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REVIEW

Application of Cement-Cassava Peel Ash Mix for the Stabilisation of Marine Clay Soil: A Review

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Abstract

This review investigated the application of cement and Cassava Peel Ash (CPA) for stabilising Marine Clay Soil (MCS). This material exhibits unusually high plasticity and compressibility and low shear strength, creating challenging conditions for stabilisation. In recent decades, lime and cement have been utilised to enhance the resilience of MCSs. However, the environmental and economic sustainability of this practice has come into question due to the substantial carbon dioxide emissions produced during cement manufacturing. Cement-free stabilisation using the scientifically innovative agricultural by-product CPA has been developed as an eco-friendly and cost-effective alternative, leveraging its improved pozzolanic activity to enhance the structural characteristics of MCS, such as strength, stiffness, and permeability. Although the combination of cement and CPA could significantly benefit the structural engineering of MCS, understanding the detailed mechanisms of cement-free stabilisation remains complex, limiting its widespread application. This review indicates that the CPA-cement mix can enhance key aspects of MCS, including permeability, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS).

Keywords CPA · MCS · Stabilisation · Pozzolanic properties · UCS · Sustainable construction

1 Introduction

Engineers often face the complex challenge of constructing roads, dams, foundations, and other critical infrastructure on naturally weak or low-quality soils. Advanced engineering techniques are essential for supporting substantial structural loads under such conditions. One problematic soil type is MCS, commonly found in coastal areas and continental shores [1, 2]. MCS exhibits unfavourable engineering properties, notably high plasticity, which refers to its significant water absorption capacity and its tendency to swell and shrink with moisture changes [3]. This plasticity leads to pronounced volume changes that undermine the stability of foundations and structural elements. Moreover, the high plasticity of MCS reduces its shear strength, a critical parameter indicating the soil's ability to withstand load [4]. As a result, MCS is often unable to support the heavy structural loads required by essential infrastructure, such as bridges, roads, and coastal installations. MCS's instability is a significant reason it poses problems in construction and is closely tied to broader infrastructure resilience issues. These limitations make the reuse of MCS in construction particularly challenging, especially in space-constrained urban developments [5]. Marine clay is found around the world, particularly in Southeast Asia [6], China [7], Malaysia [8], India [9], Vietnam [10], Nigeria [11], Singapore [12], etc., and its thickness varies from a few meters to more than ten meters, depending on its location. Therefore, it is necessary to research the properties of these soils to ensure that construction can be carried out on them without being carted away. Depending on the resources (finance and equipment) available for building infrastructure foundations, engineers believe it is imperative to improve the behavior of these

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deposits using appropriate ground modification techniques [1]. Consequently, soil stabilisation has become crucial in civil engineering when building in MCS-dominated environments.

Stabilised soils reduce the need for frequent and costly maintenance, thereby increasing the longevity of structures built upon them. Thus, choosing an appropriate stabilisation method is vital, as it significantly influences the performance and durability of the resulting structure [13]. Traditional stabilisation techniques often use hydraulic binders such as lime, cement, and fly ash, which chemically react with soil particles to form more potent and stable compounds [14, 15]. Lime, for instance, is widely used to reduce the plasticity of clayey soils, enhancing their load-bearing capacity. However, lime and cement stabilisers have notable disadvantages: they are expensive and raise significant environmental sustainability concerns [16]. Cement production, in particular, is associated with high levels of CO_2 emissions. Projections suggest these emissions could increase by 12–25 per cent by 2050 [17, 18]. The cement industry currently accounts for 5–8 per cent of global CO_2 emissions [19–21], with significant regional variations resulting from differences in production processes and the utilisation of raw materials. China, for instance, leads in cement-related emissions [22]. The International Energy Agency, [23] reports that cement emissions reached 2.4 Gt, making up 26 per cent of global industrial emissions. Reducing this environmental impact is imperative: to align with the Paris Agreement, the cement sector must cut annual emissions by at least 16 per cent by 2030 [24]. This reduction is complex due to the nature of the process, where 50–60 per cent of CO_2 emissions arise from the calcination of limestone ($CaCO_3$) into lime (CaO) [21, 25, 26].

The complex nature of reducing CO_2 emissions and its increasingly high cost have led researchers to progressively explore eco-friendly and innovative alternatives to conventional chemical stabilisers [27]. One promising material is CPA, derived from the fibrous, woody waste produced during cassava processing. Cassava is a staple crop in many developing countries, particularly sub-Saharan Africa. CPA is rich in silica, alumina, and other oxides, which give it pozzolanic potential—a desirable property for cementitious applications [28]. CPA offers multiple benefits as a soil stabiliser: it is both environmentally sustainable and cost-effective, turning agricultural waste into a valuable construction resource [29]. As an alternative to cement, CPA reduces the environmental burden of cassava farming while simultaneously lowering the reliance on expensive, resource-intensive industrial stabilisers. Studies have shown that combining CPA with cement yields soils with superior mechanical strength, loss on ignition, and water resistance compared to soils stabilised with cement alone [28–30]. These improvements are attributed to the enhanced waterproofing and binding effects that CPA imparts to the stabilised matrix. CPA's economic and mechanical advantages are especially promising for rural and low-income regions, where access to conventional stabilisers may be limited. CPA enables the development of affordable, locally sourced, and sustainable construction methods, helping to bridge the infrastructure gap in under-resourced areas.

This review examines the current state-of-the-art in utilising MCS for sustainable soil stabilisation, with a focus on the performance of cement and CPA as stabilising agents. It examines trends, research findings, and practical applications in MCS construction while identifying the key challenges in their implementation. Special attention is given to the synergistic effects of cement–CPA blends, particularly their impact on engineering parameters such as UCS, CBR, and soil permeability. This review aims to inform future efforts in sustainable infrastructure development by utilising innovative soil stabilisation strategies.

2 Challenges Posed by MCS

The primary engineering issues associated with MCS are its high impermeability, high plasticity, low strength, high compressibility, and very high shrink-swell potential. Compressibility is the tendency of a soil medium to settle under the influence of a load, compressing and deforming under dynamic load application [31]. Combined with a high moisture content, the high compressibility of MCSs also results in excessive settlement, which in turn increases the risk of differential settlement. Differential settlement in buildings refers to the uneven settlement of the foundations, which can lead to cracking, tilting, and collapse if not addressed promptly. Numerous phenomena contribute in some part to the mechanism of differential settlement—but by far, the highest rates of differential settlement are recorded where the soil beneath the buildings has undergone significant subsidence (compaction) as a result of the high primary compressibility of the soils (that is, initially high moisture content and high organic matter content, which is gradually compacted down over time from the load exerted by the overlying buildings) [32]. The deformations severely induce failure after the material of the structures reaches the elastic limit [33].

The high sensitivity of clay minerals (often montmorillonite), which possess a high activity, plays a significant role in the primary problem in marine clay engineering: shrink-swell potential [34]. The principal response to this condition is substantial volume changes in clay due to a decrease in water content, resulting in sites that are affected by cracking and distortion of the structures built above the soil. If MCS dries, it shrinks significantly, and the elements of the MCS, such as foundations and pavements, crack. On the contrary, if MCS gets wet, it swells and puts pressure on the material, causing the heaving and displacement of the structural elements. This cyclic swelling and shrinkage subject structures built in MCS to intense long-term wear and tear, especially when there is tidal variation in marine areas [29]. A low load-bearing capacity is another major problem—MCS has a low shear strength of less than 25–50 kPa [2] due to its fine-grained nature and high moisture content, it is unsuitable for supporting loads of any significant magnitude without some soil improvement. Low shear strength also increases the risk of shear failure under load, which poses a considerable risk to highways, bridges, and other critical infrastructure during construction projects [35]. Because of the reasons enumerated above and many more weaknesses, MCS is inadequately used for many constructions and should either be carted entirely away and replaced with adequate material or be stabilised using appropriate methods when warranted [31], which makes construction hectic and costly.

3 Physical and Chemical Properties of MCS

MCS is a fine-grained, uniformly graded, often over-consolidated, cohesive soil mainly found in coastal and deltaic environments. Its unique physical and chemical properties and behaviour have profound implications for construction projects that manipulate large amounts of it. The most crucial property of MCS is its particle-size distribution. Because fine-grained soils are composed of tiny particles, it isn't easy to distinguish individual fine particles [36]. However, their distribution can be evaluated using standard table sieves and a hydrometer to determine and illustrate the proportion of the sample that is silt—and clay-sized. Kamaruddin, Nahazanan [8] report that MCS typically consists of more than 50 per cent clay-sized particles. As will be seen, these physical properties play a central role in the plasticity of MCS. In geotechnical engineering, plasticity is measured using a method that evaluates the clay's Atterberg limits [37]. According to Deng, Cai [37], these limits represent a soil's plasticity characteristics such that a more significant proportion of water within a clay structure will increase its plasticity. MCSs exhibit this characteristic in the context of elevated plasticity because they contain more significant proportions of hygroscopic minerals, emphasising the importance of the mineralogical composition. Montmorillonite, a constituent of MCS, is a swelling mineral [38]. The physical and index properties of some studies on MCS are summarised in Table 1.

The engineering property that significantly influences MCS's high moisture content is its compressibility, referred to as its index property. This conditioning factor causes the plasticity of MCS to increase as the moisture contents increase, thus increasing its plasticity and ability

Table 1 Physical & index properties of MCS

Reference	Location	Particle size distribution				NMC (w) (%)	Specific Gravity (Gs)	Atterberg Limits			Shrinkage limit (%)	Organic Content (%)
		Gravel (%)	Sand (%)	Silt (%)	Clay (%)			LL (W_L) (%)	PL (PL) (%)	PI (IP)		
[11]	Nigeria	0.0	19.0	40.0	41.0	67.0	2.2	70.0	37.0	33.0	18.0	7.0
[3]	Singapore	0.0	8.7	66.1	25.2	NA	NA	73.0	32.0	41.0	NA	NA
[39]	China	0.0	11.3	55.5	33.2	NA	NA	74.0	31.0	43.0	NA	NA
[40]	China	0.0	8.0	72.0	20.0	NA	NA	88.0	38.0	50.0	NA	NA

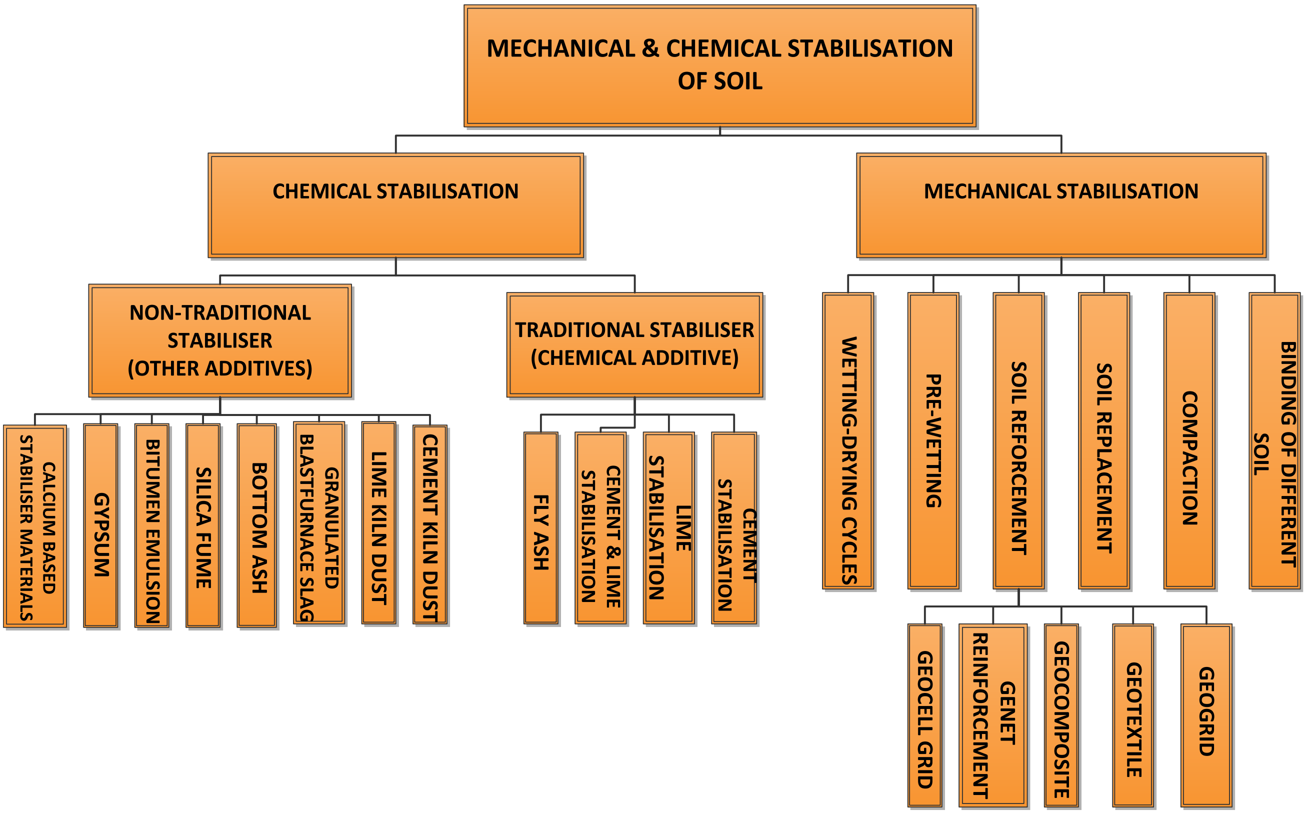


Fig. 1 Classification of soil stabilisation methods [56]

to undergo settlement and shear failure in engineering projects [4]. Using MCS in engineering construction requires very critical soil stabilisation techniques. Furthermore, the high cation exchange capacity—mainly determined by the sum of contents of electrolytes such as sodium and magnesium—is another significant chemical property contributing to the overall chemical activity of MCSs, which in turn affects the stability and plasticity of MCS significantly [41, 42]. What exacerbates the situation is that the dissolution of soluble salts alters soil solubility, resulting in an increase in plasticity and a decrease in shear (or resistance to deformation). Moreover, engineering properties of soil, such as compressibility, can be affected by higher organic matter contained in some types of MCS, which can cause deformation and settlements, leading to considerable challenges in the foundation design phase, as well as stability problems in the long term [4].

4 Soil Stabilisation

Soil stabilisation means enhancing the soil's mechanical characteristics to increase its strength, stability, and resistance to erosion [7]. Onyelowe, Van [43], Solihu [44], Mai-Bade, Chinade [45], and Pooni, Robert [46] described soil stabilisation as modifying soil properties through physical, chemical, and non-chemical means to increase the soil's durability and strength by applying additives. Several materials, such as binders and admixtures, as well as geosynthetic materials, enhance the soil's strength, stability, and load-bearing capacity through chemical, mechanical, or biological methods, including the use of bacteria or hydrological techniques, which regulate temperature [2, 47, 48]. These processes and techniques are illustrated in Fig. 1. Concerning highway engineering, Jayaram [49] defined stabilisation as permanently fusing soils, base, and subbase materials by markedly increasing their strength and load-bearing capacity, firmness, and withstanding adverse environmental conditions, while minimizing displacement under traffic. This can be done mechanically or chemically by incorporating admixtures like lime, cement, bitumen, and, nowadays, industrial and agricultural solid waste ashes to stabilise or treat the soil [50]. Stabilisers, cementitious materials, and soil minerals are the constituents of stabilisation technology [51]. Mechanical and chemical procedures are occasionally used to stabilise soil, and the following effects rely on the contribution of each component. When stabilising compounds come into contact with water or pozzolanic minerals, they react to form cementitious composite materials. These stabilising agents can be hydraulic (primary binders) or non-hydraulic (secondary binders). The most frequently employed additives for soil stabilisation include fly ash, lime, and cement [52–55].

4.1 Stabilisation Options for MCS

MCSs exhibit high plasticity, relatively low permeability, low mechanical strength, and display swelling behaviour when wet and shrinking behaviour when drying out, which causes numerous problems during construction. [57]. Therefore, houses, buildings, installations, or infrastructure constructions are potentially vulnerable to instability, particularly in MCSs with a shallow groundwater level. Stabilisation measures and means are required to improve their geotechnical behaviour and achieve long-term performance and durability of artificial constructions. Stabilisation comprises necessary engineering measures that eliminate adverse effects, negative influences, or impacts by MCSs and associated risks on artificial constructions.

As stated by Wang, Guo [58], the most frequently used and convenient practical soil stabilisation method involves the application of conventional chemicals, such as lime—and cement-based stabilisation. Nonetheless, the discussion regarding environmental pollution caused by traditional chemical stabilisation methods has increased in the last few decades, and calls for more sustainable alternatives have become more intense. CPA, the residue product of Cassava processing, is sorted as an alternative.

4.2 Choice of Chemical Stabiliation

Chemical stabilisation is achieved by supplementing the soil with chemicals or stabilisers [56, 59–63]. Chemical stabilisation improves soil properties, especially for difficult materials like clay and expansive soils [51]. Unlike mechanical methods that depend solely on compaction or reinforcement, this process modifies the soil's internal structure, enhancing its strength, durability, and resistance to moisture and environmental changes [64]. Materials like lime, cement, fly ash, and polymers interact with soil particles to decrease plasticity, control moisture sensitivity, and enhance load-bearing capacity [65]. One significant advantage of chemical stabilisation is its quick effectiveness. It accelerates project completion by rapidly increasing soil strength, which is particularly beneficial for time-sensitive construction activities such as highways, runways, and foundations. Additionally, it offers long-lasting performance with minimal maintenance requirements, even in extreme conditions such as high moisture or freeze–thaw cycles. This durability often makes the initial higher cost worthwhile, considering the extended service life of the treated soil [66].

Chemical methods offer versatility and responsiveness, providing tailored solutions for different soil varieties and specific site challenges. Chemical stabilisation acts as a feasible and effective alternative in situations where mechanical techniques fall short, such as in wet, soft, or inaccessible locations [64]. Given these advantages, chemical stabilisation is a proactive and strategic option for establishing stable, resilient, and sustainable ground conditions in construction and infrastructure initiatives. Chemical stabilisation of fine-grained materials and problematic clays is impactful in civil engineering applications, particularly in pavement structures, the mitigation of expansive soil swelling, and building foundations, as it helps prevent damage due to settlement [48, 51].

4.2.1 Cement Stabilisation

Cement stabilisation is a technique used to improve the engineering qualities of soil by mixing cement with it. Introduced as a soil stabiliser in the 1960s, cement is considered one of the earliest and most traditional methods for stabilising soil [67]. A more conventional method widely used is cement stabilisation, which is employed to achieve a high degree of strength and stiffness, primarily for weaker soils like MCS. Silicate and aluminate calcium undergo hydration to form cement structures to attach soil particles, elevating soil bearing capacity up to fivefold when compared to natural soil [68]. Two major reactions possessing great potential for cement stabilisation are hydration and pozzolanic reaction, represented as:

$$2CaO + SiO_2 + H_2O \rightarrow CaO \cdot SiO_2 \cdot H_2O + Ca(OH)_2$$

This reaction produces calcium silicate hydrate, which lends strength and stability to the soil. At the same time, calcium hydroxide is formed and reacts with alumina and silica in the soil to produce more cementation compounds in the future. For this reason, hydration in MCSs, which are rich in silica and alumina and considered an ideal soil type for cement stabilisation [69], is typically more efficient. The primary benefit of cement stabilisation is the improvement in the early and significant strength of soils, particularly when time to construction becomes a critical issue. In other words, captured cement-stabilised soils also offer higher strength, improved durability, and the ability to resist prevailing environmental conditions such as freeze–thaw and wetting–drying cycles for extended periods [70]. Cement is a widely and commonly adopted soil stabiliser in civil engineering projects, utilised as quicklime or hydrated cement. Its application to soil promotes hydration, pozzolanic reaction, and cementation, which improve the strength and firmness of the soil. Cement stabilisation primarily results in cementation, but a secondary response related to the calcium hydroxide generated during cement hydration also occurs. The end product is a cemented material consisting of the

Table 2 Chemical composition of cement

References	SiO_2	CaO	K_2O	Fe_2O_3	Al_2O_3	SO_3	MgO	Na_2O	LOI
[73]	18.3	60.1	0.1	2.8	5.0	3.2	1.2	0.0	7.2
[74]	20.7	65.8	0.3	3.3	6.2	2.2	1.1	0.2	NA
[28]	51.4	13.5	1.6	6.5	20.6	NA	0.1	1.1	3.9
[75]	20.8	64.5	0.9	2.5	3.1	2.5	1.7	0.2	3.4
[67]	61.0	10.5	NA	4.0	20.5	2.0	2.0	NA	2.2
[72]	44.6	34.4	1.6	2.8	2.5	8.5	1.0	NA	NA
[76]	20.7	65.3	NA	3.1	4.7	4.8	2.8	NA	0.9
[77]	21.53	65.56	0.81	3.84	5.93	NA	1.6	NA	0.7
[78]	18.2	60.1	0.1	2.7	5.1	3.3	1.3	0	7.2
[79]	24.5	68.0	1.7	5.8	7.6	5.4	7.1	0.8	NA

original soil, in which any clay minerals would have been partially destroyed or altered (reduced plasticity). Cement-based pavement has the advantage of great strength and durability [71]. Additionally, it is widely available and therefore becomes the best material for stabilising soil. The hydrated cement product binds with soil to form a cement-stabilised or cement-treated aggregate base. As stated by Wahab, Roshan [72] and Roshan and Rashid [47], cement significantly improves soils' mechanical characteristics and resilience in terms of efficacy and long-term resilience, surpassing other stabilisation techniques. Table 2 presents the mineralogical composition of cement from previous works.

However, despite the attributes mentioned above, cement has some setbacks, amongst which is the production of CO_2 during its production and its seemingly high cost in an emerging infrastructure-demanding world, especially from developing nations. Again, [80] has raised concerns that the cement may not fully meet the design objectives. In the long term, the modified layer will deform, damaging all the road's structural layers.

4.2.1.1 Lime Stabilisation Lime stabilisation is a widely accepted remedial method for the improvement of soil (mainly clayey soils with higher plasticity, such as MCS) [58]. When lime is added to the soil, chemical reactions will be triggered. These chemical reactions occur within a specific period and result in various improvements to the soil. These chemical reactions can be roughly categorised into two groups: short-term reactions and long-term reactions. In the short term, cation exchange reacts with lime adsorbed onto the clay particles, reducing the plasticity of the soil and rendering the soil more workable [81], which is essential for stabilising the soil for construction projects. In the long term, lime reacts with silica and alumina in the clay minerals in a pozzolanic reaction to form cementitious compounds such as calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), as shown in the following equation:

$$Ca(OH)_2 + SiO_2 \rightarrow CaO \cdot SiO_2 \cdot H_2O$$

Lime stabilisation of soil has been used in various road construction, foundations, and embankment works with swelling clays. The reduced swelling capacity and increased strength potential of marine clays in difficult ground have led to the technique being used in areas of high reactivity [58]. However, lime stabilisation is more influential on soils with low reactivity, particularly those with a high proportion of organic matter. The lime reacts with organic matter (for example, humic and fulvic material), reducing the need for pozzolanic active material that controls strength development.

4.2.2 Fly Ash Stabilisation

Fly ash, as a hybrid artificial material generated as a waste product of combusting coal in thermal power plants, has been widely used in soil stabilisation due to its Pozzolanic properties [82]. In fly ash, silica (SiO_2) and alumina (Al_2O_3) are the two primary ingredients that react with calcium hydroxide in the presence of water to form cementation products. This mechanism improves the mechanical characteristics of MCSs, and fly ash serves as a better economic and efficient alternative to prepare cementation products than lime and cement stabilisers [83]. Fly ash behaves similarly to other pozzolanic materials, such as cement. Some fly ash hydrates when water is present, while the remainder forms calcium-silicate hydrates (CSH) and calcium-aluminate hydrates (CAH), which behave exactly like aluminum siliceous oxides in pozzolanas. The long-term strength gain is attributed to the CSH and CAH, whose development depends on the CaO/SiO_2 or $CaO/(SiO_2 + Al_2O_3)$ ratio. Zimar, Robert [84] describe the behaviour of calcium-silicates with the following Eqs. (1)–(4):

$$2Ca_3SiO_5 + 7H_2O \cdots 3CaO \cdot 2SiO_2 \cdot 4H_2O(C - S - H) + 3Ca(OH)_2 \quad (1)$$

Table 3 Comparison of characteristics of lime, cement, and fly ash stabilisation methods

Stabiliser	Mechanism	Advantages	Limitations
Lime	Cation exchange, pozzolanic reaction	Reduces plasticity, improves workability	Less effective in organic soils
Cement	Hydration, pozzolanic reaction	Immediate strength gain, durable	High cost, environmental impact, and cracking issues
Fly Ash	Pozzolanic reaction	Cost-effective, sustainable	Variable effectiveness based on fly ash type

$$2Ca_2SiO_4 + 5H_2O \cdots 3CaO \cdot 2SiO_2 \cdot 4H_2O(C-S-H) + Ca(OH)_2 \tag{2}$$

The following equations describe the fundamental pozzolanic reactions:

$$Ca(OH)_2 + SiO_2 \cdots CaO \cdot SiO_2 \cdot H_2O(C-S-H) \tag{3}$$

$$Ca(OH)_2 + Al_2O_3 \cdots CaO \cdot Al_2O_3 \cdot H_2O(C-A-H) \tag{4}$$

The stabilisation of fly ash has several benefits, particularly when it is readily available as a waste product of thermal power stations. Stabilising soil using fly ash is relatively cheaper than cement and lime. It can be considered an environmental advantage because fewer wastes are deposited into landfills [85]. Additionally, it is common knowledge that fly ash is more environmentally friendly than cement, as it has a similar but, in fact, smaller carbon footprint on large-scale projects. However, it has been found that the final results depend on the kind of fly ash used and the nature of the soil. Class-C materials contain more than 50 per cent calcium, making them more reactive and compatible with the soil than Class-F fly ash, which may require lime or cement to achieve the necessary strength [82]. Moreover, significantly lower fly ash stabilisation may be achieved in high organic matter or variable moisture content, since this limits the pozzolanic reaction for strength. Table 3 presents a tabular comparison of the characteristics of lime, cement, and fly ash stabilisation methods.

4.3 Advantages and Limitations of Cement Stabilisation

Through cement stabilisation, engineers realise several advantages that make it an often-selected choice. The addition of cement helps make MCSs far more robust, stiffer, and more durable. The rapid cementation process prompts improvements in soil characteristics, mainly compressive strength, which is essential for supporting heavy infrastructure [68]. Additionally, cement possesses two attractive characteristics: it is readily available and easily modifiable, making it an ideal choice for various construction projects. Still, cement stabilisation has many restrictions. One essential worry is the cost associated with the project. Cement is costlier than all other stabilisers, so large-scale projects would not be economically viable, especially in developing countries [85]. Besides, cement production consumes much energy and produces a large amount of carbon dioxide, which causes climate change [86]. According to [17, 87, 88], the cement industry is responsible for approximately 7 per cent of global CO_2 emissions. This aspect highlights the profound environmental impact of cement stabilisation and underscores the urgent need for eco-friendly substitutes. Furthermore, soils stabilised with cement are prone to long-term shrinkage and cracking problems. Shrinkage and cracking are two common engineering problems in soils, often caused by differential drying and variations in moisture. These problems are most apparent in MCSs subjected to wetting and drying cycles [70]. Cracking tends to reduce the stability of the stabilisation, which, besides causing performance issues, may demand expensive long-term maintenance. Hence, there is a need to employ different environmentally friendly and performance materials to substitute cement stabilisation [70]. The discussion regarding environmental pollution caused by traditional chemical stabilisation methods has increased in the last few decades, and calls for more sustainable alternatives have become more intense. CPA, the residue product of Cassava processing, is one such alternative.

5 CPA to the Rescue

As previously highlighted, despite their effectiveness in construction activities, traditional stabilisers have inevitable setbacks, which have necessitated the search for alternatives to achieve cost-effectiveness and mitigate associated environmental problems. Portland cement could be replaced with cheap, readily available cementitious materials from local agricultural waste [89]. In the past forty years, the use of agricultural waste in extensive soil stabilisation as a partial replacement for cement has increased significantly [73, 78, 90]. An emergent material not sufficiently utilised in soil stabilisation is CPA, a by-product of incinerating CP waste (Fig. 3b) derived from Cassava tuber processing. The world Cassava production stood at 302.66 million metric tonnes in 2020 [91, 92]. Africa is the world's largest Cassava-growing region, with a total output of 193.62 million metric tonnes [93]. Nigeria remains the world's leading cassava producer,

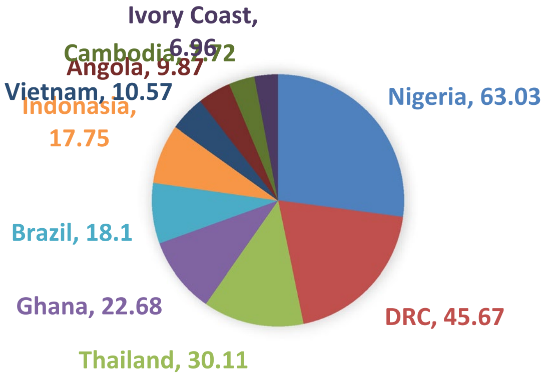


Fig. 2 Leading Cassava-producing countries worldwide in 2021(in million metric tons) [96]

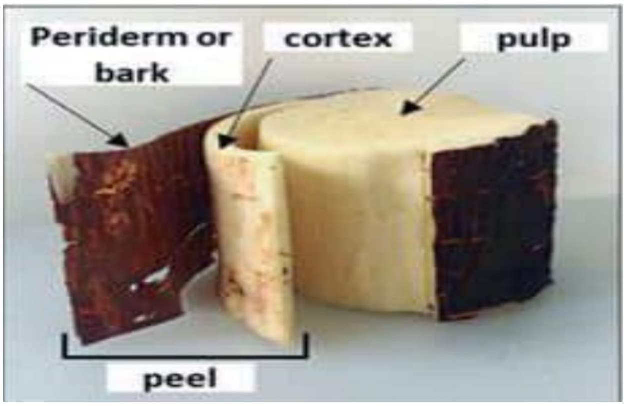


Fig. 3 Peeling Cassava roots [105]

as shown in Fig. 2, with an annual average of 3 per cent since 1995, reaching approximately 60 million metric tonnes. Cassava (Manihot esculenta) is a significant crop grown in sub-Saharan Africa for commercial and subsistence purposes [92, 94, 95].

Additionally, global Cassava production, measured by total harvested area, has increased substantially in recent years. Nigeria led the world in this aspect, with a total harvested area of 7.7 million ha in 2020 [95]. About 15 million tonnes of wet peels are produced annually from the 59 million tonnes of Cassava that Nigeria harvests (20 per cent of the crop) [97]. More than 90 per cent of the Cassava crop is used for human consumption in Africa, with very little being processed industrially [93]. Once considered a poor person's crop, Cassava is rapidly becoming a commodity with many uses, supporting rural development, poverty alleviation, food security, and value addition with macroeconomic benefits [98–100]. Cassava tubers (Fig. 4a) serve as a primary food source for most homes in tropical Africa, particularly in Nigeria, Ghana, and Togo, where they are also cultivated as an industrial raw material [101].

As stated by Oghenejoboh, Orugba [102] CP constitutes a sizable percentage (20 to 35 per cent) (Fig. 3) of the waste derived from tuber processing, which is abundantly generated in several localities where it is processed for food [103, 104]. The annual generation of CP waste across Cassava-producing locales poses not only a disposal issue but also increases environmental contamination and health risks.

According to Nyamekye, Ofosu [106], CPs dumped in landfills could be a stabiliser for expansive soil. CPA– the ash from CP solid waste (Fig. 4b), after burning and sieving, contains enough silica and alumina to be used as a pozzolan, according to literature gathered from previous works. The inorganic component of the ash is mainly potassium in crystalline form, which can be easily converted to potassium oxide (K_2O) by burning and calcining in the air at a reasonable temperature, and used as pozzolana [107]. Olonade and Mohammed [107] stated that CPA can be used alone or combined with cement as a cementitious material in road construction and rehabilitation. For laterite soil stabilised by CPA, Ogunbode, and Akanmu [108] reported a specific gravity of 3.04 and uncompacted and compacted bulk densities of 1394 kg/m^3 and 1649 kg/m^3, respectively. Studies have utilised CPA as an agent for stabilising expansive and lateritic soils. Similarly, laboratory studies have supported

Fig. 4 Heaps of **a** Cassava tubers. **b** Wastes (CP) from *Cassava* tubers

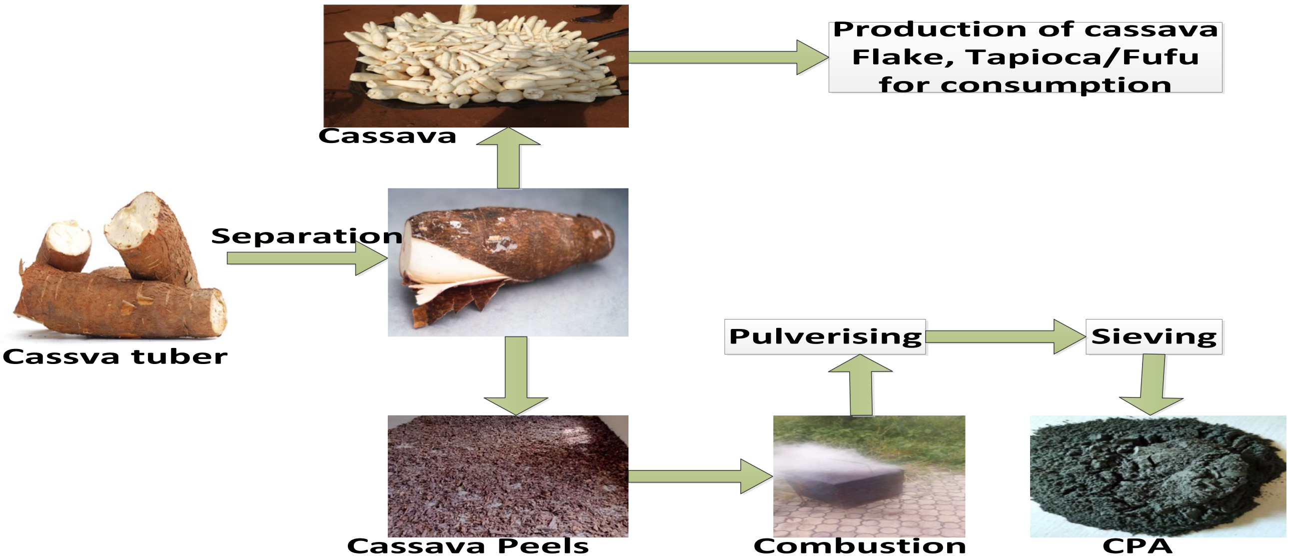


Fig. 5 CPA production sequence

the effectiveness of using CPA instead of cement to stabilise expansive soils for flexible pavement designs [106]. Nonetheless, published reports on MCSs, which form a significant part of Nigeria's Niger Delta soil with CPA, are scarce or limited compared to other agricultural wastes in terms of their engineering performance or basic stabilisation mechanisms. Furthermore, no studies have been identified on the macro- and microstructure, as well as the efficiency, of the CPA-mixed MCS. It is, therefore, essential to fully understand the physicochemical behaviour of this CPA-stabilised soil and its performance in field applications.

5.1 Production Sequence, Physical Properties, and Chemical Composition of CPA

CPA is generated by burning the CP waste. CP is often obtained from local Cassava processing industries and domestic waste dump locations. The CPs are cleaned to remove dirt and other contaminants, ensuring optimal combustion during the burning process. Figure 5 illustrates a likely sequence of events in producing CPA, as outlined in the literature reviewed.

To make the ash, the peel is first thoroughly dried in the sun and then burned for 90 min at between 500 and 850 °C [109, 110]. The resulting ashes were allowed to cool to obtain fine ash before being pulverised into a powder and sieved through a 75 µm BS sieve. The process, temperature, length of combustion, and the peel's cooling period all affect the characteristics of CPA.

CPA is physically a fine powder that exhibits a particle size distribution similar to that of conventional pozzolanic substances, such as cement. Thanks to its improved structure, which increases surface area, it displays exceptional catalytic activity for pozzolanic reactions. The specific gravity of CPA lies between 2.1 and 2.6, which is lower than that of Portland cement (3.15), thereby helping to reduce the overall weight of the mix. This fits perfectly for simple construction applications [111]. In addition, the LOI for CPA usually lies between 2 and 15 per cent, illustrating the presence of not entirely burned organic matter. Retaining constructed wetlands prefers low LOI values for sustained and superior stabilisation, since too much organic content can disrupt the cement-ash reactions [112]. The chemical and physical properties of CPA obtained from literature are shown in Table 4.

Ash made from CPs is extracted from solid waste dumped in landfills. The wastes are gathered from several Nigerian locations, including landfills, rubbish dumps, and Cassava processing factories. After that, they were burned at a temperature ranging from 500 to 850 °C, and to extract organic materials from the ashes, they were calcined in a muffle furnace at a higher heating rate of 100 C/min. Several researchers employed X-Ray Fluorescence (XRF) to determine the chemical composition of CP ashes. According to the researchers, more than 70 per cent of the oxides of CPA were silica (SiO_2, Al_2O_3, and Fe_2O_3), with a considerable proportion of CaO, SO_3, and LOI following closely, as shown in Table 5. According to different findings about the chemical compositions of CPA, as reported in Table 5, the predominant oxides were SiO_2, CaO, and Al_2O_3, with the highest CPA silicon dioxide content at 59.72 per cent [78], indicating that CPA contains pozzolanic properties. Based on Rasheed, Samson [117], Aladegboye, Oguntayo [29], Adetoye Olubunmi, Afolayan Taiye [75], etc., shown

Table 4 Chemical and physical properties of CPA compared to cement

Property	CPA	Cement	Remarks	References
SiO_2 (%)	60–70	20–25	CPA exhibits a significantly higher silica content, enhancing its pozzolanic activity, which contributes to improved concrete strength	[28, 30]
CaO (%)	10–15	60–65	Cement's higher calcium content is crucial for early strength gain, making it more suitable for rapid construction	[29, 113]
Al_2O_3 (%)	6–8	8–12	Both materials exhibit similar alumina content, which plays a role in cementitious properties	[3, 30]
Fe_2O_3 (%)	5–6	4–7	Similar iron oxide levels in CPA and cement contribute to the overall strength and density of the resulting concrete	[29, 114]
MgO (%)	0.5–2	3–5	CPA has a lower magnesium content, which can be beneficial in preventing efflorescence-related issues in concrete	[28, 115]
Specific Gravity	2.1–2.6	3.15	CPA's lower specific gravity is advantageous for lightweight construction, as it reduces the overall weight of the concrete	[28, 116]
LOI (%)	15–20	1–2	A higher LOI in CPA indicates the presence of organic matter, which can impact durability and performance	[31, 113]
Particle Size (μm)	30–50	15–25	CPA typically has a coarser particle size than cement, influencing the workability and strength of concrete mixtures	[37, 117]

Table 5 Chemical composition of CPA

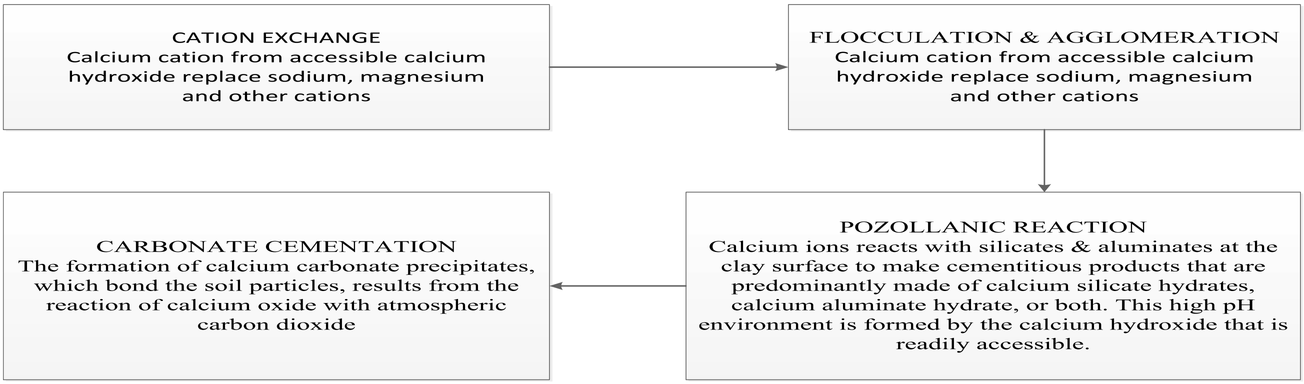
References	SiO_2	CaO	K_2O	Fe_2O_3	Al_2O_3	SO_3	MgO	Na_2O	LOI	$SiO_2+Fe_2O_3+Al_2O_3$ (%)
[73]	58.02	8.53	7.67	1.41	12.80	2.18	5.02	0.03	4.18	72.23
[78]	59.72	8.42	6.82	1.52	11.1	2.08	5.22	0.05	5.07	72.34
[120]	22.60	10.10	14.20	9.67	19.67	4.68	2.52	0.39	13.40	51.94
[121]	51.76	6.89	6.43	7.86	11.32	2.17	4.73	0.42	NA	70.94
[122]	34.67	11.64	NA	NA	NA	NA	NA	NA	NA	34.67
[30]	43.16	21.09		3.32	3.95	NA	3.40	NA	15.27	50.43
[75]	51.79	10.20	10.74	4.23	9.57	1.52	2.9	1.37	6.10	65.59
[110]	54.39	10.41	13.09	5.81	11.85	0.44	0.15	1.05	2.81	72.05
[118]	42.26	0.43	1.31	14.57	19.79	0.33	0.4	0.38	0.03	76.62
[123]	39.26	5.03	4.36	14.76	16.98	4.54	2.42	0.30	NA	71.00
[109]	55.93	9.85	NA	6.02	19.88	NA	3.2	0.98	12.5	81.83
[68]	56.81	6.94	4.64	7.21	7.74	4.05	3.93	0.43	6.78	71.76

in Table 5, which presents a summary of the chemical compositions of CPA by different works, all CPA samples except [75] would comply with [119]. Based on the table and the oxide compositions, they should be classified as pozzolans with class N. Table 5 lists the chemical makeup of CPA, classifying it as a pozzolana following ASTM [119].

Table 5 shows that approximately 60–70 per cent of the pozzolanic compounds within CPA are silicon dioxide. Such a high percentage enables it to combine with $Ca(OH)_2$ to yield stable calcium silicate hydrates (C-S–H) [116] that promote the binding abilities of the cement-CPA blend. The substantial SiO_2 content is vital for improving strength over time [30]. The variability in the chemical composition of CPA (due to the Cassava variety used, its growth conditions, and the temperature at which it is burned) can influence the extent of its pozzolanic reactions [124, 125]. Lower in concentration than silica, calcium oxide still offers self-cementing traits that improve cementitious reactions. Alumina's existence boosts the early strength growth rate when combined with cement and CPA [30]. Approximately 3–6 percent alumina (Al_2O_3) provides early-stage strength reinforcement and regulates the setting time of the mix, ensuring consistency in the reaction between rapid hydration and sustained strength development. [3, 30]. The contribution of Fe_2O_3 to the CPA-cement matrix is the suppression of void formation, the improvement of durability, and the delivery of additional compressive strength [29, 114].

5.2 Cement-CPA and Soil Mix Mechanism

When cement, CPA, and soil constituents are combined for stabilisation, the interaction mechanisms are crucial for enhancing the soil's mechanical characteristics and stability. Cement and CPA work together to improve the overall



CATION EXCHANGE
Calcium cation from accessible calcium hydroxide replace sodium, magnesium and other cations

FLOCCULATION & AGGLOMERATION
Calcium cation from accessible calcium hydroxide replace sodium, magnesium and other cations

POZOLLANIC REACTION
Calcium ions reacts with silicates & aluminates at the clay surface to make cementitious products that are predominantly made of calcium silicate hydrates, calcium aluminate hydrate, or both. This high pH environment is formed by the calcium hydroxide that is readily accessible.

CARBONATE CEMENTATION
The formation of calcium carbonate precipitates, which bond the soil particles, results from the reaction of calcium oxide with atmospheric carbon dioxide

Fig. 6 Soil stabilisation mechanism [56]

effectiveness of soil stabilisation. Various activities, including mineral actions (pozzolanic reaction), physical processes (flocculation and agglomeration), and chemical processes (cation exchange), contribute to these interaction mechanisms. A straightforward MCS stabilisation with cement and CPA is summarised in the mechanism process shown in Fig. 6. Figure 6 further illustrates these interactions at different phases. Cement releases calcium ions into the soil solution during hydration to exchange monovalent cations. Including divalent or trivalent ions in this exchange significantly reduces the thickness of the double layer, enhancing its stability and cohesiveness due to their higher charge density.

The process through which soil particles transition from a flat, parallel arrangement to a more asymmetrical position with edges and faces is known as flocculation. Pozzolanic reactions occur when cement and CPA combine, forming additional cementitious compounds. These substances fill spaces, bind soil particles, and enhance soil strength [126]. Figures 7a, b, and c illustrate this phenomenon.

6 Cement-CPA Blend on Engineering Properties of MCS.

A handful of studies have evaluated the use of CPA as a partial replacement material for cement. According to [127, 128], the environmental burden of vast waste disposal problems caused by CP solid waste deposition has been minimised using CPA. CPA may not possess many cementitious properties [28, 118]. Consequently, cement, which serves as an activator, is frequently applied. By raising the soil's pH, the cement encourages a pozzolanic reaction. Cementitious gels are created with the calcium in cement and the silica content of the CPA mix. Because CPA alters the engineering properties of the soil, researchers are investigating the use of CPA to modify troublesome soil. Table 6 details the effects of CPA and other stabilising agents on various soil characteristics.

CPA-stabilised soil has several advantageous engineering properties, making it a promising alternative to traditional materials [68]. The source of aluminosilicate materials or CPA precursors, the alkali-activated solutions utilised, the mixing techniques, the kind and number of aggregates, and the curing procedure are some of the variables that affect these characteristics [131–133]. The highly alkaline atmosphere will facilitate the hydrolysis of raw materials, resulting in improved engineering behaviour. However, if OH – ions are free to migrate about the matrix, the polymerisation process can be affected, and the strength might decrease [134].

6.1 Particle Size Distribution (PSD)

In the test for particle size analysis, the soil sample is shaken through a series of stacked sieves placed in descending order. The dirt was sent through the sieves after being cleaned and dried in an oven. A receiving pan is used in conjunction with the following sieve sizes: 4, 10, 16, 20, 40, 60, 100, and 200. The weights of the sieves were measured and recorded. The cleaned samples were oven-dried at temperatures exceeding 100 °C, placed in sieves, and vibrated electronically for 15 min. They were then weighed and recorded accordingly. The examination follows the standard procedure outlined in codes such as BS 1377-2 1990, AASTHO M145, or ASTM D3282.

A typical PSD graph is presented in Fig. 8. The curve indicates that the clay, silt, and sand occupy approximately 55.51, 43.87, and 0.62 per cent of the total soil (MDC) particles. According to AASHTO [135] Soil samples are categorised according to the percentage that passes through a 75 µm sieve. If less than 35 percent passes through, the soil is classified as granular material, deemed to be good or excellent subgrade soil. Conversely, if 35 per cent or more passes, it is categorised as silty-clay, regarded as fair to poor subgrade soil.

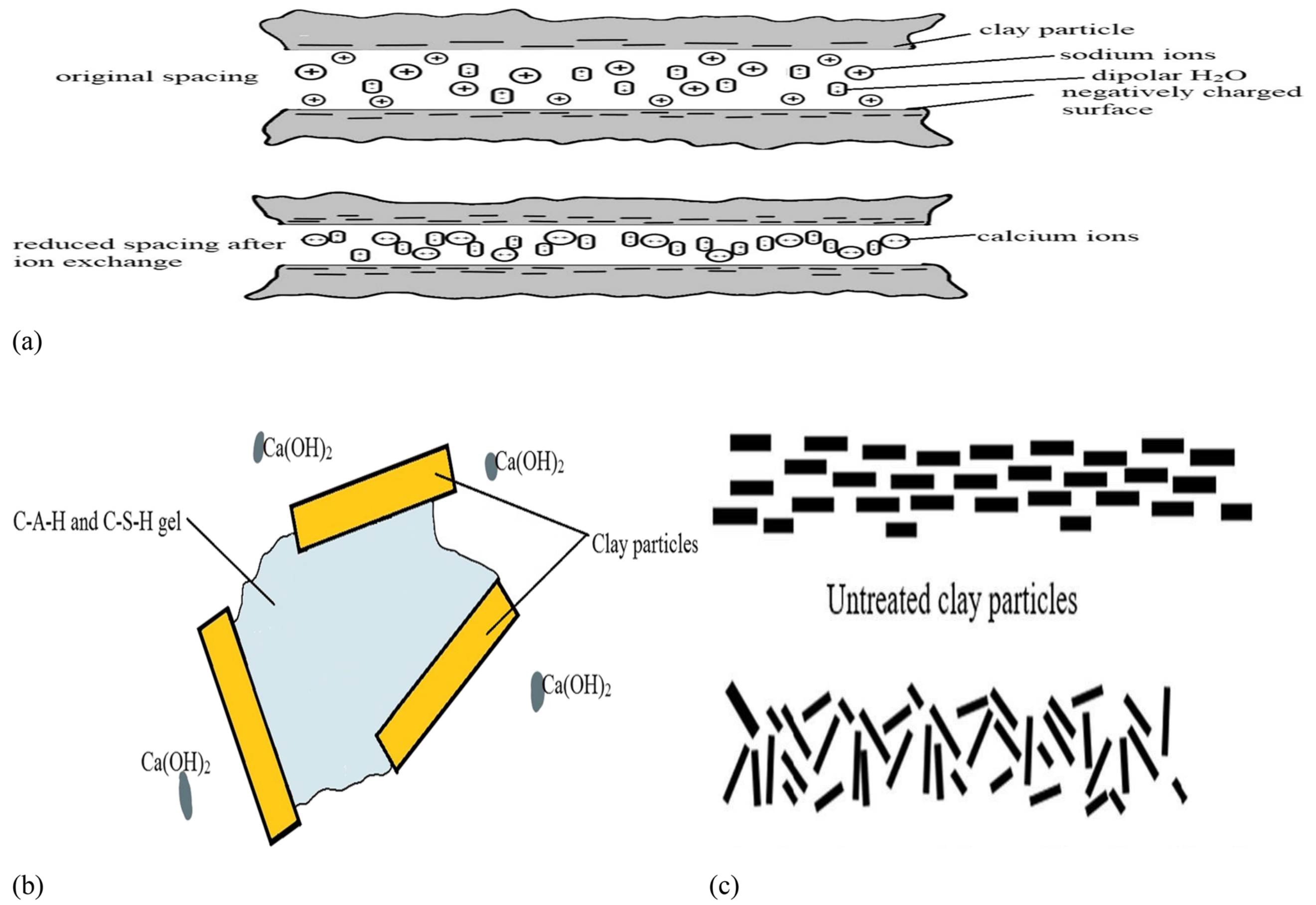


Fig. 7 Mechanism of interaction for soil stabilised by cement and CPA: **a** Cation exchange, **b** Pozzolanic reaction, and **c** Flocculation and agglomeration of clay particles [125]

6.2 Improved Soil Strength, Reduction in Permeability, and Enhancement Through Pozzolanic Reaction

By becoming hydrated, cement contributes to the soil's foundational strength by transforming most of its chemistry into calcium silicate hydrates (C–S–H), which bind the soil particles together. By adding CPA, the existing strength is further enhanced through secondary pozzolanic reactions; the silica in CPA interacts with the excess calcium hydroxide ($Ca(OH)_2$) formed during cement hydration. The development of new C–S–H further enriches the soil matrix, increasing its UCS and CBR values considerably [112].

The following simplified reaction can represent the role of CPA in the cement-CPA mix:

$$SiO_2(CPA) + Ca(OH)_2(Cement) + H_2O \rightarrow C - S - H\,(Calcium\ \ Silicate\ \ Hydrate)$$

In this equation:

SiO_2 represents the silica content in CPA, a key component in the pozzolanic reaction.
$Ca(OH)_2$ is calcium hydroxide, slaked lime, released during cement hydration.
H_2O is water, which acts as the medium for the reaction.
C-S–H (Calcium Silicate Hydrate) is the product of this reaction, which is responsible for the increased strength and stabilisation of the marine clay.

The response enhances the soil's robustness while increasing its resilience by reducing the availability of free lime, which is prone to leaching during rainy weather.

MCS is very porous before treatment due to its small particle size and poor water retention properties. The

Table 6 Results of findings on CPA-stabilised soil

References	Treated soil	Alteration Agent	Test Carried out	Research Findings	Remarks
[129]	Lateritic Soil	CPA + Lime	Atterberg limit, OMC, MDD, CBR, & UCS	Reduced OMC: 18.15–14.4%. Increased MDD: 1.68–1.92 mg/m^3, Soaked CBR: 8.18–19.1%, & UCS: 83.37–851.98 kN/m^2	They discovered that a CPA-lime admixture could improve the geotechnical properties of lateritic soils and suggested admixtures of 4% CPA + 2% lime and 6% CPA + 3% lime
[130]	Lateritic Soil	CPA + Steel Dust	Atterberg limit, OMC, MDD, CBR, & UCS	MDD, CBR, OMC, & UCS: 1938–2042 kg/m^3, 8–10%, 18.4–22.2%, 186–305 kN/m^2; 1935–2144 kg/m^3, 4–6%, 16.8–19.6%, 195–295 kN/m^2, & 2880–3020 kg/m^3, 5–8%, 11.8–15.1%, 159–230 kN/m^2, respectively	The CBR value reached its peak at 4% CPA. Every sample shows an increase in UCS with a rise in CPA. To determine the optimal percentage required for soil stabilisation, the amount of CPA should be increased above 8%
[106]	Indigenous Akwadum Soil	CPA + Quarry Dust	Atterberg limit, OMC, MDD, & CBR	Improved MDD: 2268- 2318 kg/m^3. Reduced OMC: 6.1–5.8%, CBR: 33–174%	The study demonstrated that CPA and QD are appropriate chemical additives for natural soil treatment
[68]	Lateritic Soil	CPA + Cement	Atterberg limit, OMC, MDD, CBR, & UCS	Decreased MDD: 1.8–1.7 g/cm^3. Increased OMC: 15.2–17%, CBR: 23–76% Unsoaked, & 15–84% Soaked, UCS: 21.09–35.95 kN/m^2	Stabilised lateritic soil with CPA will work best as fill material. Lateritic CPA, combined with 5% cement-stabilised admixed soil, will be ideal for base courses
[110]	Black cotton soil	CPA	Hydraulic conductivity, OMC, MDD, CBR, & UCS, Volumetric shrinkage strain,	OMC:10–18.8%, MDD: 1.65–1.89 kg/m^3, CBR, UCS: 120–368 kN/m^2,	Black cotton soil can successfully meet design standards for use as a liner or cover in an MSW facility at a CPA content of 16%, provided the moulding water content is between 9.6% and 15.3%, and the compacted soil has a compaction energy that is not less than the Standard Proctor

Optimum Moisture Content (OMC), Maximum Dry Density (MDD), and Unconfined Compressive Strength (UCS)

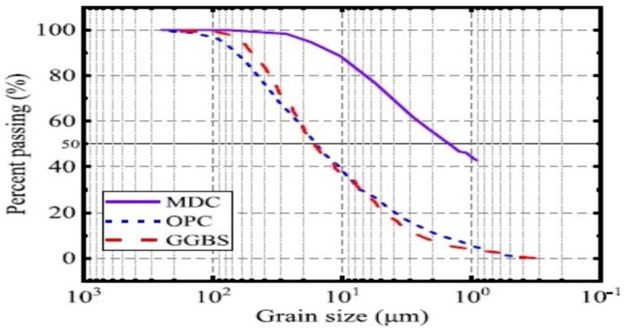


Fig. 8 Graph showing PSD curve of marine dredged clay (MDC) [7]

contribution of cement reduces soil permeability by tightening the soil fabric, with the additional benefit of sealing voids by pozzolanic reactions from the CPA. This leads to a reduction in the water infiltration rate, resulting in the lower vulnerability of the stabilised soil to hydraulic degradation. In the final architecture of the stabilised marine clay, a pozzolanic reaction occurs whenever there is particulate silica (SiO_2) and alumina (Al_2O_3) contained in the CPA reacting with the calcium hydroxide [$Ca(OH)_2$] generated during cement hydration [116]. Based on the moisture content of CPA, the cassava peel ash behaves as a pozzolan—a siliceous material that sets cementitious bonds in the presence of water and calcium hydroxide [116]. In response, the design of the stabilised clay changes drastically during its optimisation for strength and sustainability. The primary reaction responsible for the stabilisation can be described as:

$$SiO_2 + Ca(OH)_2 \rightarrow C-S-H \text{ (Calcium Silicate Hydrate)}$$

$$Al_2O_3 + Ca(OH)_2 \rightarrow C-S-H \text{ (Calcium Aluminate Hydrate)}$$

As a result of this interaction, both the newly formed calcium aluminate hydrate (C–A–H) and calcium silicate hydrate (C–S–H) can provide binding functionality that can propagate throughout the structure of the clay by being distributed within clusters of clay particles to form an overall denser and more cohesive architecture in which the strength of the clay will be increased gradually as it gains cohesiveness. Clay plasticity and compressibility would consequently be reduced as clay particles become more firmly embedded within the newly built matrix of hydration products [136].

Improved performance under compression can be attributed to how C–S–H and C–A–H can reduce the soil's plasticity and increase its overall stiffness. These cementitious compounds bind clay particles efficiently, drastically reducing soil degradation when stress is present. However, access to calcium hydroxide, with which to react with CPA, must be guaranteed for durability. In a geochemically active site with changing pH and moisture, the stability of the reaction products might also be attacked [3].

7 Comparison Between Cement and Cement-CPA Stabilised Soil

Cement has undoubtedly proven to be an effective soil stabiliser. However, cement alone is sometimes ineffective in stabilising soil, such as silt and clay. Additives can sometimes be incorporated into soil cement to enhance its effectiveness, reduce the amount of cement needed due to CO_2 emission concerns, reduce construction cost, and help stabilise soil that does not respond to cement alone [63]. Other issues, such as cracking and carbonation, are included and will have significant adverse effects if ignored [44]. Due to these factors, as well as environmental and economic considerations, alternative materials like CPA are being investigated as potential replacements. For CPA to effectively replace cement in soil stabilisation, specific criteria must be fulfilled to ascertain its effectiveness. Table 7 presents an analysis of cement and cement-CPA, comparing the engineering parameters of cement alone to those of cement–CPA–stabilised soil.

Table 6 presents the results of previous studies on soil stabilised with CPA, cement, and lime, confirming these possibilities. Results obtained by [68, 106, 109, 128, 129] on the engineering properties after stabilising with CPA alone and in conjunction with other materials confirm that CPA can be a suitable replacement for not just cement but also other materials.

8 Microstructure Assessment of CPA Stabilised Soil

The divalent cations in the soil matrix and the behaviour of the soil characteristics following treatment are typically examined to evaluate the microstructure of CPA-stabilised soil. According to pertinent literature publications, the following are some frequently employed techniques for microstructural analysis of CPA stabilised soil:

Table 7 Properties to consider in cement and cement-CPA stabilisation

Criteria	Cement stabilisation	Cement + CPA stabilisation
Soil strength (e.g., CBR, UCS)	High initial strength gain	Slightly lower early strength, which improves over time
Durability	High, especially in wet conditions	Good, but slightly less resistant to prolonged saturation
Pozzolanic activity	Cement is the primary binder	CPA acts as a supplementary pozzolan, aiding long-term strength
Setting time	Faster	May slightly increase the setting time
Environmental impact	High CO_2 emissions (cement production)	Reduced CO_2 footprint due to partial cement replacement
Cost	Higher due to cement price	Lower—CPA is a low-cost agro-waste byproduct
Sustainability	Less sustainable	More sustainable and eco-friendly
Availability	Widely available	CPA availability depends on cassava farming regions
Waste utilisation	No direct impact	Promotes reuse of CPs
Long-term performance	Excellent if maintained	Good, but still under research for long-term reliability

8.1 X-Ray Diffraction (XRD)

To identify the mineral phases that are present in the soil and ascertain their relative proportions, XRD is a potent technique for analysing the crystal structure of CPA-stabilised soil, offering crucial information about the composition, structure, and properties of the material [130]. A tiny portion of the stabilised soil sample is ground into powder and put in a holder for XRD examination. The holder is then fixed on a diffractometer, producing an X-ray beam focused on the powdered material. The atoms in the sample react to the X-rays, creating a diffraction pattern that may be used to determine the crystal structure of the various soil types. The different mineral phases present in the soil sample, including calcium-silicate hydrates, zeolites, and aluminosilicate gel, can be identified using XRD.

According to Baenla, Mbah [119], the mineralogical composition of CPA (Fig. 9) includes the following: Anatase [TiO_2:PDF 86-1157], magnesium oxide [MgO_2: PDF 76-1363], calcite [$CaCO_3$: PDF 83-0578], quartz [SiO_2: PDF 86-1629], beusite calcian [(Mn_2+, Fe+2, Ca)(PO_4)2: PDF 16-1353], potassium phosphate [a-K_2P_3O10:PDF 45-0209], and beusite calcian [(Mn_2+, Fe+2, Ca)$(PO_4)_2$: PDF 86-1653], as well as potassium phosphate [a-$K_2P_3O_{10}$:PDF 45-0209]. In addition, a broad hump between 14 and 38^0 (2 h) represents the amorphous percentage (Rc) in CA that is required for geopolymerisation. The leaching test result is supported by the fact that the area in C_A which indicates a broad hump, is more significant than the area in Ma. Furthermore, the crystalline phases in C_A's chemical composition exhibit a small presence of oxides such as Al_2O_3 and Fe_2O_3, which may indicate that these oxides exist in the reactive phase of the material.

8.2 Scanning Electron Microscopy (SEM)

The microstructure of CPA-stabilised soil can be examined using SEM, which provides crucial insights into the soil's composition, morphology, and properties. It offers high-resolution photos of the soil materials' sizes, shapes, textures, and surfaces to distinguish between the matrix stages. A part of the powdered soil sample stabilised with CPA is placed on a conductive substrate for SEM examination. The sample is covered with a thin coating of conductive material, such as carbon or gold, to enhance conductivity and avoid charging during imaging [137]. Next, a high-energy electron beam is focused onto the sample's surface using the SEM. The signals generated when electrons in the sample interact with the atoms can produce an image of the surface. The pictures acquired can reveal details about the many stages in the soil, including their size, shape, and distribution.

The soil treated with 16 per cent CPA and the natural sample's SEM micrographs of CPA are shown in Fig. 10a and b by Adeyemo, Yunusa [109]. Figure 10a, a micrograph of the natural soil, displays a surface structure with inter-grain holes and networks of cracks caused by desiccation and particle rearrangement. It also shows a micrograph of a specimen treated with the ideal 16 per cent CPA. This demonstrates how the interaction between the soil and CPA modifies the material's morphology by enhancing particle bonding and reducing inter-grain porosity. When 16 per cent CPA was added to the native soil, improvements in every design parameter under study may have resulted from these morphological alterations. Ion exchange, particle aggregation, pozzolanic activities, and wholly occupied inter-grain pores are the causes of these increases [138]. Baenla, Mbah [119], have reported similar findings.

8.3 Thermogravimetric Analysis (TGA)

The TGA technique examines the thermal stability and degradation behaviour of various materials, such as soil, offering valuable insights into the material's performance and longevity under varying temperature circumstances. When heated under controlled circumstances, the material's weight loss and thermal stability can be ascertained using

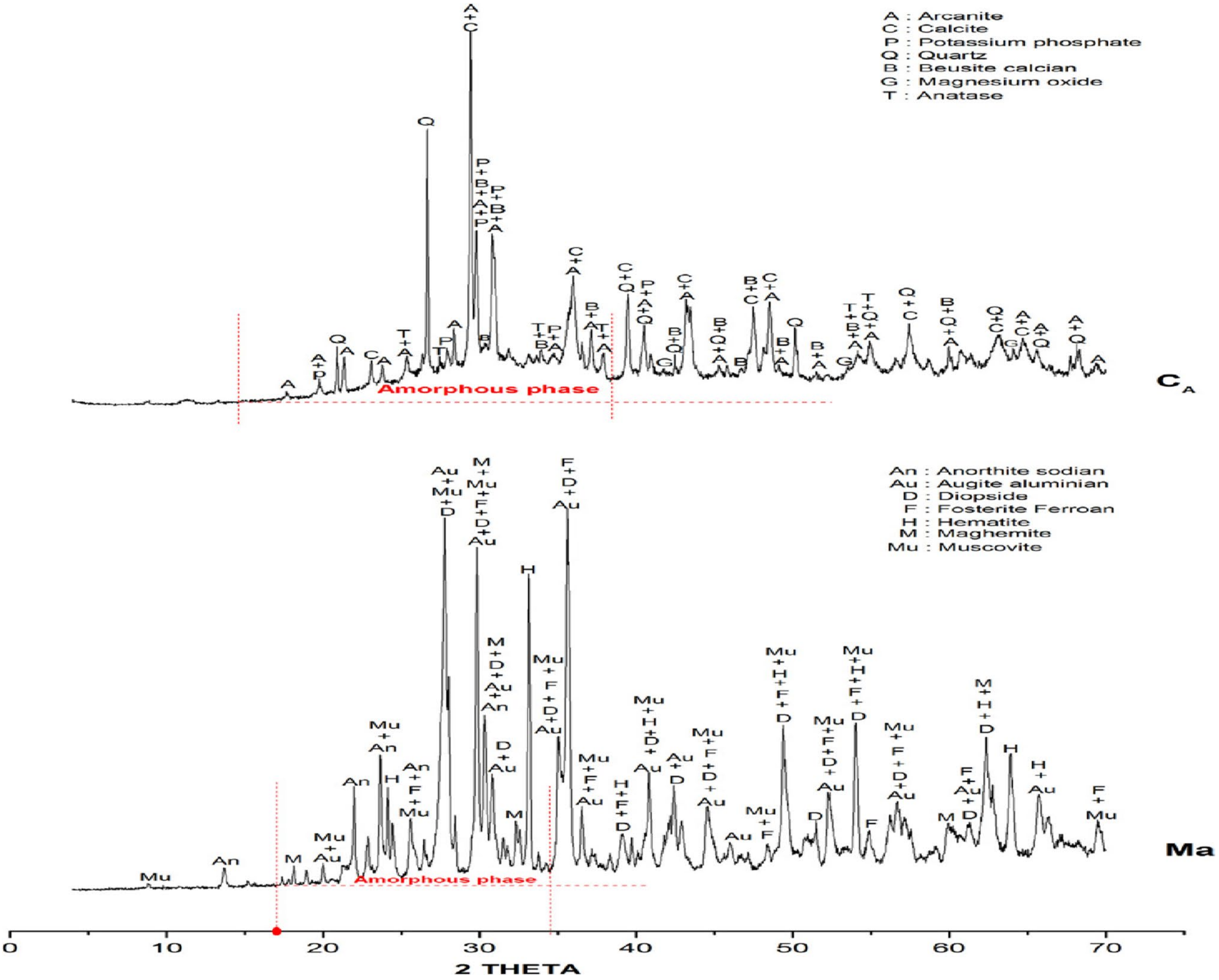


Fig. 9 X-Ray diffractograms of CPA & volcanic ash [119]

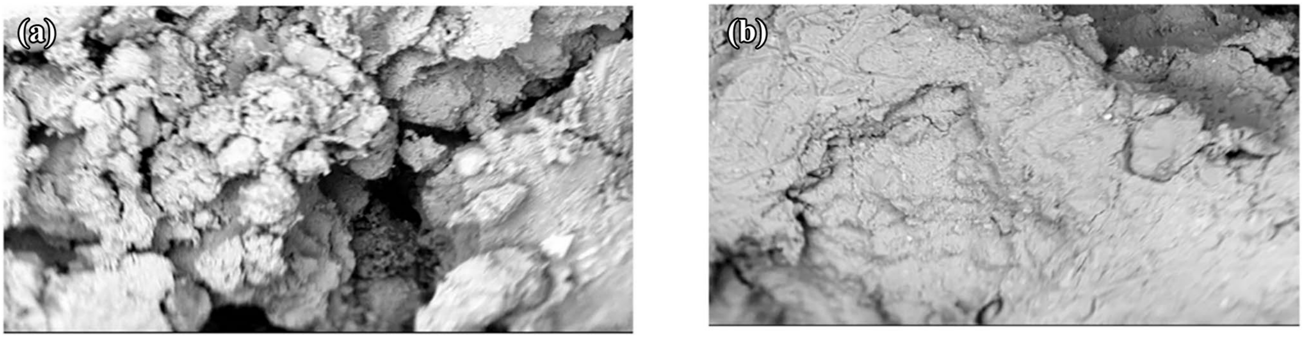


Fig. 10 SEM micrograph at 320 magnification **a** natural soil **b** admixed soil with a 16% CPA blend [109]

TGA [139, 140]. A tiny portion of the soil sample is dried and crushed into a fine powder before being subjected to TGA analysis of the CPA-stabilised soil sample. After that, the powder is put inside a TGA apparatus, which heats the sample at a regulated rate and records the weight loss as the material breaks down and releases gases [141]. TGA is a valuable tool for assessing the thermal stability of the various phases found in the stabilised soil, including zeolites, calcium silicate hydrates, and alumina-silicate gel. Information regarding the resilience and functionality of the soil at varying temperatures can be gleaned from the weight loss and thermal stability of these phases. Moreover, this technique can assess how well different admixtures and curing techniques alter the soil's thermal stability [142, 143].

8.4 Fourier Transform Infrared Spectroscopy (FTIR)

Soil particles can also be subjected to chemical composition analysis using FTIR. FTIR can be used to identify the functional groups and chemical bonds present in the material, providing information about its composition, structure, and attributes [144]. A small portion of the soil sample is ground into a fine powder and combined with a matrix material for FTIR soil analysis. After that, the mixture is compressed into a thin pellet and put into the FTIR spectrometer. The spectrometer produces an infrared light beam and directs it at the material. A spectrum that may be utilised to distinguish between the various components of the material is made when the infrared light interacts with the functional groups and chemical bonds in the sample [145]. FTIR can distinguish phases in stabilised soil, including zeolites, calcium silicate hydrates, and alumina-silicate gel.

9 Identified Gaps in the Literature

Cement-CPA soil stabilisation is a relatively new and evolving research area, especially when integrated with various agro-waste materials. Although considerable advancements have been made, specific gaps in the literature remain to be explored. Below are some potential gaps identified in the reviewed literature:

Limited Studies: The available literature on cement-CPA stabilised soil is notably less abundant compared to other materials that have been extensively researched. Consequently, additional thorough research is necessary prior to any field application.

Standardisation: Currently, no standardised mix design or testing method exists for CPA-stabilised soil, which hinders the comparison of results across various studies. Additional research is required to establish standardised procedures and guidelines for production and testing.

Durability: While the CPA-cement mix demonstrates encouraging mechanical properties, there is limited research on its durability potential. Additional studies are needed to evaluate the performance of cement-CPA stabilised soil over several years or even decades.

Environmental impact: Cement-CPA stabilised soil is advocated as a more eco-friendly option than traditional cement; however, limited research exists on the ecological effects of CPA production and application. Additional studies are essential to assess the carbon footprint and other environmental implications of cement-CPA stabilised soil in relation to conventional stabilisers.

Industrial-scale production: Although laboratory-scale studies have been conducted on CPA-stabilised soil, there has been limited investigation into its production and efficacy on an industrial scale. Additional research is needed to explore how CPA-stabilised soil can be manufactured and applied in large-scale infrastructure projects.

Field applications: While laboratory tests have shown that CPA can stabilise weak soil, confirmed field applications are presently lacking. This lack may stem from the previously mentioned gaps. It is thought that addressing these gaps could enable practical field applications.

10 Conclusion

This review assessed the technical implications of using a cement-CPA mix to stabilise MCS. Given its significant potential as a cost-effective engineering solution, particularly in regions where cassava cultivation is prevalent, this practice deserves greater attention and promotion. CPA contributes to advancing a global circular economy by transforming agricultural waste into building materials, aligning economic development with environmental protection [116]. However, its application also requires further research to optimise usage and account for performance variability across different soil types and environmental conditions [115].

Despite these challenges, the benefits of CPA as a soil stabiliser make it an appealing option. CPA offers a compelling alternative for regions seeking to balance infrastructure development, economic efficiency, and environmental sustainability. Yet, the literature highlights practical challenges, including variability in ash quality, inconsistencies in mix design and application methods, and difficulties achieving consistent results under different geographical and environmental conditions. Large-scale implementation remains limited, and concerns persist regarding the long-term durability of CPA-based hydration products, particularly in highly acidic or alkaline microenvironments.

To overcome these issues, region-specific experimental studies should be conducted to determine optimal mix ratios, supported by long-term field trials under diverse conditions. Pilot programs could also help assess CPA's real-world feasibility and performance in infrastructure projects. A key issue is the lack of standardised mix design and testing protocols. Studies have reported significant variations in CPA dosage and distribution patterns, which can result in localised weaknesses if proper on-site mixing techniques are not applied [28]. Therefore, improving on-site mixing practices ensures consistent soil stabilisation outcomes.

Additionally, more comprehensive assessments of CPA's environmental footprint are needed to solidify its potential as a low-carbon technology. Addressing these research gaps will provide a foundation for developing region-specific guidelines and ensure the development of reliable, scalable applications. Beyond initial stabilisation outcomes, future studies should also investigate how ambient factors, such as temperature, moisture, and pH, affect the long-term durability of CPA-stabilised soils. Cement–CPA mixtures could redefine sustainable soil stabilisation by overcoming these barriers, minimising reliance on more environmentally damaging methods.

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Data availability No data was used for the research described in the article.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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