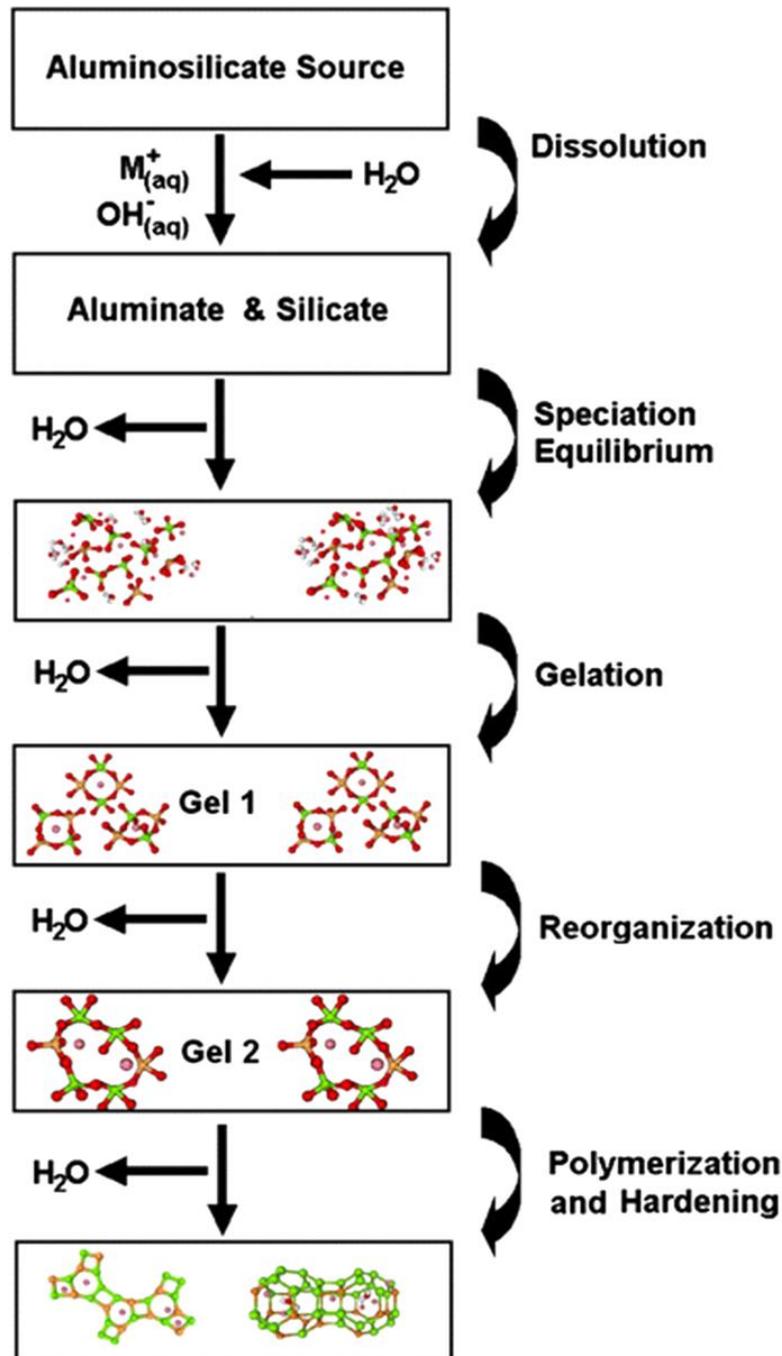


Figure 2. Model I Geopolymer Formation Mechanism [73]

On the other hand, the second reaction model, called Model II, consists of precursor materials with high calcium oxide and silicon oxide content, i.e., Blast Furnace Slag. The aluminosilicate material can be activated using alkaline solutions with moderate molarity and does not require elevated temperature conditions for the Model II reaction to commence. This reaction model produces Calcium Silicate Hydrate (C-A-S-H) gel.

In the context of this review, the focus shall be on the mechanism of Model III geopolymerization, which is a combination of both Model I and Model II geopolymer reaction models. More specifically, Geopolymer Reaction Model III involves the use of precursor materials rich in aluminosilicate (Coal Fly Ash, Palm Oil Fuel Ash) mixed with an optional enhancer calcium oxide material (Blast Furnace Slag), which can be activated with low molarity alkaline solutions, and the reaction model can be cured at a wide range of temperatures (including at ambient conditions). The reaction product consists of both Sodium Aluminate Silicate Hydrate (N-A-S-H) and Calcium Aluminate Silicate Hydrate (C-A-S-H) gels. From the soil stabilisation aspect, the Model III reaction is the most ideal one to be applied on site since the curing process can proceed without introducing high curing temperatures (as required for Model I reactions).

4.3. Unconfined Compressive Strength of Peat Soils treated with Non-Traditional Stabilisers

Table 4 shows a summary of the recent studies conducted on the stabilisation of peat soils using non-traditional stabilisers. Subsequently, the findings of these studies are discussed below.

Table 4. Summary of recent studies on peat soils stabilised with Non-Traditional Stabilisers

Stabiliser	Peat Origin	Peat Classification	Moisture Content (%)	Stabiliser Dosage	Peat UCS (kPa)	Stabilised Peat UCS at 28 days curing (kPa)	Percentage of Strength Improvement (%)	Remarks
Palm Oil Fuel Ash (POFA) - OPC Blends	Pontian, Johor, Malaysia [30]	Fibric (H ₅)	938	25% OPC + 5% POFA	8.7	107.6	1,136	Addition of 5% POFA and 25% OPC for soil stabilisation falls short of the ASTM requirement. Pozzolanic material i.e., biochar powder [52] should be added to counteract the humic acid content in the peat soil.
	Matang, Sarawak, Malaysia [32]	Not Available	306 - 450	35% OPC + 15 % POFA	18	304	1,588	Dosage of 35% OPC and 15% POFA to treat Matang peat yielded a UCS value of 304 kPa. OPC dosage should be increased beyond 35%.
	Sepang, Selangor, Malaysia [33]	Fibric (H ₅)	211	20% OPC + 10% POFA	40	130 (14 days)	225	Curing period of 14 days produced stabilised peat UCS value of 130 kPa. Projected UCS value at 28 days curing is 220 kPa, which is unsatisfactory. Ahmad et al. [33] recommends the use of 30% OPC dosage in future studies.
Magnesium Chloride (MgCl)	Pontian, Johor, Malaysia [34]	Fibric (H ₅)	150	6% MgCl	13	84	546	A new compound, M-A-H was created by adding 6% MgCl to Pontian peat, producing the 28 day UCS value of 84 kPa. Pozzolanic materials should be added to the peat-MgCl mix to fulfil the ASTM requirement.
	Mukah, Sarawak, Malaysia [35]	Hemic (H ₅)	-	6% MgCl	13	96	638	Using 6% MgCl as recommended by [34] the UCS value of stabilised Mukah peat was deemed unsatisfactory. Recommended to add pozzolanic materials to the peat-MgCl mix to achieve the ASTM requirement.
SS299 Liquid Polymer	Pontian, Johor, Malaysia [36]	Fibric (H ₅)	150	3% SS299	9.5	70 (14 days)	636	Curing period of 14 days yielded SS299 stabilised peat UCS value of 70 kPa. Curing period should be prolonged to 28 days, and cementitious materials should be added to the mix to comply with the ASTM standard.
Vinyl Acetate Acrylic Copolymer (VAAC)	Batu Pahat, Johor, Malaysia [37]	Hemic (H ₅)	605	70% VAAC	16.6	2000	11,948	Using 70% VAAC to stabilise Batu Pahat peat, the 28 day UCS value of 2000 kPa was achieved. The resin bonded effectively with the peat soil and fulfilled the ASTM D 4609 stabilisation requirement.
Rice Husk Ash Geopolymer	Assam State, India [39]	Fibric (H ₁ -H ₄)	431	Same dosage for all peat types: 20% RHA, NaOH (6 M), A/B Ratio: 0.7	9.6	1200	12,500	With NaOH concentration of 6 M, the optimum Alkali/Binder (A/B) ratio was 0.7 with 20% RHA content to produce stabilised samples complying with ASTM for all three (fibric, hemic, sapric) Indian peat soils. UCS values of RHA Geopolymer treated peat soils increased rapidly within the first 14 days and had negligible gains after the two week duration.
		Hemic (H ₅ -H ₇)	564		8.3	1129	13,600	
		Sapric (H ₈ -H ₁₀)	198		10.5	1397	13,300	
Ground Granulated Blast Furnace Slag Geopolymer	Assam State, India [38]	Fibric (H ₁ -H ₄)	431	20% GGBFS, NaOH (9 M), A/B Ratio: 0.7 (Sapric & Fibric), A/B Ratio: 0.9 (Hemic)	9.6	2088	21,650	Using NaOH concentration of 9 M, the optimum A/B ratio was 0.7 with 20% GGBFS content to produce stabilised samples complying with ASTM for fibric and sapric Indian peat soils. Hemic peat required a higher A/B ratio of 0.9, due to its elevated acidity. UCS values for Fibric and Sapric peat treated with GGBFS Geopolymer was higher compared to specimens treated with RHA Geopolymer. Strength values of GGBFS Geopolymer treated peat soils increased rapidly within the first 7 days of curing.
		Hemic (H ₅ -H ₇)	564		8.3	558	6,622	
		Sapric (H ₈ -H ₁₀)	198		10.5	2344	22,223	

In a recent investigation performed by Wahab et al. [30], the use of POFA-OPC blends to enhance the strength of Pontian fibrous peat was examined. The natural peat strength was valued at 8.7 kPa, with an elevated level of moisture content of 938%. The high moisture content and acidic pH level (pH 4.12) necessitated the use of POFA to be added to the OPC-peat mix in order to create a conducive environment for cement hydration to take place. As mentioned in Section 3.2 previously, the POFA material addition was imperative to counteract the presence of humic acid in the soil-stabiliser mix. Adding POFA to the OPC-soil blend is beneficial to the stabilisation process since POFA has smaller average particle sizes (65 μm) compared to OPC particles (100 μm). This promotes the better formation of cementitious compounds required for soil strength enhancement. Wahab et al. [30] further state that the silica or alumina oxide in POFA shall react with the Calcium Hydroxide compound (created from the peat-OPC chemical reaction) and create new Calcium Silicate Hydrate (C-S-H) or Calcium Alumina Silicate Hydrate (C-A-S-H) compounds to improve the strength of the POFA-OPC-peat soil matrix. The optimum POFA-OPC dosage was found to be 25% OPC and 5% POFA, with a resultant 28-day curing UCS of 107.6 kPa. Again, this value is much lower than the required 345 kPa strength enhancement as stipulated in ASTM D 4609 and suggests that the soil-stabiliser mix requires a reduction in the moisture content of the peat soil to improve its shear strength by means of adding pozzolanic material. Paul and Hussain [40] stated that the reaction between OPC and humic acid contained in the peat soil will produce an insoluble calcium humic acid, which hinders the calcium crystallisation formation, whereby this crystallisation is responsible for the soil strength gain. To neutralise this humic acid problem, the findings reported by Lau et al. [52] recommended the use of biochar powder to increase the alkalinity of the peat-stabiliser mix while also reducing the overall moisture content of the mix. They were able to produce a stabilised UCS value of 500 kPa for Irish moss peat that had a reconstituted moisture content of 1000%.

Rahman et al. [32] conducted a study that focused on the application of POFA-OPC blends to increase the strength of Matang peat soil. The natural peat soil possessed a UCS value of 18 kPa but had increased to 304 kPa after treatment with 35% OPC and 15% POFA, with 28 days of curing time. Despite the encouraging boost in soil strength of up to 1588% from its original strength value, the stabilised soil falls short of the 345 kPa requirement of the ASTM. In comparison to the findings made by Wahab et al. [30], it seems that an OPC dosage of more than 35% blended with POFA is a viable solution to achieve the 345 kPa increase in the stabilised soil strength. However, some caution must be exercised with the use of excessive amounts of POFA as a partial replacement for OPC for the stabilisation process. This is because the surplus POFA, which remains unreacted after the primary (C-S-H) and secondary (C-S-H or C-A-S-H) cementitious compound formation, contains a high amount of moisture content and is detrimental to the strength gain of the POFA-OPC-peat soil mix.

Meanwhile, in the research program undertaken by Ahmad et al. [33], the utilization of POFA-OPC blends to improve the strength of Sepang fibric peat was explored. The Sepang peat had a fairly low moisture content of 211%, resulting in a natural UCS value of 40 kPa, which is quite high compared to typical values of Malaysian peat soil. After applying the POFA-OPC treatment on the peat soil at 20% OPC and 15% POFA content, the 14-day curing UCS value was found to be 130 kPa. Unfortunately, the ASTM requirement of effective soil stabilisation cannot be applied to this study, as the curing time was only 14 days as opposed to the required 28 days. Nonetheless, the increment of 90 kPa within the 14-day duration is not encouraging, as a linear projection of the POFA-OPC-peat mix strength value at 28 days would be approximately 220 kPa. This suggests that the chosen POFA-OPC dosage is not adequate to counteract the effect of the humic acid within the organic soil. Abu Talib and Noriyuki [82] stated that the stabilisation of peat is effective if there is a sufficient amount of binder to initiate the cement hydration and pozzolanic reactions in the cement-pozzolan-soil mix. Therefore, an additional amount of OPC and POFA shall be recommended in order for the stabilised soil to fulfil the 345 kPa UCS requirement at 28 days of curing time. Moreover, Ahmad et al. [33] also concluded that the total OPC-POFA binder content of 30% used for the treatment of peat should be increased in future studies.

In 2016, Latifi et al. [34] initiated a study on the use of Magnesium Chloride (MgCl) solution to remediate Pontian fibric peat. The natural peat UCS had a value of 13 kPa and was treated with a 6% dosage of MgCl. After 28 days of curing, the resultant UCS value had an average of 84 kPa, a 546% increase compared to its strength, and the said dosage was the optimum content because the UCS value had reduced when it went beyond the 6% mark. The hydroxyl ions from the MgCl solution have bonded with the soil to create a new compound called Magnesium Aluminate Hydrate (M-A-H) that has improved the peat soil's strength. However, since the 84 kPa value does not comply with the ASTM requirement of 345 kPa, it is recommended that additional cementitious materials be added to the MgCl-peat soil mix to achieve the said requirement. Adding more alkaline to the present MgCl-peat mix beyond its optimum level suggests that the available calcium, silica, and alumina ions required for the pozzolanic reaction are not sufficient and should be provided by cementitious materials such as OPC or fly ash. With the presence of more calcium, silica, and alumina ions in the stabilised soil mix, the hydration and pozzolanic reactions may take place even with higher concentrations of the MgCl solution, further reinforcing the stabiliser-soil matrix with the creation of more Magnesium Aluminate Hydrate compounds.

In the following year, Hassan et al. [35] attempted to utilise Magnesium Chloride to enhance the strength of Matang hemic peat soils. By using 6% MgCl as recommended by Latifi et al. [34], the stabilised soil UCS had a value of 96 kPa

after 28 days of curing. A rapid increase in soil strength was seen in the first three days of curing, when the UCS value reached 80 kPa. This means that MgCl is an effective soil stabiliser if the peat soil requires strength gain in a short amount of time. In addition, the researchers stated that the reduction of UCS value when the soil is treated with MgCl dosages higher than 6% is due to the presence of excess positive charge (provided by the alkaline solution) causing the soil particles repulsion within the soil mix, and this finding is corroborated with the outcome study conducted by Latifi et al. [34]. However, in line with the requirement of ASTM D 4609, the treatment with MgCl does not comply with the 345 kPa increment, but the stabilisation can be further improved by the addition of other materials that can provide calcium, silica, and alumina ions.

On the other hand, Latifi et al. [36] carried out an investigation that analysed the effect of a liquid polymer called SS299 on the UCS value of Pontian fibric peat. With a low initial UCS of 9.5 kPa and a relatively low moisture content of 150%, this peat soil was a suitable specimen for remedial methods using alkaline solutions. This is because the use of alkaline solutions to stabilise soils with high moisture content will in turn produce a stabilised soil with elevated levels of moisture, making it susceptible to having lower density and strength. At 14 days of curing time, the SS299-treated peat soil produced samples with an average UCS value of 70 kPa and a 3% liquid polymer dosage. Perhaps with a longer curing time (up to 28 days of curing) and with the addition of cementitious materials, an adequate strength gain of 345 kPa according to ASTM can be achieved.

As seen in Table 4 previously, the examples of using POFA-OPC blends and alkaline solutions to remediate peat soils have not been very effective, and most of the aforementioned studies produced stabilised soil samples that did not meet the ASTM requirement of a 345 kPa soil strength increase. Therefore, to address this shortcoming, the use of polymers will be discussed below, with an emphasis on geopolymers due to their ability to transform industrial and agricultural waste into a soil-strengthening compound, made possible via alkali activation.

The investigation conducted by Razali et al. [37] aimed to analyse the effects of adding Vinyl Acetate Acrylic Copolymer (VAAC) in terms of enhancing the strength of Batu Pahat hemic peat. Despite its low UCS value (16.6 kPa) and high moisture content (605%), the stabilised soil had achieved a UCS value of 2000 kPa after being treated with 70% VAAC after 28 days of curing. The researchers concluded that VAAC was an effective stabilising material due to its ability to form a resin bond with the peat soil particles. Based on the ASTM requirement, the VAAC is indeed effective since the soil strength gains have reached the 345 kPa requirement with ease.

More recently, a comprehensive study carried out by Khanday et al. [39] utilised alkali-activated Rice Husk Ash in an attempt to increase the strength characteristics of three types of peat (fibric, hemic, and sapric) obtained from the Assam State, India. By mixing 20% Rice Husk Ash with a small dosage of Aluminium Oxide and activating both binder materials with 6 M Sodium Hydroxide, Alkali/ Binder ratio of 0.7, a significant increase in soil strength was observed. With this dosage, the UCS values of the three types of peat started at 9.6 kPa (fibric), 8.3 kPa (hemic), and 10.5 kPa (sapric) and had increased to 1200 kPa, 1129 kPa, and 1397 kPa, respectively, after 28 days of curing. The RHA-geopolymer treatment has fulfilled the ASTM 345 kPa strength increase requirement and is an environmentally friendly solution to remediate peat soils due to its use of agricultural waste material.

Within the same year, Khanday et al. [38] also examined the use of alkali-activated Ground Granulated Blast Furnace Slag (GGBS) to treat three types of Indian peat (fibric, hemic, and sapric). The researchers found that the optimum dosage is 20% GGBS activated with 9 M Sodium Hydroxide, and Alkali/Binder ratio of 0.7. After 28 days of curing, the UCS values of the three types of peat increased from 9.6 kPa (fibric), 8.3 kPa (hemic), and 10.5 kPa (sapric) to 2088 kPa, 558 kPa, and 2344 kPa, respectively. Similar to the RHA-geopolymer, this GGBS-geopolymer material has been proven to be a very effective solution to the weak peat soil problem and is in line with the ASTM effective soil stabilisation requirement. In addition, the use of GGBS (an industrial waste material) as a geopolymer precursor material also manages to solve the GGBS disposal issue, which has a negative impact on the ecosystem.

For the use of POFA-OPC blends to improve peat soil, an OPC content of at least 30% should be used with POFA, as recommended by researchers. However, in this section, it can be seen that the POFA-OPC blends are ineffective as stabiliser materials for tropical peat soils, which possess very high moisture contents. In order to use POFA-OPC blends effectively, it is suggested that the peat soil moisture content be lowered first by using more pozzolanic or filler material to increase the alkalinity and reduce the overall moisture content of the stabilised soil mix. Some improvements to the existing POFA-OPC stabiliser studies are suggested in the "Remarks" column in Table 4.

Meanwhile, the use of liquid stabiliser materials is not recommended for tropical peat soils. This is because the liquid stabilisers will further increase the moisture content of the soil and weaken it even more by lowering its overall density. Suggestions to improve the use of liquid stabilisers to remediate peat soil can be seen in the "Remarks" column in Table 4, where it is stated that more pozzolanic or filler material should be added to the stabilised soil mix to lower the overall moisture content of the mix.

Conversely, the use of copolymers such as VAAC and alkali-activated pozzolanic waste materials is highly recommended, as the outcomes of these soil stabilisation studies are encouraging. For example, the use of alkali-

activated GGBFS, which improved the UCS values of Indian peats to a range of 558–2344 kPa, proves that agricultural and industrial wastes can be repurposed as green materials produced for soil stabilisation.

However, the outcome of this review of non-traditional stabilisers showed that the application of Palm Oil Fuel Ash as a geopolymer precursor material to treat peat soils has yet to be explored. In the following section, the use of POFA geopolymer material as a weak soil stabiliser will be assessed, with particular focus on the suitability of POFA as a precursor material, the recommended alkaline activator types, and concentration.

4.4. Unconfined Compressive Strength of Soils Stabilised with POFA Geopolymer

Geopolymer material was originally used to enhance the strength of concrete [83–86], but this technique has been applied in the geotechnical field, more specifically to improve the engineering properties of weak soils [87–89]. Geopolymer POFA is obtained by mixing a pozzolanic material (Palm Oil Fuel Ash), with an Alkali Activator Solution (such as Sodium Hydroxide or Sodium Silicate) [56]. In order for geopolymer POFA material to work effectively with the weak material, it should preferably consist of substantial amounts of aluminates and silicates to facilitate the pozzolanic reactions that enable the geopolymerization process to occur. Table 5 shows a summary of the recent studies conducted on the stabilisation of weak soils using POFA-based geopolymers. Further discussions on the results of these research findings are given in the following paragraphs:

Table 5. Summary of recent studies on weak soils stabilised with Palm Oil Fuel Ash (POFA) Geopolymer cured at Ambient Temperature

Soil Origin	Soil Type	POFA Average Size and Dosage	Alkali Activator and Concentration*	Peat UCS (kPa)	Stabilised Peat UCS at 28 days curing (kPa)	Percentage of Strength Improvement (%)	Remarks
Pasir Gudang, Johor, Malaysia [43]	Laterite Soil (Very Silty Sand)	Size : 150 μm Dosage: 15 %	NH: 5 M and NS NS/NH Ratio: 0.5	106	340 (7 days curing)	220	Curing period should be prolonged to 28 days. The increase of 234 kPa within 7 days shows that POFA Geopolymer has potential as a soil stabiliser material.
Selangor, Malaysia [89]	Residual Soil (Low Plasticity Clay)	Size : 17 μm Dosage: 40 %	NH: 12 M and NS NS/NH Ratio: 2.5	260	4180	1,507	At 40% POFA, 12 M NaOH and 2.5 NS/NH ratio, the stabilised clay soils easily fulfils the 345 kPa UCS improvement requirement, which was reached at 7 days curing.
	Marine Clay (High Plasticity Clay)	Size : 17 μm Dosage: 40 %	NH: 12 M and NS NS/NH Ratio: 2.5	130	2860	2,100	
Selangor and Johor, Malaysia [44]	Low Plasticity Silt (ML)	Size: 21.9 μm Dosage: 20 %	KOH: 10 M	380	1930	407	At 20% POFA and 10 M KOH, the stabilised silt and clay soil produced samples that complied with the ASTM requirement. Soils with higher kaolinite content produced higher UCS values.
	High Plasticity Clay (CH)	Size: 21.9 μm Dosage: 20 %	KOH: 10 M	190	1320	594	
	High Plasticity Silt (MH)	Size: 21.9 μm Dosage: 20 %	KOH: 10 M	100	900	800	

* NOTE: NH: NaOH (Sodium Hydroxide), NS: Na₂SiO₃ (Sodium Silicate), KOH: Potassium Hydroxide

A very recent study was published by Zainuddin et al. [43] pertaining to the use of Palm Oil Fuel Ash geopolymer to increase the strength properties of Pasir Gudang laterite soil. The soil, which is classified as very silty sand, was found to have a natural UCS value of 106 kPa. Using 5 M Sodium Hydroxide (NH) and Sodium Silicate (NS), with a NH/NS ratio of 0.5, the researchers prepared the POFA geopolymer 24 hours prior to mixing it with the laterite soil. The POFA-geopolymer dosage applied in this study ranged from 0 to 20% geopolymer, and they have found that the highest UCS value of 340 kPa was obtained with 15% POFA geopolymer content after 7 days of curing. The researchers stated that the increase in UCS values is attributed to the formation of new compounds as a result of the geopolymerization process. At 20% geopolymer content, the researchers found that the excess moisture content as a result of surplus geopolymer had caused the deteriorating bonds of the silica and alumina compounds, causing the 7-day curing UCS value to drop to 274 kPa. In addition, Pourakbar et al. [45] also stated that the presence of unreacted POFA (due to the insufficient time allowed for geopolymerization) causes the POFA to act as a filler and not a geopolymer precursor material, causing a reduction in the stabilised soil mix. Since the reported UCS values of the stabilised soil were limited to a 7-day curing time only, the performance of POFA geopolymer as a stabiliser material in laterite soil warrants a further investigation before it can be compared to the ASTM D 4609 standard requirements.

Khasib et al. [89] carried out a study on the application of POFA geopolymer to remediate the strength of two soil samples, namely the Serdang low plasticity clay and Tanjong Karang high plasticity marine clay. The chosen soil samples are considered quite strong in comparison to peat soils, whereby the Serdang clay had a UCS value of 260 kPa and the Tanjong Karang Marine clay had a strength value of 130 kPa, while West Malaysian peat soil UCS values typically range from 3–15 kPa, as stated by Huat et al. [4]. In this study, the optimum dosage was found to be 40% POFA, activated with a mixture of 12 M Sodium Hydroxide and Sodium Silicate, where an NS/NH ratio of 2.5 was used. At 28 days of curing, the Serdang clay strength had improved to 4180 kPa, while the Tanjong Karang Marine Clay achieved a UCS value of 2860 kPa. The marked improvement in the UCS values of the POFA geopolymer treated clay is due to the formation of two compounds: the Sodium Aluminate Silicate Hydrate (N-A-S-H) created from the alkali

activation of POFA and the Calcium Silicate Hydrate (C-S-H) compound created from the reaction of dissolved calcium and silica in the POFA material [78]. Therefore, this treatment is considered effective based on the guidelines of ASTM D 4609, where the 345 kPa strength increase requirement was reached as early as 7 days after curing (1710 kPa for Serdang clay and 1060 kPa for Tanjong Karang clay).

Abdeldjouad et al. [44] performed a comprehensive investigation into the strength behaviour of three types of cohesive soils treated with 20% POFA activated and 10 M Potassium Hydroxide (KOH). More specifically, this study examines the effect of clay content on the outcome of the POFA geopolymer treatment. The three soils were obtained from Selangor and Johor and are of low plasticity silt (ML), highly plastic clay (CH), and highly plastic silt (MH), with the natural soil UCS values of 380 kPa, 190 kPa, and 100 kPa, respectively. After the POFA geopolymer was mixed with the clay soils and cured for 28 days, the resultant UCS values for the soils were as follows: 1930 kPa (ML), 1320 kPa (CH), and 900 kPa (MH). The researchers theorised that the alkaline activation with KOH was most effective with a higher content of kaolinite in the soil sample, i.e., in the low-plasticity silt soil. In POFA geopolymer-treated soil, the geopolymerization had produced mullite and brucite, but in soils with elevated contents of kaolinite, an additional compound was detected by the researchers: the hematite compound that was produced as a result of the reaction between KOH and kaolinite. Moreover, the treatment of 20% POFA and 10 M KOH to remediate the clay soils in this study is considered effective as the strength gains have exceeded the 345 kPa mark indicated in ASTM D 4609.

In this section, the results of studies on the use of POFA geopolymers to stabilise clayey and silty Malaysian soils show that this geopolymer has the potential to be applied to other types of weak soils. For example, relatively weak clay soils treated with POFA activated using NS and NH saw an increase in the UCS to 2860–4180 kPa. Subsequently, weak silt and clay soil samples were improved with POFA activated with KOH, with UCS values ranging between 900–1930 kPa. These stabilised soil UCS values easily surpassed the ASTM D 4609 requirement of 345 kPa UCS value improvement of the untreated soil; therefore, the results of these studies can be used as a guide to further optimise the stabiliser dosages by lowering the alkali activator concentration and lowering the POFA dosage while still adhering to the effective stabilisation requirement.

5. Factors Affecting POFA Geopolymerization in Ambient Temperature

In the field of material engineering, most research studies are focusing on POFA geopolymerization that involves oven curing at least 60–85°C [61, 64, 70, 90]. Salih et al. [91] discovered that for POFA geopolymers created at ambient temperature (AT), it takes 3.2 times longer to harden compared to the sample cured at 60 °C (137 minutes for oven curing and 450 minutes for AT curing). Furthermore, the same study concluded that the 28-day compressive strength of POFA geopolymer for both samples is comparable (31 MPa for AT, 32.5 MPa for 60°C curing temperature). Based on this encouraging finding, this section is dedicated to the discussion of pertinent factors affecting the geopolymer synthesis in ambient temperature conditions since the application of oven-cured geopolymers is not practical for on-site soil stabilisation.

5.1. Geopolymer Source Material

Previously in Section 4.1, the Palm Oil Fuel Ash material was classified as a Low-Calcium Fly Ash (Class F), a viable material considered a geopolymer source material. For low-calcium materials, the geopolymerization process involves a polycondensation process that results in the formation of Si—O—Si bonds and Si—O—Al bonds, creating the 3D structure of a geopolymer [92].

One of the important aspects of choosing a geopolymer precursor material is evaluating its initial Si/Al ratio, as this ratio is directly correlated to the resultant strength of the geopolymer. More specifically, higher Si/Al ratios enhance the amount of strong Si—O—Si bonds created in the synthesised geopolymer [93, 94]. This is in line with the recommendation of Garcia-Lodeiro et al. [78], as shown in Table 6, which stipulated a minimum Si/Al ratio of 1.5 with a minimum SiO₂ content of 40% for a geopolymer precursor to be deemed a suitable material for geopolymerization. The variation in the chemical composition can be attributed to the quality of the palm oil waste material, the boiler burning temperature, and parts of the palm oil tree subjected to burning [57, 95].

Table 6. Chemical Composition of Treated Lumadan, Selangor and Johor POFA compared to the Recommended Requirements of Class F Fly Ash Geopolymer [78]

Chemical Compounds	CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	Si/Al Ratio
Class F Fly Ash for Geopolymer Synthesis [78]	≤ 10	> 40	–	≤ 10	> 1.5
Lumadan POFA [65]	10.5	59.77	1.8	3.2	33.21
Selangor POFA [89]	9.73	43.52	24.7	6.68	1.76
Johor-2 POFA [44]	11.93	55.78	17.29	4.17	3.22

It can be seen in Table 6 that a proper evaluation of the chemical composition of the geopolymer precursor should be made before considering the material as a geopolymer source material, with particular emphasis on the SiO_2 and Al_2O_3 contents to ensure that the Si/Al ratio exceeds 1.5. In order to develop geopolymer material with adequate strength, Farhan et al. [96] suggest that a target Si/Al ratio of 2–2.5 for Class F fly ash material should be applied to the design mix, with Si values around 45–55% and Al content around 22–28%, and additives like Blast Furnace Slag are recommended to adjust the Si/Al ratio to ensure a robust geopolymer material with high compressive strength is produced. The use of Selangor and Johor-2 POFA to remediate weak soils has been proven to be a successful endeavour, as reported by Khasib et al. [89] and Abdeldjouad et al. [44], where these POFA materials possessed a low Si/Al ratio. In the case of Lumadan POFA, the author plans to use this material for the application of POFA geopolymer to remediate Klias peat soil. Based on the recommendation of Farhan et al. [96], due to the high Si/Al ratio observed for Lumadan POFA, the addition of Ground Granulated Blast Furnace Slag (GGBFS) to the POFA material will be considered for the adjustment of the Si/Al ratio in order to create an effective geopolymer mix as a weak soil stabiliser. The addition of GGBFS to the geopolymer material was also discussed previously in Section 4.2, where the combination of POFA and GGBFS is expected to create a Model III-type geopolymer with the reaction products N-A-S-H and C-A-S-H will be produced. Previous studies have used geopolymers made from binary blends of fly ash and GGBFS for soil stabilisation purposes with encouraging results, i.e., to remediate silts and clays, in recent years [96–102]. The application of POFA-GGBFS geopolymer for peat soil shall be investigated by the author due to the promising results shown for its use to remediate clay soils. Furthermore, since Model III geopolymers do not require alkaline solutions with very high concentrations, the characteristics of alkali activators required for synthesising this type of geopolymer will be discussed in the following subsection.

5.2. Alkali Activator Type, Concentration and Ratio

The alkali activator selection is another crucial step towards creating an effective geopolymer mix. Based on previous studies, the use of two types of Alkali Activators, Sodium Hydroxide (NaOH or NH) and Sodium Silicate (Na_2SiO_3 or NS), for the geopolymer synthesis of aluminosilicate materials is recommended. The Sodium Hydroxide acts as a material to dissolve the aluminosilicate materials, and the Sodium Silicate acts as a binder material [71, 103].

Sodium Hydroxide can also be substituted with Potassium Hydroxide (KOH), and the study comparing the use of KOH and NaOH for the dissolution of aluminosilicate products was conducted by Panagiotopoulou et al. [104], where the study uncovered that at similar concentrations (10 M), the NaOH solution was able to dissolve more fly ash material after a leaching duration of 24 hours. Farhan et al. [96] support this finding by highlighting the fact that the inherent differences in the ionic sizes of Na^+ and K^+ are responsible for the difference in dissolution abilities of both types of solutions, where Na^+ has a smaller ionic size of 116 pm compared to the 152 pm size of K^+ , hence making the NH solution a more efficient alkaline activator material at a given concentration.

Kwek et al. [67] conducted a series of experiments that examined the workability and compressive strength of alkali-activated POFA created at ambient temperatures. It was discovered that with a 12 M NaOH concentration, the optimum ratio for NS/NH was 2.5, and the highest compressive strength of 16.27 MPa was achieved after 28 days of ambient temperature curing. The NS/NH optimum ratio of 2.5 was also recommended by previous researchers studying oven-cured alkali-activated fly ash [105] and oven-cured alkali-activated POFA [69, 70]. Conversely, Kwek et al. [67] also found that the POFA activated solely with 12 M NaOH only reached 5.54 MPa compressive strength after 28 days of curing. Therefore, it is imperative to mix both NS and NH in the appropriate ratio to create a geopolymer with adequate strength.

Past studies have shown that the recommended NH concentration for geopolymerization purposes is 12 M [67–69] or even at 10 M NH concentration [97, 106]. However, lower NH concentrations are also effective, and an 8 M NH concentration was adopted by several researchers [59, 107–109]. Very high NH concentrations, such as 15 M, should be avoided, as they create a semi-plastic geopolymer compound [39] that cannot be mixed properly due to the reduced workability. Similarly, very low NH concentrations, such as 3 M, must not be used for geopolymerization because not enough aluminosilicate materials were dissolved to enable the geopolymer synthesis to take place [38]. Subsequently, the recommended alkali activator should contain both Sodium Silicate (NS) and Sodium Hydroxide (NH), where the NS/NH ratio plays a huge role in the geopolymer mix design optimisation, as stated by Kwek et al. [67].

6. Conclusions

In this paper, an in-depth review of the existing literature on soil stabilisation using various stabilisers has been conducted, with particular emphasis on the use of non-traditional stabilisers, i.e., waste-derived geopolymers, to remediate peat soils. Based on the published literature pertaining to peat soil stabilisation, the authors have drawn the following conclusions:

- The use of traditional stabilisers to stabilise peat soils largely revolves around the use of Ordinary Portland Cement (OPC), as recommended by the European Design Guide for Soft Soil stabilisation. Peat soils with very high moisture content, especially those originating from tropical countries, require a reduction in the moisture content and the formation of hydration products during the stabilisation process to produce a stabilised soil mix with acceptable strength characteristics. This can be achieved by increasing the OPC dosage (>10% of dry peat weight) and by introducing filler material such as biochar to the peat soil.

- In the case of POFA-OPC blends, an OPC content of at least 30% should be used, with POFA acting as an additional pozzolanic material to improve the soil shear strength. However, since the resultant UCS value of tropical peat soils stabilised with POFA-OPC blends falls short of the ASTM requirement, the use of more pozzolanic or filler material to increase the alkalinity and reduce the overall moisture content of the stabilised soil mix is recommended.
- Using liquid stabiliser materials such as Magnesium Chloride and liquid polymer to stabilise peat soils is only recommended for peat soils with relatively low moisture content (< 200%). Adding more moisture to the peat soil lowers the overall density of the stabilised soil mix, but marginal strength gains are observed due to the formation of reaction products as a result of the chemical reaction between the liquid stabiliser and the peat soil. This method is not recommended for tropical peat soils with very high moisture contents.
- The use of VAAC, a copolymer material, had managed to improve the strength properties of Batu Pahat hemic peat from a low UCS value (16.6 kPa) to a stabilised UCS value of 2000 kPa as a result of the strong bonds formed between the soil particles and the resin. Moreover, the use of alkali-activated RHA to improve peat soil strength from 8.3–10.5 kPa to stabilised UCS values ranging between 1129–1397 kPa and alkali-activated GGBFS, which improved the UCS values to a range of 558–2344 kPa, shows the potential of alkali-activated agricultural and industrial waste to form geopolymers as a sustainable soil stabiliser material.
- Limited studies on the use of POFA geopolymers to stabilise clayey and silty Malaysian soils have the potential to be applied to other types of weak soils. For instance, relatively weak clay soils with UCS values ranging between 130–260 kPa treated with POFA activated using NS and NH saw an increase in the UCS to 2860–4180 kPa. In another study, weak silt and clay soil samples with UCS values ranging between 100–380 kPa were improved with POFA activated with KOH and produced stabilised soil samples with UCS values ranging between 900–1930 kPa. In the context of effective soil stabilisation entailed in ASTM D 4609, the aim of 345 kPa UCS improvement can be achieved with lower alkali activator molarity and at lower POFA dosages.
- The recommended alkaline activator solutions are NS and NH, where the former works to dissolve the aluminosilicate materials while the latter acts as a binder material. Recommended NH concentrations are between 8–12 M, and the optimum NS/NH ratio is 2.5 for effective ambient-temperature geopolymerization.

7. Recommendations

As a result of this review, it can be concluded that an attempt to use POFA geopolymer (with the addition of GGBFS) to enhance the engineering properties of peat soils has yet to be explored. At present, there are limited studies that delve into the effectiveness of POFA-GGBFS geopolymer material to improve peat soil engineering properties. As explained in Section 4.4, the use of POFA material as a geopolymer precursor material for the purpose of soil stabilisation has only been applied to sandy silt, low plasticity silt, and high plasticity clay. Conversely, there are only two studies that have used geopolymers to remediate peat soils in existence, which were conducted with Rice Husk Ash (RHA) geopolymer [39] and with Ground Granulated Blast Furnace Slag (GGBFS) geopolymer [38]. Therefore, a comprehensive experimental investigation should be initiated to study the use of POFA-based geopolymers for the stabilisation of peat soils.

In the proposed research framework, the physical, engineering, chemical, and microstructural characteristics of North Borneo peat soil treated with POFA-GGBFS geopolymer will be studied. By establishing the characteristics of stabilised peat soils with an environmentally friendly soil stabiliser, this study is hoped to provide a practical and economical solution for developers that are dealing with peat deposits on their construction sites. For the proposed study, the geopolymer precursor material used is ground POFA enhanced with GGBFS, mixed with two types of alkaline activator materials: Sodium Silicate (NS) and Sodium Hydroxide (NH), with the NH concentration ranging from 5 to 6 M. As such, some recommendations for future studies are listed below:

- Previous research involving the use of RHA and GGBS geopolymer materials to enhance the strength of peat soils shows promise, as it fulfils the ASTM effective soil stabilisation requirement. However, the use of POFA as a geopolymer precursor material for the remediation of peat soil has yet to be attempted.
- The engineering standard for the selection of geopolymer source (aluminosilicate) materials subjected to alkaline activation is not available. Instead, the suitability check for the chosen geopolymer source materials, POFA and GGBFS, shall be made based on existing engineering standards for the use of agricultural or industrial waste materials used as precursors for mortar and concrete materials, i.e., ASTM C618-19 [58], ASTM C989-09 [110], and ACI 233R-17 [111]. In addition, the extensive works of previous researchers that focused on the state-of-the-art regarding the alkali-activation of geopolymer pastes [112] and geopolymer concrete [113] have provided an array of physicochemical properties of the aluminosilicate materials, together with the acceptable range of these chosen materials. The POFA and GGBFS materials should pass the suitability check based on the criteria outlined by the aforementioned standards before proceeding with the POFA-GGBFS geopolymer paste testing phase.

- A thorough investigation shall be conducted on the fresh and hardened properties of POFA-GGBFS geopolymer paste created with agricultural and industrial waste materials, activated using alkaline solutions with moderate molarity, and cured in tropical ambient temperature conditions. The outcome of this investigation will be used to recommend the optimum dosage of POFA-GGBFS geopolymer mix suitable for soil stabilisation, where the geopolymer with the highest compressive strength with acceptable workability is chosen as the optimum stabiliser content.
- Next, with the optimum POFA-GGBFS geopolymer mix design, this stabiliser mix will be used to remediate the North Borneo peat soil at different levels of peat soil replacement, e.g., 5–20% geopolymer content based on the dry weight of the peat soil. The soil shear strength and compaction characteristics of untreated and stabilised peat soil will be established. An assessment of the shear strength and compaction characteristics of the untreated peat and the geopolymer-treated peat soil shall be made to ascertain the effectiveness of the soil stabilisation, with the aim of improving the UCS value by at least 345 kPa (as stipulated in ASTM D 4609).
- Lastly, analytical techniques shall be employed to establish the chemical, microstructural, and mineralogical characteristics of the natural and POFA-GGBFS geopolymer-treated North Borneo peat soil. These findings will be correlated to the shear strength and compaction characteristics of the stabilised soil. In addition, this detailed investigation will highlight the findings pertaining to the formation of crystalline phases associated with the various stages of the Model III geopolymerization mechanism proposed by Garcia-Lodeiro et al. [78].

8. Declarations

8.1. Author Contributions

Conceptualization, A.E.A. and H.A.; resources, A.E.A, H.A., and H.M.M.; writing—original draft preparation, A.E.A.; writing—review and editing, H.A. and H.M.M.; visualization, A.E.A and H.A.; supervision, H.A. and H.M.M.; project administration, A.E.A. and H.A.; funding acquisition, H.A. and H.M.M. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

Data sharing is not applicable to this article.

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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