Viability of calcinated wastepaper sludge ash geopolymer in the treatment of road pavement subgrade materials

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ABSTRACT

Problematic ground conditions constituted by weak or expansive clays are commonly encountered in construction projects and require some form of chemical treatment such as lime and cement to re-engineer their performance. However, in the light of the adverse effects of these traditional additives on the climate, alternative eco-friendlier materials are now sourced. In the current study, the viability of calcinated wastepaper sludge ash geopolymer in enhancing the engineering behaviour of a problematic site condition is evaluated. A highly expansive clay (HEC) constituted with a blend of kaolinite and bentonite clays is treated with calcinated wastepaper sludge ash (CPSA) geopolymer. Activation of the precursor is actualised at room temperature using a combination of NaOH and Na_2SiO_3 at various activator to soil + binder ratios (AL/P), and molarity (M). The mechanical, microstructural, and mineralogical characteristics of the treated clay were investigated through unconfined compressive strength (UCS), swell, water absorption, SEM, and EDX analysis. The performance of the stabilised samples was then compared with the requirements for road subgrade and subbase materials and that of OPC and lime-GGBS treatment. The results showed that CPSA-geopolymer enhanced the engineering properties of the treated clay better than traditional binders (OPC and lime-GGBS). UCS improvement of 220 % was observed in the CPSA-stabilised soil over that of OPC-treated ones, while the swell potential and water absorption were drastically reduced by over 95 and 97 % respectively after 28-day soaking. The SEM and EDX results showed improved crystallisation of earth-metal-based cementitious flakes (NASH) with increasing CPSA, molarity, and AL/P ratios, which enhanced the inter-particle bonds with simultaneous reduction in porosity. The modified characteristics of the stabilised materials meet the requirements for pavement subgrades. Further, the equivalent carbon emission (CO_2-e) from the stabilised materials were also evaluated and compared with that of traditional binders. The results also showed that CPSA-geopolymer had lower CO_2-e at higher subgrade strengths than OPC, making it more eco-friendly. Therefore, wastepaper sludge, a common landfill waste from paper recycling is a viable geopolymer precursor that could be utilised in enhancing the engineering properties of subgrade and sub-base materials for road and foundation construction.

Introduction

Expansive clays are commonly encountered in everyday construction projects across different parts of the world. These clays are known for extreme shrink-swell behaviour with corresponding moisture variations. The effect of this phenomenon on overlaying light-weight structures is an increased vulnerability to additional stresses, premature cracking, and subsequent failure due to differential settlement or heaving upon water ingress. In earthquake-prone regions, the situation could be worsened by rapid loss of shear strength due to increased pore pressures following ground motions and eventual reduction in the effective stress.

Traditionally, these soils are engineered to improve their strength and reduce deformation upon loading using chemical additives of which ordinary Portland cement (OPC) and lime are well established solutions in this regard [68,108,2,16,100,91,52,109]. Studies have shown that weak soils and subgrade materials after treating with OPC, and lime had higher compressive strengths and enhanced durability [69,46,86,11]. Increased CBR and reduced swell potential after 3 to 28 days curing with results that meet specifications useful for highway subgrades and subbase materials under various site conditions have been reported in various studies [76,77,47,67]. Several microstructural and mineralogical investigations via energy dispersive spectrometric analysis (EDS), X-ray diffraction spectrometry (XRD), and X-ray florescence (XRF)

Nomenclature

Abbreviation

CPSA	Calcinated wastepaper sludge ash
OPC	Ordinary Portland Cement
GGBS	Ground granulated blast furnace slag
PFA	Pulverised fuel ash
N-A-S-H	Sodium-aluminate-silicate hydrate
C-A-S-H	Calcium-aluminate-silicate-hydrate
K-A-S-H	Potassium-aluminate-silicate hydrate
C-S-H	Calcium-silicate-hydrate
AL/P	Activator liquid-to-soil-binder ratio
EDX	Energy dispersive spectrometry
XRD	X-ray diffraction spectrometry
XRF	X-ray florescence
HEC	Highly expansive clay
UCS	Unconfined compressive strength
M	Molarity
CEM1	General purpose cement
PL	Plastic limit
LL	Liquid limit
PI	Plasticity index
OAC	Optimum activator content

attribute this strength improvement to a multistep process beginning with re-orientation, re-arrangement of clay platelets following cation exchange from increased pH of the pore-fluid, and subsequent cementation of clay platelets due to these additives. This encourages rapid flocculation and agglomeration of clay particles with reduction in the free water within the soil mass and subsequent strength gain due to the formation of C-S-H gels and flakes which coat the flat surfaces of the clay particles leading to strong binding forces within the soil [29,57].

However, the use of OPC and lime in soil stabilisation contributes to the rise in carbon emissions and higher energy consumption through the calcination of limestone ($CaCO_3$) at high temperatures and the huge dependance on fossil fuels, both of which are detrimental to the environment owing to 561–900 kg of CO_2 per tonne of cement produced [38,66]. Consequently, there is an urgent need to change the narrative through adaptation to more eco-friendly techniques in stabilisation. To this end, laboratory synthesised inorganic polymers commonly referred to as geopolymers have been explored in several studies as a greener route [32,26,74,85,72,61,59]. Geopolymerisation, involving the activation and polymerisation of Al and Si ions from alumina and silica-rich industrial by-products mostly within a strong alkali medium such as hydroxides and silicates like NaOH, KOH, Na_2SiO_3, K_2SiO_3 and other combinations have been successfully explored for the treatment of weak clays [107,30,4,65,60,62]. The multi-step geopolymerisation process involving the sequential steps of dissociation, relocation and reorientation, gelation, condensation, polymerisation, and hardening, culminates in the formation of oligomers which link up in repeated units of -Si-O-Al-O-, Si-O-Al-O-Si-O-, or -Si-O-Al-O-Si-O-Si- origin referred to as polysialate, polysialate-siloxo, and polysialate-disilioxo respectively. These oligomers are further crosslinked into 3-dimensional mineral edifices and can be represented by the chemical formula below.

$$M_X \left[-(Si-O_2)_Y -Al-O \right] . zH_2O$$
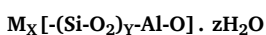
In the above formula, x is the degree of polymerisation, y is an integer which could be defined as 1, 2, 3 and so on, representing the Si/Al molar ratio, and M is the alkali [25,107]. Depending on the chemical characteristics of the by-product material, the strong bonds developed by the sodium-aluminate-silicate-hydrate (N-A-S-H) or potassium-aluminate-silicate-hydrate (K-A-S-H) gel products, through the semi-

crystalline grid of Al-Si chains in the presence of strong cations within the alkali solution, interlocks the clay particles and results in reduced pores, increased dry density and overall enhancement of the shear strength characteristics of the treated soils [103,3,5,102,39,63]. Geopolymers offer significant deviations from traditional methods, one of which is the possibility of strength improvement in the absence of a calcium-based activator due to the strong covalent bonds from crosslinking AlO_4 and SiO_4 tetrahedra. The strength improvement is the outcome of carefully controlling critical parameters of the geopolymer development process such as the quality of the precursor, alkali activator liquid to binder ratio, molarity of the solution, and curing temperatures [50,78,35,72].

The effects of the quality of the precursor on the performance of the ensuing geopolymer cannot be over emphasised [78]. It is common to use low calcium precursors for geopolymers. However, some authors have reported good result in geopolymers with precipitation of additional hydration products such as calcium-aluminate-silicate-hydrate (C-A-S-H) and calcium-silicate-hydrate (C-S-H), simultaneously with N-A-S-H or K-A-S-H gels due to the presence of calcium component in the precursor [23,79,44,3,70]. Therefore, the development of geopolymers from blended by-products continues to be an interesting exploration due to the variation of the Si/Al and Si/Na ratios which are known to impact on the strength of the bonds of the ensuing geopolymer [72]. As expected, higher Si ratios will lead to more Si-O-Si oligomers which are stronger [101]. However, the quality of the resulting precursor could be adversely affected during blending. For instance, the study by Liu [56] reported a decline in strength of alkali activated GGBS paste when incinerator flyash was incorporated into the binder mix due to its low alumina and silica content which lowered the quality of the precursor. A higher precursor to dry-soil ratio is also likely to enhance the effectiveness of the geopolymer treatment due to the increased availability of the dissociated Al and Si ions, provided other mix components are adequately controlled.

In addition, studies have highlighted the advantage of elevated initial curing temperatures on the performance of geopolymers and geopolymer-stabilised soils. Elevated temperature has the advantage of increased rate of dissociation and contributes to expediting strength gain in stabilised soils. A study by Xiea and Xi, [103] have reported an optimum curing temperature of 55 °C for strength gain using flyash geopolymer in a concrete mix, while the study by Samadi [84] has also reported strength gain of up to 8000psi for flyash geopolymer paste cured at 60 °C. However, significant strength increment has also been reported for geopolymers and geopolymer stabilised soils cured at room temperature [71,33,99,98,48]. Strength development in roomtemperature cured geopolymer treated soils is greatly influenced by the molarity of the activator liquid, the type of precursor or by-product material utilised, as well as the activator liquid to soil-binder ratio (AL/P) amongst other factors. A higher AL/P ratio increases the alkali to silicate/aluminate ratios as expected. It also increases the pH of the soilbinder medium, encourages the release of the Al and Si ions from the precursor and fast-tracks realignment and eventual polymerisation of released species. Furthermore, the molarity of the alkaline solution is a major contributing factor to the performance of geopolymers. Higher molarity of the alkaline solution results in higher density and a more compact microstructure due to reduced pores within geopolymer pastes [82,42]. This can also be linked to accelerated reaction from enhanced dissolution of precursor particles. A study by Cristelo et al. [24] on the effect of the molarity of alkaline solution on the strength of PFAgeopolymer stabilised soil samples reported that 12.5 M NaOH solution proved better than 15 M while an optimum molarity of 14 M has been reported for geopolymer concrete developed from natural volcanic ash [43].

Undoubtedly, the use of GGBS and PFA as precursors for geopolymerisation has received immense consideration due to their availability and ease to use as these materials are already processed and standardised. However, the current forecast shows a possible decline in

the availability of PFA and GGBS in the UK as shown in Fig. 1a and b. The shortage, which is linked directly to the decommissioning of coal-powered stations and a possible drop in production in the steel manufacturing industry necessitates the need to source alternative by-products materials.

One such alternative is wastepaper sludge, a by-product material from the recycling of wastepaper which has continued to contribute to landfill wastes, and as such any useful application would be advantageous in numerous ways. Currently, it is known that the quality of cellulose fibre from recycled paper continues to decrease after each recycling process and results in unusable paper sludge after 5 to 8 cycles which then ends up in landfills. Fig. 2 is a schematic diagram showing a typical sludge production process. Recent studies have investigated the use of CPSA for concretes and mortars while others have investigated the possibility of using CPSA for soil stabilisation [105,80,64,51,110,36,34]. Also, the performance of CPSA-geopolymer paste has been investigated [104,88]. However, very limited information is available on the development of CPSA-geopolymers for suppressing swell and improving the strength of expansive clays. Critical information such the influence of CPSA-geopolymers treatment on the consistency limits and compaction characteristic of treated expansive clays are currently scarce.

This study is focused on the utilisation of CPSA as a viable precursor for the development of geopolymer, as a sustainable alternative to OPC and lime in soil stabilisation. The CPSA is utilised in developing a geopolymer binder for the treatment of a highly expansive clay soil. The effects of varying molarity and alkali activator liquid ratios on the performance of the treated clay are explored with a view to finding optimum mix design for stabilisation of such highly plastic clays. The results of the experimental tests on the mechanical and microstructural performance of expansive clay samples treated with different dose of CPSA-geopolymers are investigated and compared with OPC-treated samples to explore their application as possible sustainable road subgrade, sub-base, and foundation earth materials. The study is a step towards exploring new gainful applications of wastepaper sludge to cut down on landfill wastes and the release of CO_2 through the calcination of limestone thus, providing an alternative eco-friendlier binder for the construction of greener infrastructural systems.

Materials and methods

Materials

The soil used in this study is a high plasticity clay artificially constituted by mixing kaolin and sodium bentonite in the ratio of 1:1. The choice of this type of soil was to create a problematic field condition encountered in difficult terrains to ascertain the effectiveness of the treatment in such condition. Since bentonite is highly expansive, it was pertinent to mix it with kaolin to reduce the expansive tendency to a more practical range. A 1:1 ratio proves to be a good ratio and provides extremely problematic behaviour, covering a wide range of highly plastic clays in the UK. Earlier research works have also utilised similar combinations to simulate problematic behaviours of clays [1,10]. The kaolin and sodium bentonite were supplied by Portclays Ltd, UK. The cement used is a general-purpose Portland cement (CEM1) manufactured to BS EN 197-1 by Dragon Alfa Cement Ltd while the Paper sludge was obtained from Palm Paper Ltd, UK as unrecyclable wastepaper sludge containing 30 % moisture. Preliminary characterisation shows that the sludge contains approximately 80 % calcium carbonate and 20 % cellulose. Sodium hydroxide of 98 % purity was purchased in pellet form from Fisher Chemical Ltd, UK while the sodium silicate solution was purchased from Inoxia Ltd, UK.

The chemical composition of the CPSA was determined by x-ray florescence (XRF) analysis and is given in Table 1 below. Fig. 3 compares the major chemical constituents of CPSA with that of OPC.

Methods

Preparation of CPSA and geopolymer

The wastepaper sludge was first air-dried for 7 days in plastic trays and later subjected to oven-drying in small quantities for 4 days. Samples of the sludge were weighed at 24-hours intervals during oven-drying, to monitor changes in moisture content to determine the fully dried condition of the sludge. The paper sludge was deemed to be completely dried following no change in weight after 48-hours of drying at 80 °C. Thereafter, the bone-dried wastepaper sludge was then put in a non-sterile crucible and incinerated under atmospheric conditions at 750 °C in an 800 W Carbolite electric furnace for 2-hours. The 2-hour duration of incineration was adopted following previous studies by [73,14]. A 60 % average mass-loss of the bone-dried sludge was observed after incineration. The incinerated sludge was then ground into fine powder using a HB-1580T 800 W hand blender as shown in Fig. 4.

A fixed weight of the incinerated sludge was blended each time for a duration of 15 min to produce the ash as shown in Fig. 4d. The alkaline activator solution to be used was prepared at various molarities by adding NaOH pellets in distilled water at room temperature to achieve the desired molarity. Upon addition of the NaOH pellets, enormous heat was generated as expected due to the exothermic reaction upon dissolution of the NaOH pellets in water with the temperature of the solution rising to 90 °C. To extract any toxic smell and vapour generated from the preparation of the alkaline solution, the mixture was constituted in a fume cupboard as shown in Fig. 4f.

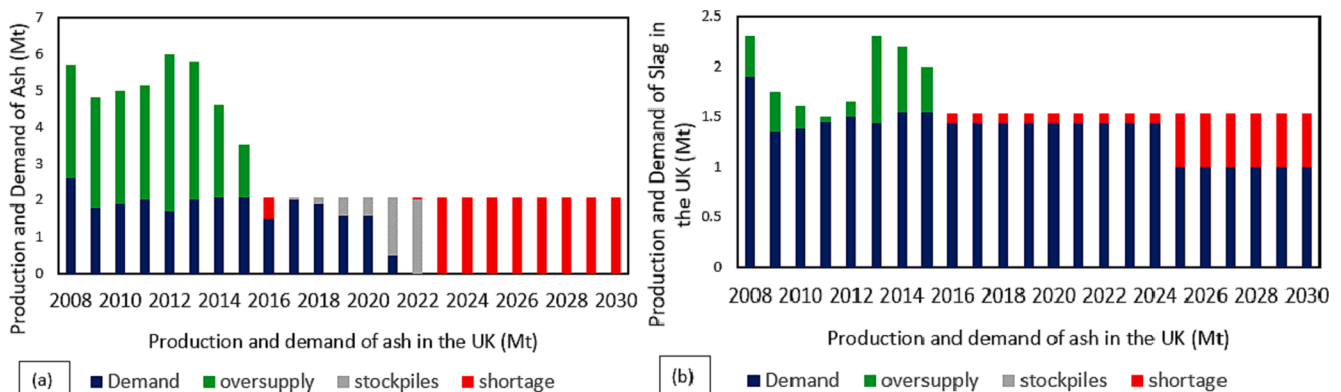Earlier studies have reported increased strength and denser

Fig. 1. Projection for future availability of PFA and GGBS. (a) Availability of PFA (b) availability of GGBS [9] (UK Government Department of Business, Energy, and Industrial Strategy)).
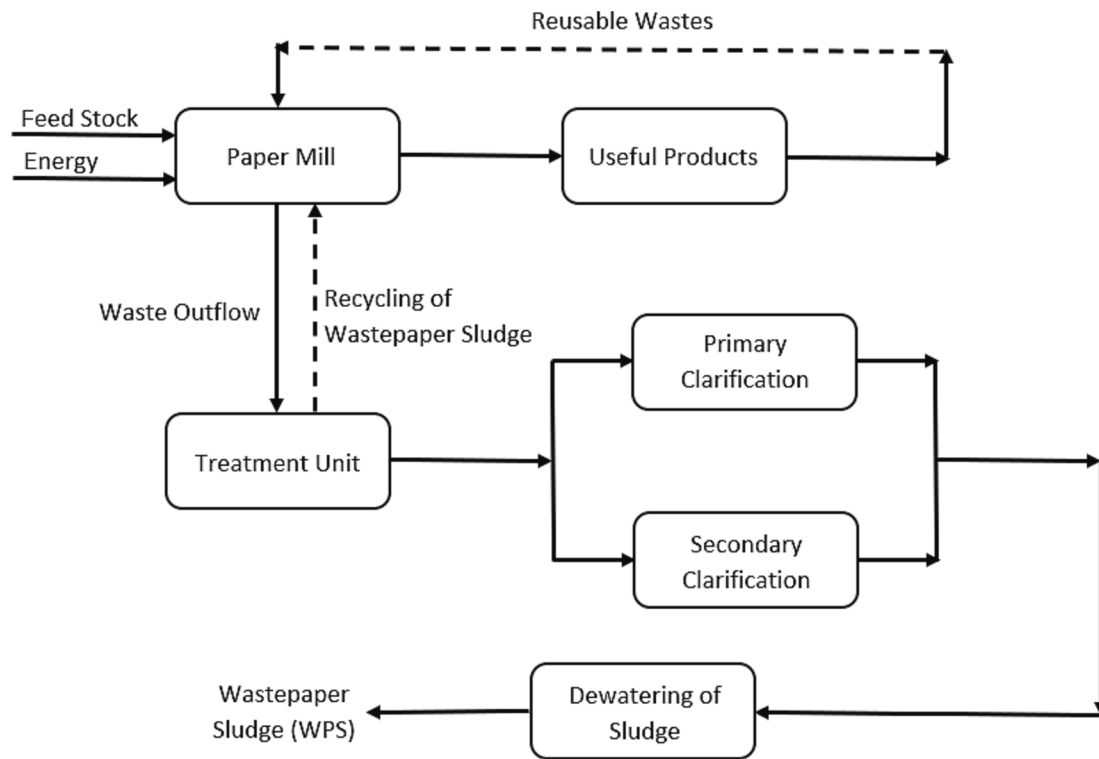
Fig. 2. Process of wastepaper sludge generation.

Table 1
Oxide composition of CPSA.

Material	Oxide Percentage (%)											
	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	P_2O_5	SO_3	MnO	L.O. I
CPSA	16.4	0.48	6.8	0.77	72.2	1.57	0.16	0.34	0.29	0.41	0.1	32.8

geopolymer-soil matrix with higher NaOH molarity. An optimum molarity of 12–12.5 has been reported in various studies [24] and other researchers have highlighted the fact that a higher concentration of hydroxyl ions from higher molarity enhances performance. Therefore, 3 different molarities of 8, 12, and 15 M NaOH were considered in the preparation of the alkaline solution. The NaOH solution was allowed to cool to a temperature of 25 °C before mixing with a predetermined weight of sodium silicate. Upon mixing both solutions, the temperature of the mixture slightly increased again to about 40 °C. The ratio of sodium silicate to sodium hydroxide was kept constant at 70:30 which has been reported as optimum in several studies [48,46]. The physical properties of the sodium silicate used are shown in Table 2 below.

Sample preparation

The expansive soil was constituted by mixing dry kaolin (K) with an equal mass of dry bentonite(B). The soil was thoroughly mixed using an electric-powered Horbot mixer for 5 min before treatment with the geopolymer was carried out. Prior to treatment, the K-B system was initially subjected to compaction test in line with BS EN 13286-2:2010 [18] to determine the optimum moisture content (OMC) and maximum dry density (MDD) of the soil. Also, Atterberg limit tests were conducted in line with BS EN ISO 17892-12:2018 + A1 [19] to ascertain the plastic limit (PL), liquid limit (LL), and plasticity index (PI) of the soil prior to treatment. The Atterberg limits and compaction characteristics of the synthesized K-B clay system are presented in Table 3.

The CPSA-geopolymer treated samples were prepared by first mixing dry K-B blended clay with appropriate amounts of CPSA before addition of the activator liquid. Three CPSA percentages of 10, 20, and 30 % were

considered. This method referred to as the dry method has been used in some earlier works [15]. The K-B plus CPSA mixture was then mixed with the activator liquid following the experimental flow chat in Fig. 5. The K-B-CPSA mixture was mixed in a Horbot Electrical mixer for 5 min before the alkaline activator liquid was gradually introduced while mixing was still on. This was done to avoid excessive agglomeration and eventually reduce the mixing time required to achieve uniform distribution of the activator liquid. It was observed that lower activator liquid to soil + CPSA (AL/P) ratio, where P represent the total mass of soil and binder, proved too dry for preparation of samples with higher CPSA content and would be below expected optimum activator liquid content (OAC). This behaviour has been observed in [53] and is related to large pores in the semi-crystalline CPSA which caused high liquid absorption in the mixture. Some recent studies have also suggested an AL/P ratio of 0.4 for optimum performance [27,54].

For this reason, 3 AL/P ratios of 0.45, 0.50, and 0.55 were used. The 3 ratios were selected following results of trial samples based on previous studies as preliminary investigation [27,54]. The preliminary analysis showed significant formation of N-A-S-H binder gels as expected and allowed better compaction from 0.45 AL/P ratio. The higher alkaline contents at AL/P of 0.50 and 0.55 caused faster reaction with increasing CPSA during mixing. Triplicate samples were prepared for each mix composition. The samples were compacted in 3 layers and extruded using a sample cutter and hydraulic jack system and thereafter trimmed to obtain 100 mm depth and 50 mm diameter cylinder samples. The extruded samples were then weighed and wrapped in polyethene bags to prevent immediate drying-out and cured for 7 and 28 days at 20 °C. Swell samples were compacted in two layers in a 25 mm depth
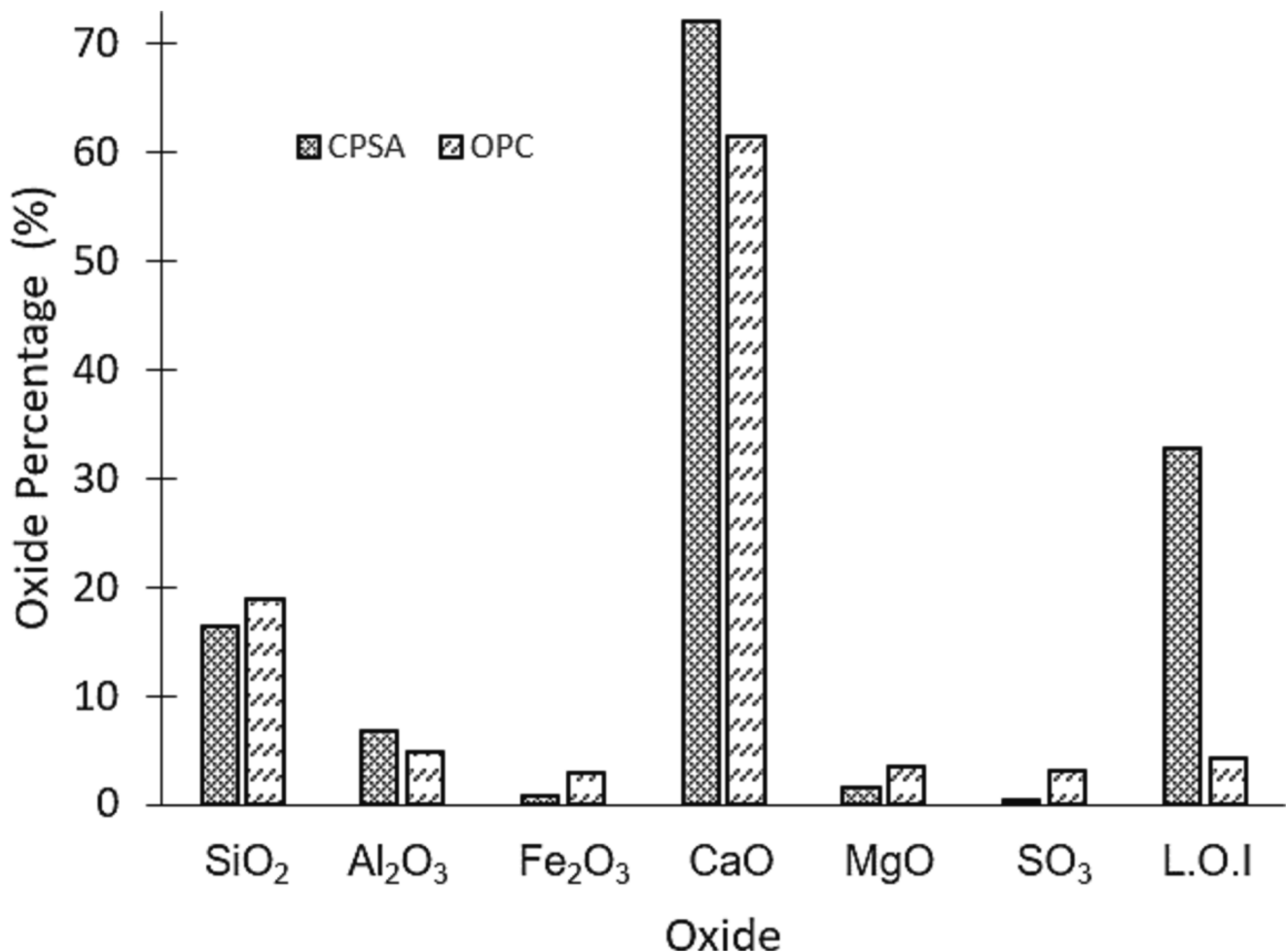
Fig. 3. Comparison of oxide composition of CPSA and OPC.

and 63 mm diameter stainless steel swell rings and thereafter wrapped with polyethene bags and cured for 7 days. The mix ratios of the constituent materials are shown in Table 4.

Experimental testing

UCS and swell tests

UCS test was conducted on 100 mm x 50 mm cylinder samples using a 50kN VJ Tech Load Frame. Samples were loaded slowly under strain-controlled conditions at a speed of 1 mm/min while the test data was automatically recorded at every 0.1 % deformation in the sample, using a dedicated computer system connected to the loading frame. Failure of the sample was determined from the deviator stress-axial strain curve when there was a continuous drop in load from peak value up to 5 % for brittle samples or at 20 % axial strain for softer samples. The test was conducted with reference to BS EN ISO 17892-7:2018 [20]. After testing, chunks of stabilised soil from failed samples were collected, wrapped in polyethene bags and sent for SEM/EDX analysis. Fig. 6 shows samples during UCS and swell tests.

The swell samples were weighed before placing between 2 porous discs and soaked in distilled water under a 60 mm diameter surcharge of weight 930 g, to simulate overburden pressure from possible road pavement layer on the stabilised clay. The contact stress from the surcharge amounts to an applied vertical stress of 3.227kN/m^2 which equates to an asphalt pavement thickness of approximately 150 mm assuming an average unit weight of asphalt of 22kN/m^3 [96]. Electronic dial gauges were set-up to monitor the vertical swell of the samples during the soaking period. The samples were monitored and readings

noted at 24-hour intervals until there was no change in the swell for 48 h. All samples achieved maximum swell well before the 28th day. However, the samples were left in soaked condition until 28 days after which the samples were weighed again to determine the absorbed water.

SEM and EDX analysis

SEM and EDX analysis were conducted on both the untreated and treated samples. An Emscope SC 500 unit was used in gold-coating chunks of stabilised soil using a current of 7.5 mA at a vacuum pressure reading of 0.1 Torr. The gold-coated samples were held onto the stage with a Leit-C conductive carbon cement and allowed for 2 days before the analysis. The samples were then put in a FEI QUANTA FEG 650 SEM Unit at a chamber pressure of $9.5x10^{-7}$ Torr and an accelerating voltage of 5–20 kV for analysis. A similar procedure has been used in [21]. After the microstructural analysis was completed, EDX was then utilised in studying the mineralogical composition at 3 different randomly chosen points on the samples. SEM micrographs were taken at 10–20 mm offset of the stage, depending on the size of the sample.

Results and discussions

UCS and density

Effect of CPSA content and molarity on density

Results of the highly expansive clay (HEC) treated with CPSA geopolymer showed rapid strength increment within 72-hours of treatment before attaining a steadier strength development phase. The increase in strength was synonymous with increasing molarity of the activator
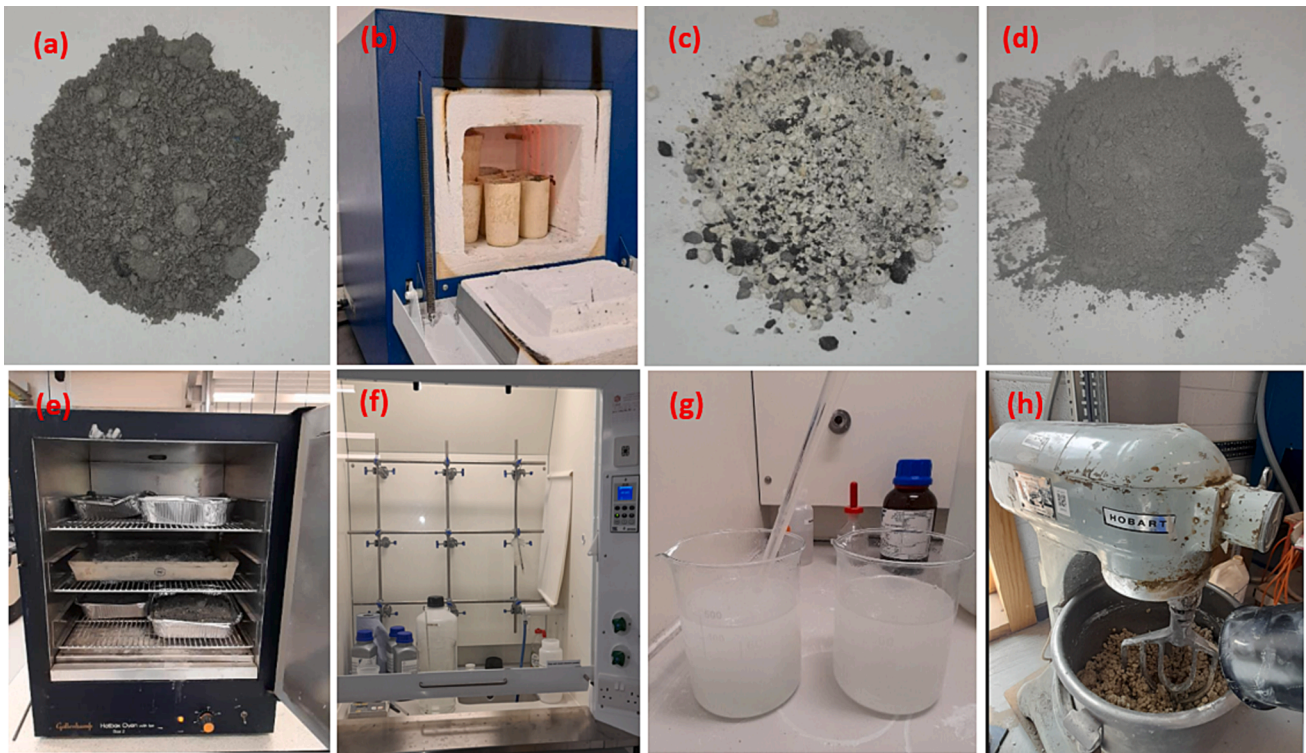
Fig. 4. Preprocessed and processed CPSA (a) Oven-dried wastepaper sludge (b) CPSA in incineration (c) Calcinated PSA (d) ground CPSA. (e) Oven-drying of wastepaper sludge (f) Preparation of alkaline solution (g) Prepared alkaline solution (h) Mixing of HEC and CPSA-geopolymer.

Table 2
Physical properties of the sodium silicate solution.

Type	Concentration	Density (sg)	Twaddle	Viscosity (Centipoise)
75Tw	35–37 %	1.36	75	100

Table 3
Atterberg limits and compaction parameters of the expansive clay.

LL (%)	PL (%)	PI (%)	MDD (Kg/m^3)	OMC
249.94	40.21	209.73	1314.98	34

solution and binder concentration within the geopolymer matrix [99,98,92,28]. As shown in Fig. 7, the density of the stabilised samples reduced with increasing CPSA content as expected, due to the light weight of CPSA in comparison with the HEC and might be advantageous in some applications where high specific strength are critical for design purposes. The density of soils is an indication of the compactness of the soil matrix and usually has a direct effect on the strength of the soil as soils with higher densities are usually characterised by lesser pore spaces and increased inter-particle interaction for enhance shear strength.

However, in some instances during stabilisation, the introduction of additives or partial replacement of the original soil by common binders reduces the density due to the light weight of the binders/additives. Hence, for such materials, a reduction in density is usually observed with increasing binder content and strength [17,75]. For most of the treated samples, optimum density was observed at 12 M, exceeding that of the 8 and 15 M samples for all CPSA contents and for all AL/P ratios. Fig. 7a and b, show the strength and density results of the HEC samples treated with an AL/P ratio of 0.45 for 7- and 28-days curing periods respectively. Samples with 10 %CPSA showed higher densities, while those containing 20 % and 30 %CPSA were lower with 30 % being the least across all molarities. The 0.45 AL/P ratio provided adequate moisture and lubrication for more compaction compared to higher

activator contents for similar samples with 10 %CPSA content. Whereas at AL/P ratios of 0.5 and 0.55, the density of samples treated with 20 % CPSA improved. The higher density at higher AL/P ratios for the samples with higher binder content was sponsored by increase in geopolymer gels with increasing alkaline solution which encourage better lubrication of the soil particles, thereby enabling coated particles to slide and fill-up interparticle void.

The density of samples treated with 12 M alkaline solution was observed to perform better. A possible reason for this might be the moderate reaction rate which slowed down the setting time and allowed effective compaction under the same applied energy. Further increase in the molarity of the activator liquid to 15 M led to a drop in the density except for the samples containing 30 %CPSA which showed optimum density at AL/P of 0.50 due to higher CPSA content with higher capacity to absorb more activator liquid.

As shown in Fig. 8, an optimum alkaline content (OAC) of 0.45 was recorded for the samples treated with 10 %CPSA while samples treated with 20- and 30 %CPSA had OAC of approximately 0.5 at 12 M. The results further showed that within the CPSA-geopolymer stabilised soils, OAC does not necessarily correspond to maximum strength which is rather defined by other parameters such as temperature, molarity and the type of precursor which could influence the geopolymerisation processs. The OAC could therefore be described as the activator liquid content required to initiate optimum formation of geopolymeric binders within the CPSA-geopolymer stabilised soil to achieve the maximum strength possible for the soil.

Effect of CPSA content and molarity on UCS

The 4-hour soaked UCS of the treated samples increased with increase in the CPSA content, molarity of the solution, and curing duration. Higher CPSA contents with sufficient activator liquid enhanced the geopolymerisation kinetics through greater dissociation of Al and Si species required for strength gain. Samples treated with 10 %CPSA showed maximum strength at a lower AL/P ratio of 0.45 and attained a maximum UCS of 902 kPa and 1059 kPa at 7- and 28-days curing
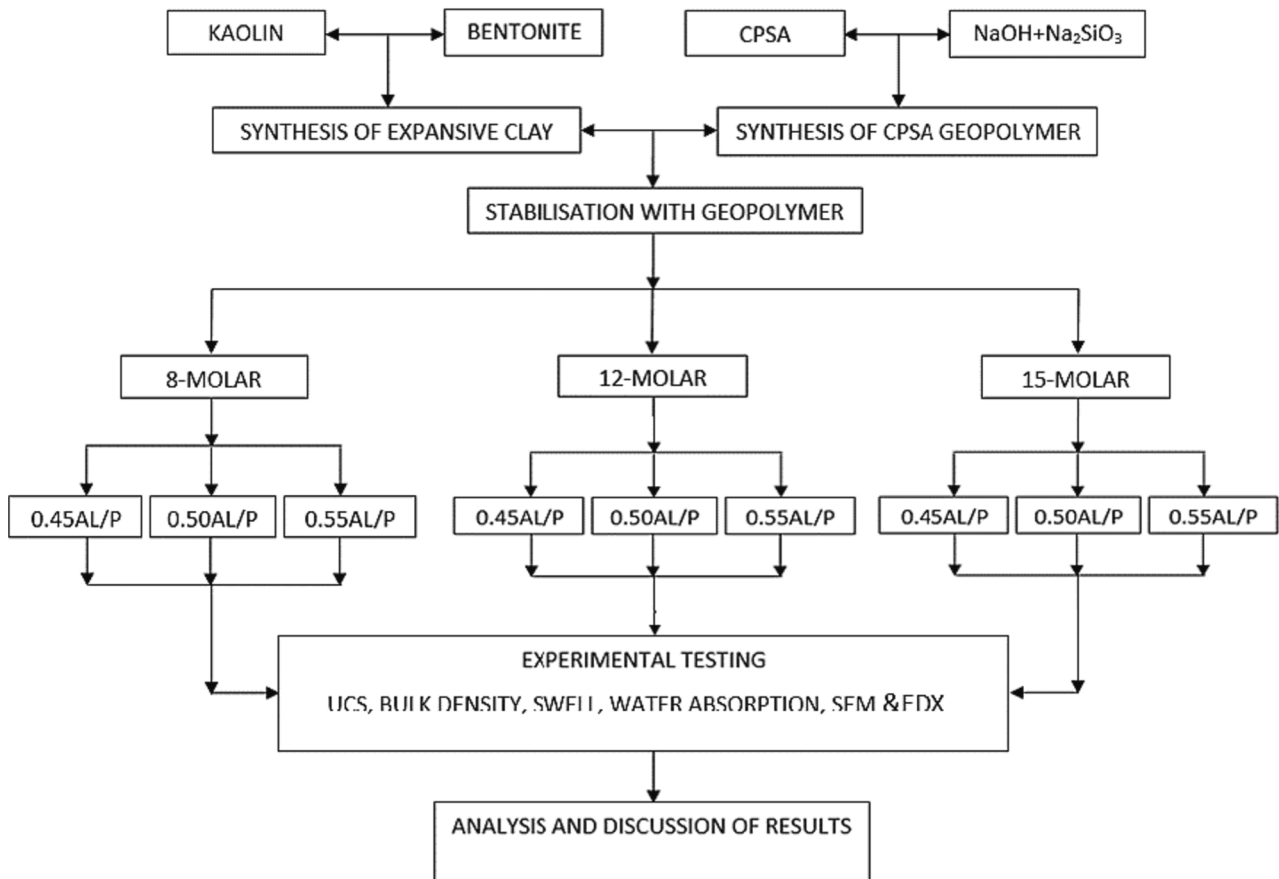
Fig. 5. Experimental flowchart.

Table 4
Sample mix composition.

| MOLARITY									10 %wt. CPSA	20 %wt. CPSA	30 %wt. CPSA	CURING (DAYS)	SAMPLE LABEL
8-M			12-M			15-M							
AL/P RATIO													
0.45	0.50	0.55	0.45	0.50	0.55	0.45	0.50	0.55					
✓									✓			7 and 28	10CPSA + 8 M + 0.45AL
	✓								✓			7 and 28	10CPSA + 8 M + 0.50AL
		✓							✓			7 and 28	10CPSA + 8 M + 0.55AL
			✓						✓			7 and 28	10CPSA + 12 M + 0.45AL
				✓					✓			7 and 28	10CPSA + 12 M + 0.50AL
					✓				✓			7 and 28	10CPSA + 12 M + 0.55AL
						✓			✓			7 and 28	10CPSA + 15 M + 0.45AL
							✓		✓			7 and 28	10CPSA + 15 M + 0.50AL
								✓	✓			7 and 28	10CPSA + 15 M + 0.55AL
✓										✓		7 and 28	20CPSA + 8 M + 0.45AL
	✓									✓		7 and 28	20CPSA + 8 M + 0.50AL
		✓								✓		7 and 28	20CPSA + 8 M + 0.55AL
			✓							✓		7 and 28	20CPSA + 12 M + 0.45AL
				✓						✓		7 and 28	20CPSA + 12 M + 0.50AL
					✓					✓		7 and 28	20CPSA + 8 M + 0.55AL
						✓				✓		7 and 28	20CPSA + 15 M + 0.45AL
							✓			✓		7 and 28	20CPSA + 15 M + 0.50AL
								✓		✓		7 and 28	20CPSA + 15 M + 0.55AL
✓											✓	7 and 28	30CPSA + 8 M + 0.45AL
	✓										✓	7 and 28	30CPSA + 8 M + 0.50AL
		✓									✓	7 and 28	30CPSA + 8 M + 0.55AL
			✓								✓	7 and 28	30CPSA + 12 M + 0.45AL
				✓							✓	7 and 28	30CPSA + 12 M + 0.50AL
					✓						✓	7 and 28	30CPSA + 12 M + 0.55AL
						✓					✓	7 and 28	30CPSA + 15 M + 0.45AL
							✓				✓	7 and 28	30CPSA + 15 M + 0.50AL
								✓			✓	7 and 28	30CPSA + 15 M + 0.55AL
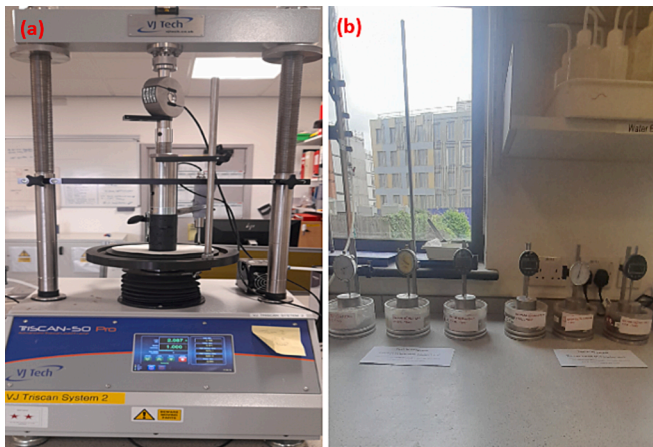
Fig. 6. UCS and swell tests (a) UCS test (b) Swell test.

respectively. However, further increase in activator liquid was synonymous with a decline in strength. The decline in strength was initiated by excessive activator liquid at 0.5 and 0.55 which caused the HEC to swell with increased agglomeration. Across the molarity spectrum, even at low CPSA content, samples treated with 10 %CPSA showed significant rise in strength with increasing molarity. As shown in Fig. 7a, an increase in molarity from 8 to 12 M increased the UCS of 10 %CPSA-treated samples by 83 % after 7-days curing. Further increase in the molarity of the activator liquid from 12 to 15 M, had only little benefit as this only increased the strength of 10 %CPSA-treated samples by 9.8 % after 7 days curing. Although the 15 M alkaline solution provided a more aggressive environment for the breakdown of the existing Al-Si bond in the amorphous CPSA, the low binder content negated the effect, leading to excessive formation of crystals of the activator liquid around the clay platelets and on the surface of the samples with rather low binder gel formation for coating of clay platelets and increasing interparticle bonds and ultimate strength development. As a result, longer curing period was required for the additional strength gain from a higher molarity to be attained. This result is line with earlier studies highlighting cost-benefit implications of higher molarities on the performance of geopolymer systems [106,22,58]. Furthermore, the UCS of samples treated with 10 %CPSA exceeded that of samples treated with 8 and 10 %OPC at AL/P of 0.45 after 28-days curing. The strength of the 10 %CPSA samples compared closely to those treated with OPC even at AL/P ratios of 0.5 and 0.55, which shows the effectiveness of CPSA geopolymer in enhancing the strength of the stabilised clay and indicates that CPSA geopolymer might be a viable alternative to calcium-based binders.

Similarly, at AL/P ratio of 0.45, samples treated with 20 %CPSA showed significant increase in strength with increase in molarity of the activator liquid. Upon increasing the molarity of the activator liquid from 8 to 12 M, the UCS of the treated clay increased from 769.10 kPa to 1500.25 kPa amounting to 95 % increment in strength after 7-days curing as shown in Fig. 7a and b. The results show the effect of CPSA on the strength gain and the influence of the molarity of the activator liquid. However, further increase in the molarity to 15 M only contributed to a further 74 % increase in UCS at AL/P ratio of 0.45. The increase in molarity would have been of more benefit at higher CPSA content. The lower CPSA at AL/P of 0.45 influenced the formation of geopolymer gel with reduced availability of precursors for polymerisation and cross-linking. This behaviour is later confirmed by SEM results which showed significant distribution of unreacted CPSA particles. An AL/P ratio of 0.50 enhanced the mixing and compaction but rather resulted in strength reduction of the treated samples. The higher density achieved at an AL/P ratio of 0.5 was not synonymous with strength gain. Although an increase in molarity from 12 to 15 M was still beneficial considering a rise from 1160.7 kPa to 1700.3 kPa which amounted to an increment of 46 %. Samples treated with 15 M activator liquid and at

higher AL/P ratio were less ductile, and experienced higher shrinkage at 28-days curing, which led to the development of microcracks on the surface of the specimens and was exacerbated upon loading and contributed to reducing the UCS of the samples. However, the result of 20 %CPSA geopolymer treated HEC surpasses that of the OPC-treated samples across all molarities and AL/P ratios. The results extend the findings of earlier research on useful applications of wastepaper sludge and show that wastepaper sludge could be useful in ground improvement applications.

Overall, the samples treated with 30 %CPSA performed better in strength across all AL/P ratios. This is expected as the 30 %CPSA content provided more binding compounds within the absorbed activator liquid for the formation of gels hence, at AL/P ratio of 0.55, the use of 30 % CPSA binder content still produced a high strength subgrade material. Although the strength of the stabiliised HEC reduced with increase in AL/P ratio due to the excessive moisture and shrinkage, the availability of more Al-Si species was effective in enhancing the strength and optimizing the higher molarity at 12 and 15 M. A maximum UCS of 3694.38 Pa and 3792.67 kPa at 7- and 28-days curing respectively, was achieved at 15 M and AL/P ratio of 0.45 as shown in Fig. 7. The 0.50 AL/P ratio proved better due to reduced drying shrinkage compared to that of 0.55 as shown in Fig. 10e and f. However, early strength gain is usually a function of a faster reaction which is either sponsored by elevated temperature curing, higher molarity, or by higher precursor within the activator to dissociate and re-orient more Al-Si species with available Na^+ ions in a shorter time [8,83,31]. Therefore, the availability of sufficient CPSA and adequate liquid at AL/P ratio of 0.45 yielded highest early strength of 3694.38 kPa at 7-days curing at 15 M. A significant drop in UCS was observed upon further increase in AL/P ratio due to the development of microcracks within the soil-geopolymer matrix.

The strength of the treated HEC under soaked condition indicates useful applications of the stabilised materials when compared with the minimum requirement for cement stabilised materials for road subgrade construction according to U.S. Army corps of Eingineers as shown in Table 5 [55]. The 4-hour soaked UCS of the CPSA-geopolymer stabilised clay meet the requirement for application as subgrade materials at 20 and 30 %CPSA contents with an activator liquid of molarity 12 and 15 M with less carbon footprint while doubling as an alternative waste disposal means. Considering the strength requirement for OPC-treated materials for both flexible and rigid pavement subgrades, samples of the HEC treated with CPSA geopolymer meet these requirements at different mix ratios. For example, HEC samples treated with 20 %CPSA at AL/P of 0.45 meet the requirements for application as subgrade materials for both flexible and rigid pavements when an activator liquid of molarity of 12 and 15 M was used.

Also, samples treated with 30 %CPSA meet the requirement for both flexible and rigid pavement subgrade at 15 M across all AL/P ratios. At an AL/P ratio of 0.45, samples treated with 30 %CPSA satisfy the strength requirement for base application at molarity of 15 M. At 15 M, the strength of the samples exceeds the requirement for subgrade materials for both flexible and rigid pavements. Due to the highly plastic nature of the clay utilised in the study, the samples treated with 8, 10, and 12 % OPC neither met the requirements for subgrade materials for flexible or rigid pavements. The soaked UCS results of the 28-day cured OPC-treated samples were also below the requirement for both rigid and flexible pavements subgrade materials. The performance of the CPSA-geopolymer was also compared to the requirement for cement stabilised materials in other regions such as shown in Table 6 [12].

Based on the strength requirement from Table 6, other useful applications of the CPSA-geopolymer could be deduced. The strength of the CPSA-geopolymer stabilised materials meet several applications even at 8 M and as such, samples treated with 10 %CPSA also find useful applications such as modified materials for backfill. Most of the stabilised samples at 20 and 30 %CPSA find useful applications even at higher activator liquid contents when compared with the requirements in Table 6. The results of the CPSA geopolymer suggest that under practical
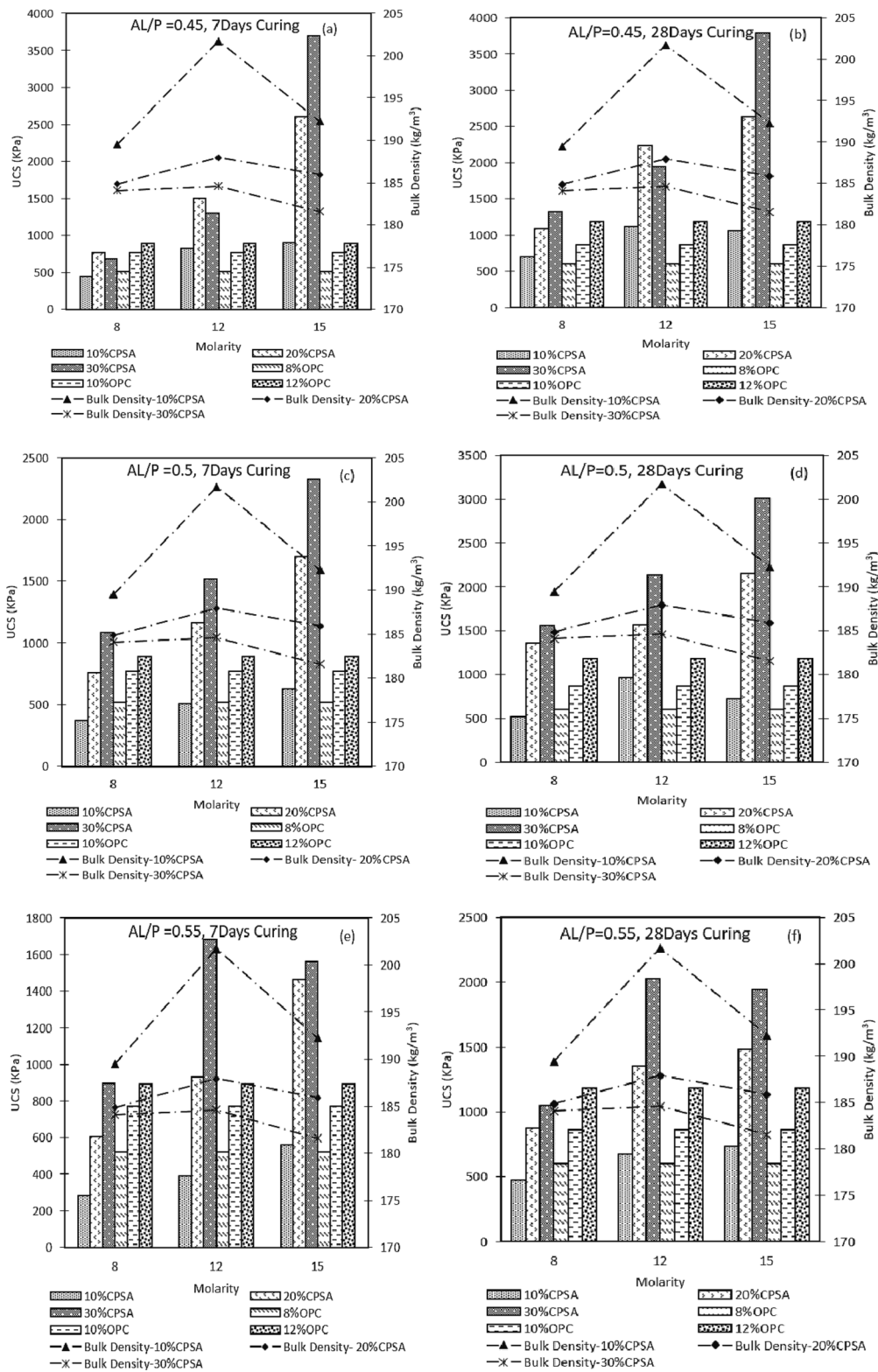
Fig. 7. Effect of CPSA content and molarity on density and UCS of treated HEC.

conditions, on sites with clays of lower plasticity indices, better performance could be expected and as such poor sites could easily be improved, resulting in strength enhancement which meet base applications for both flexible and rigid pavement. Although more investigation is required in this regard to extend the applicability of the treatment across various site conditions, recent studies have shown that geopolymers are suitable as road pavement subgrades and these agree with

the current findings [41,94,45,49].

Performance of CPSA-geopolymer in comparison with traditional binders

The strength of CPSA-geopolymer treated HEC was compared to that of OPC and lime-GGB treated samples to evaluate the performance of the CPSA geopolymer. The results show that CPSA-geopolymer provides better strength enhancement than OPC for the chosen dosage as shown
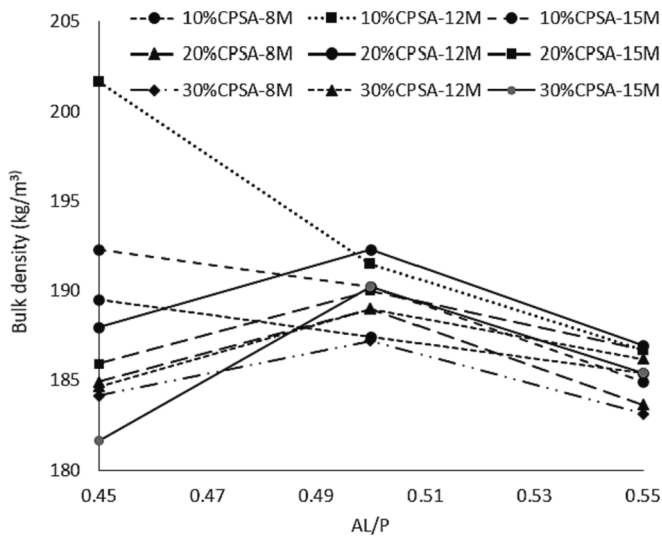
Fig. 8. Density curves of CPSA-geopolymer stabilised HEC.

Table 5

Minimum 7 days UCS for road subgrades and sub-bases.

Application	Flexible Pavement	Rigid Pavement
Base Course (7 days, 4hrs soaking)	5170 kPa	3450 kPa
Subbase, select material or subgrade (7 days, 4hrs soaking)	1720 kPa	1380 kPa
Construction of lower layers in high embankments (EN 16907-4:2018)	250–500 kPa after 28-days curing	

Table 6

7-days undrained shear strength of stabilised soils for practical application.

Application	Undrained Shear Strength Q_u (Mpa)
Stabilised earthwork materials	0.75
Modified materials	0.25
Lightly bound cemented materials	0.75
Bound cemented materials	1

in Fig. 9. It is well known that the use of OPC treatment is largely a function of the characteristics of the in-situ soil and is not encouraged for clays with plasticity index > 20 [87,90]. Hence, under field conditions, for such a highly expansive clay, the use of OPC will be of very little impact due to difficulties in mixing in-situ and because of the strong affinity of the clay to retain adsorbed water from the strong electro-chemical bonds between the di-polar water molecules and clay platelets. Consequently, lime-GGBS or other combinations have been recommended [55]. However, in many countries, the use of OPC still remains the main binder option as it is more readily available than lime-GGBS and other alternatives. For the OPC-treated samples, even under laboratory conditions with adequate mixing due to the low volume of mixed materials, the OPC-treated samples still performed below the CPSA-geopolymer-treated samples. The results show that problematic sites with clays which would rather be very difficult to treat with traditional binders could easily be re-engineered to improve their strength and reduce plasticity with CPSA geopolymers. Comparing the plasticity indices of typical London clays sampled by Skempton and Henkel [89] shown in Table 7 with the HEC used in the current study, the lower PI of the London clays indicates that the HEC utilised in the current study poses an extremely more difficult site condition for construction purpose and that the use of CPSA geopolymer could be applied in many practical cases with better results.

Fig. 9 compares the performance of OPC-treated samples at various

cement contents in comparison to CPSA-geopolymer-treated samples. The UCS curves show that by varying the CPSA content and the molarity of the activator liquid, strength like that of OPC-treated samples could be achieved. For example, with 10 %CPSA at a molarity of 10, similar result to that of 9 %OPC treatment could be achieved. Therefore, a 9 % OPC treatment on the HEC, is equivalent to a 10 %CPSA treatment at a molarity of 10 and AL/P of 0.45.

Similarly, a UCS of 800 kPa at 7-days curing could be achieved in multiple ways such as using a CPSA-geopolymer constituted with 30 % CPSA and 9 M activator liquid or 10 %CPSA and 12 M activator liquid at AL/P of 0.45 or 11 %OPC treatment. Furthermore, at AL/P of 0.5, CPSA-geopolymer containing 20 %CPSA with activator liquid of 9 M yields the same UCS as samples treated with 12 %OPC. Considering the carbon footprints of the binders, at lower target strengths, OPC treatment yields lower carbon emissions than CPSA-geopolymer due to the contribution to embodied carbon from the alkaline activator. Indeed, the carbon emissions from geopolymers could vary considerably compared to OPC and is dependent on several factors but mainly the mix design and could fluctuate below or above that of OPC depending on the desired strength [81]. However, based on results from the current study, at higher target strengths of over 2 MPa, OPC-treatment becomes more carbon-intensive for such a highly plastic material. This shows that to meet the requirements for subgrades and base, OPC-treatment would be highly carbon-intensive. Higher strength enhancement from CPSA-geopolymer treatment is achieved with reduced carbon footprint when compared with OPC treatment [97]. This lower carbon footprint can be expressed in terms of the equivalent carbon emitted during the production of a specific quantity of the stabilised materials. Table 8 shows the materials required to stabilise 1 tone of the expansive subgrade to achieve a target 7-day UCS of 2250 kPa for both CPSA-geopolymer and OPC treatment. For the OPC treated subgrade, 57 % cement content yields the desired strength whereas CPSA-geopolymer constituted with 20 %CPSA at 14 M yields the same result at an AL/P of 0.45.

The equivalent carbon emission (kgCO$_2$-e/T) from the stabilisation of 1 tone of the expansive subgrade using CPSA-geopolymer and OPC treatment to achieve a 7-day UCS of 2250 kPa is shown in Fig. 10. The estimated carbon emissions do not consider the contribution from the original soil which in practical road subgrade stabilisation applications, would be in-situ and as such having zero carbon footprint. The carbon emission of the stabilised materials was calculated using the equivalent carbon of the constituent materials from literatures. For CPSA and water, the equivalent emission of 0.498kgCO$_2$-e/kg and 0.03 kgCO$_2$-e/kg respectively as reported in [6] was adopted. While the values of 0.82 kgCO$_2$-e/kg, 0.424 kgCO$_2$-e/kg, and 0.82 kgCO$_2$-e/kg were utilized for NaOH, Na$_2$SiO$_3$, and OPC respectively, as reported in [37,40,95]. Fig. 10 essentially shows that a substantial reduction in carbon emissions could be achieved by using alternative binders such as geopolymers constituted from industrial waste materials for subgrade applications. A significant drop of 36 % carbon emissions is actualised by replacing OPC with CPSA-geopolymer for a target 7-day UCS of 2250 kPa. This percentage difference increases as the desired strength increases since a higher cement content would be required to achieve higher compressive strength, considering the highly plastic nature of the clay but increasing the CPSA content could yield the same result with lower carbon emission. The equivalent carbon associated with the stabilised HEC is also plotted in Fig. 11. The results show that CPSA-geopolymer provides a low carbon option in the treatment of HEC for road pavement subgrade applications.

Swell and water absorption

Swell and water absorption are very common phenomena in subgrades exposed to fluctuations in moisture content with seasonal changes and pose serious threats to the performance and lifespan of road pavements. Submerged highly expansive road subgrades result in heaves underneath the pavement which could lead to excessive internal stresses
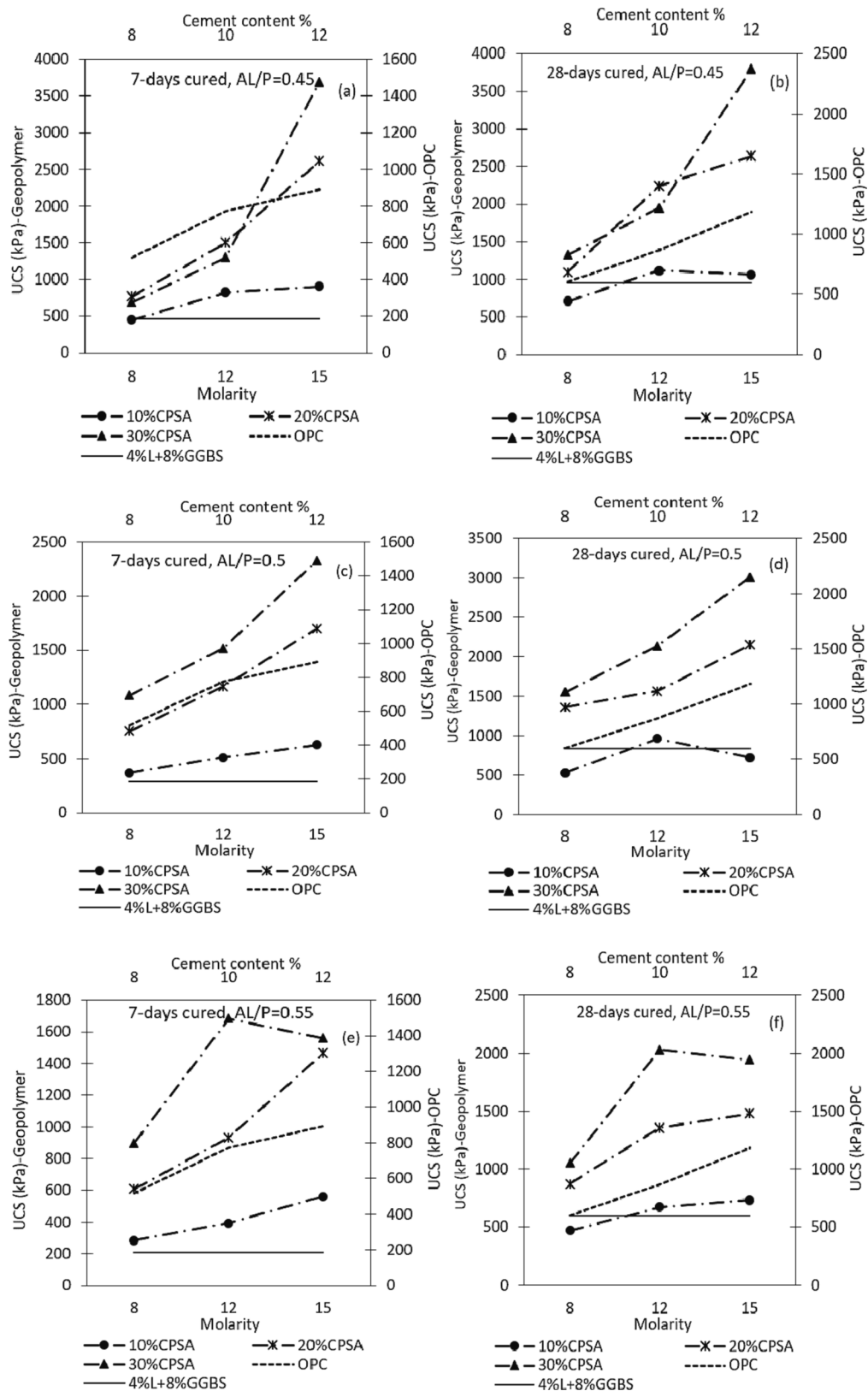
Fig. 9. Performance of CPSA-geopolymer and OPC treated HEC.

within the pavement. This condition could be worsened by the application of traffic loads and therefore, it is imperative that stabilised subgrades meet the requirements in terms of swell. The performance of the treated subgrade after soaking for 28 days was evaluated based on the vertical swell and water absorption capacities of the treated

subgrades as shown in Fig. 12. The Untreated HEC showed severe swelling up to 94 % after 28 days soaking, exceeding the 2.5 % limit [7] allowable for road pavement subgrade materials as expected leading to a complete loss of shear strength and volume stability. Both CPSA-geopolymer and OPC-treated samples showed far less reduction in

Table 7

Plasticity indices of some London clays.

Location	Victoria	Sheppey	South Bank	Paddington	Waterloo Bridge	St. Paul's Cath.	Current study
PI (%)	*44	**52	*50	*55	*50	*49	209

**Bagheri and Rezania [13], *Skempton and Henkel [89].

Table 8

Materials required for stabilisation of 1tonne of expansive subgrade for a 7-days UCS of 2250 kPa.

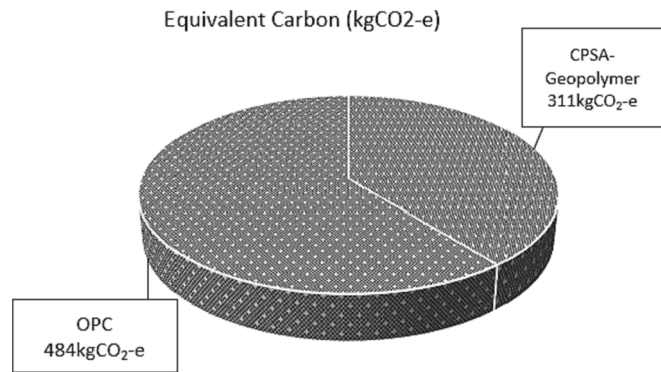| Sample	Soil (kg)	Binder (kg)	AL/P	M	Na_2SiO_3 (kg)	NaOH (kg)	Water (kg)
CPSA-geopolymer	1000	200	0.45	14	378	58	104
OPC	1000	570	–	–	–	–	549.50

Fig. 10. Comparison of carbon emission per tonne of stabilised HEC subgrade at 7-day UCS of 2250 kPa.

vertical swell at the end of the 28-day soaking compared to the untreated HEC. The use of OPC encouraged sealing of the soil fabrics with the cement gel which reduced the expansive tendencies of the HEC and resulted in reduced absorption capacity of the OPC-treated samples. A significant reduction in swell and water absorption of 93 % and 82 % respectively was recorded following treatment with OPC. A reduction in swell and water absorption was noticed across the OPC stabilised samples with increasing cement content which is an indication of enhanced bond strength between the clay platelets at higher cement content. For example, increasing the cement content from 8 % to 10 % reduced the vertical swell from 0.96 % to 0.28 % resulting in a 71 % further reduction in swell as shown in Fig. 12a.

The CPSA-geopolymer treatment also significantly enhanced the resistance of the treated subgrades to swell and water absorption. The reduction in swell and water absorption was synonymous with increasing CPSA content and molarity. The swell and water absorption increased as the AL/P ratio increased as shown in Fig. 12b-d. Samples treated with higher CPSA content and molarity showed more resistance to swell. The reduction is linked to increased N-A-S-H gel formation and reduced pores from the availability of more Si-Al species. The AL/P ratio
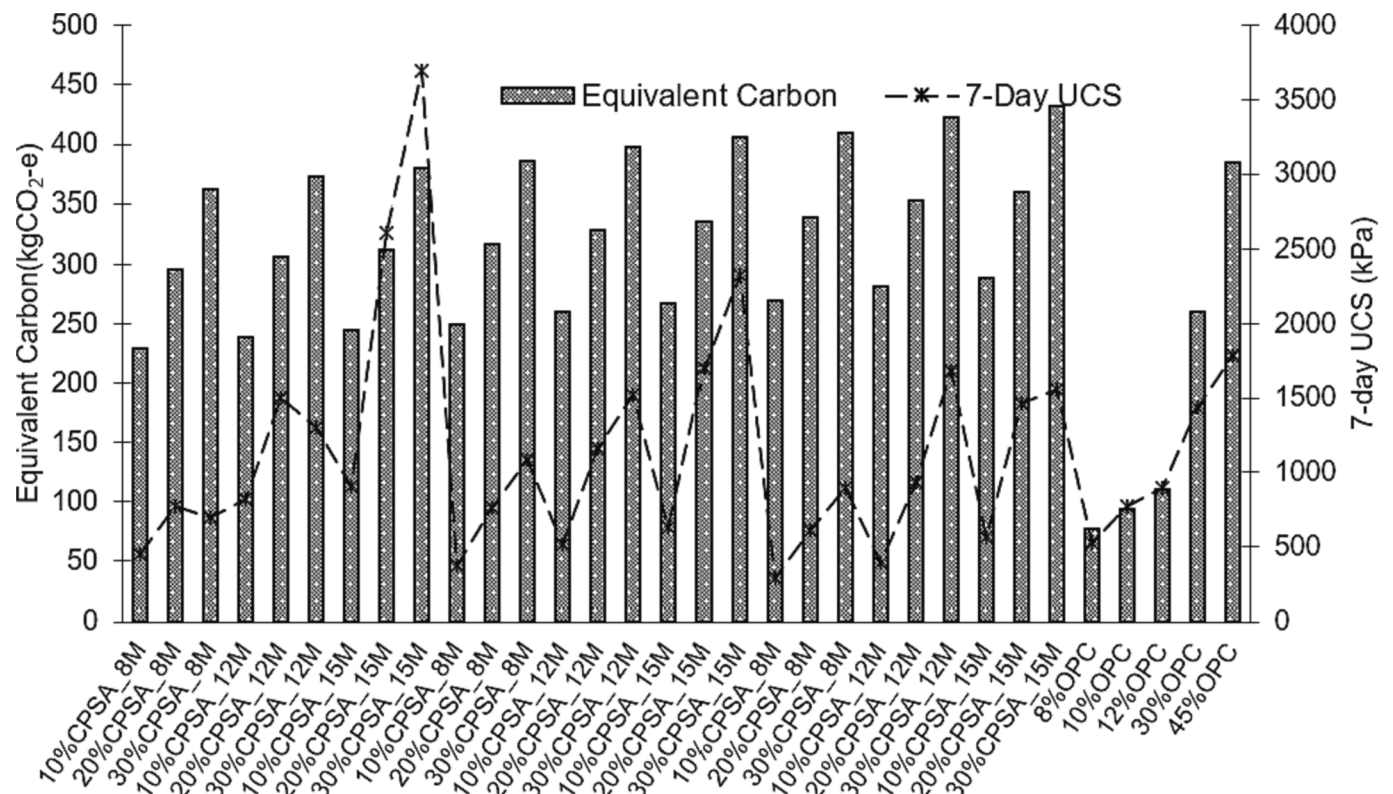

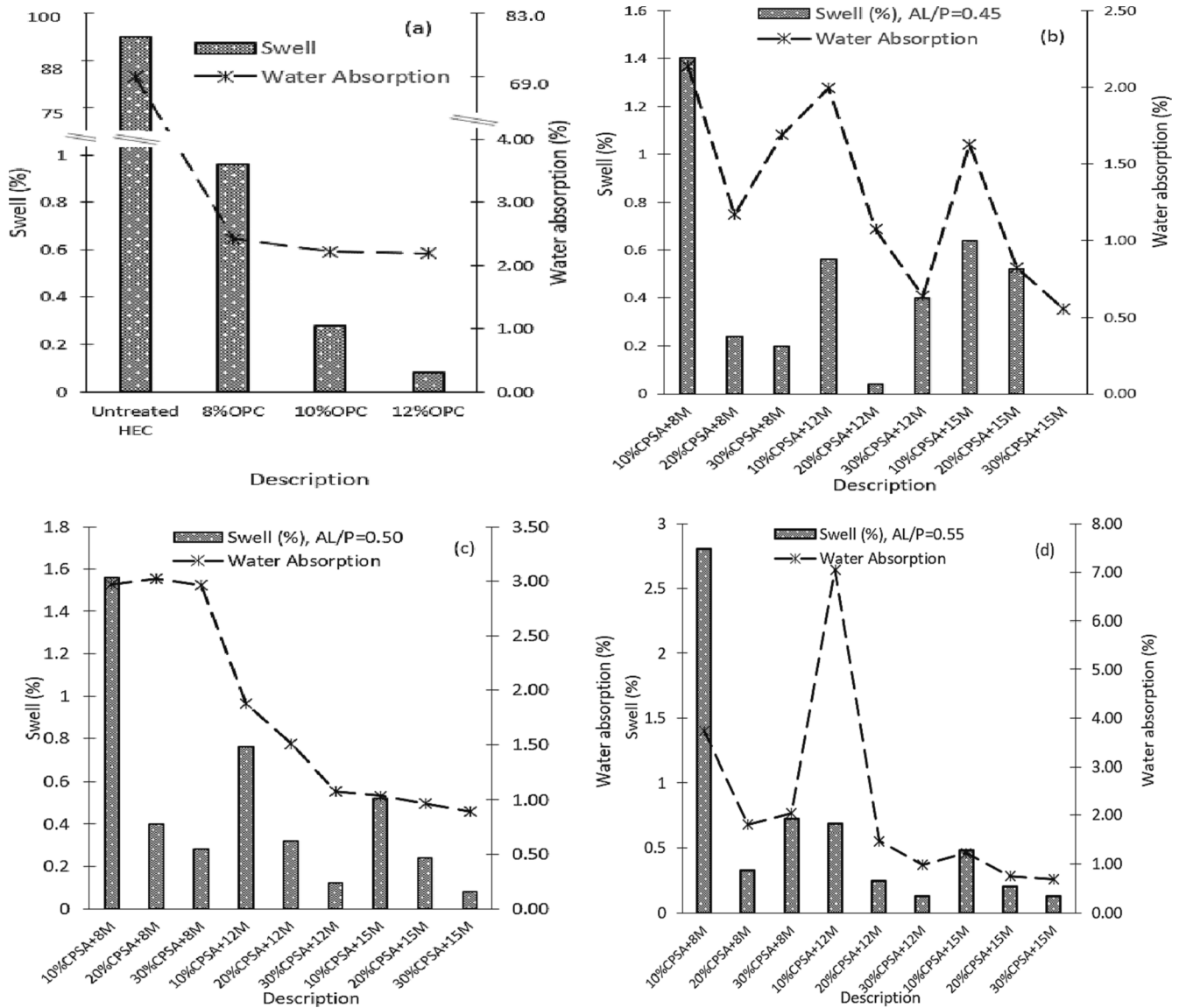**Fig. 11.** Equivalent carbon emissions for CPSA-geopolymer and OPC treated HEC.

Fig. 12. (a-d). Swell and water absorption treated HEC.

influenced the behaviour of the samples during soaking like the compressive strengths. Comparing Fig. 12b and d, lower AL/P ratios performed better due to optimum synthesis of geopolymer binder which increased the binding strength of the gel between particles and enhanced the resistance of the samples against swell. With higher AL/P ratios, the cementation effect was low with more microcracks as expected. More of the activator liquid impregnated within the boundaries of agglomerated clay particles crystallised during curing allowing microtubes to develop through which water penetrated the treated samples and led to an increase in the swell and water absorption. For example, the sample containing 30 %CPSA had higher swell potential at AL/P of 0.55 owing to excess activator solution, resulting in a more porous material with higher water absorption as shown in Fig. 15b.

The effect of molarity of the alkaline solution on the swell and water absorption performance is also seen from Fig. 12. For instance, increasing the molarity of the sample containing 10 %CPSA from 8 M to 12 M, reduced the swell and water absorption by 74 % and 78 % respectively. The 15 M alkaline solution was more favourable in reducing swell and water absorption of the samples and agrees with the results of both compressive strength and microstructural analysis. The reduction in swell and water absorption capacity of the CPSA-

geopolymer-treated samples compares very well to the use of OPC and are below expected maximum allowable swell for road subgrades.

SEM and EDX analysis

Microstructural examination based on SEM analysis of the fractured surface of the samples reveals that the morphology of the stabilised HEC is altered through the effects of cementation and gluing of clay platelets from the formation of cementitious gels. The development of a denser soil-geopolymer matrix can be noticed by comparing it with the microtextural characteristics of the untreated HEC. Fig. 13a is the micrograph of the untreated HEC showing loosely packed clay platelets in an almost regular book-like orientation. The clay platelets are seen to be without gels and held together simply by cohesion between the soil particles initiated in the presence of water molecules. The untreated matrix is obviously predominated by large pores indicating a highly compressible material.

On the other hand, the stabilised samples are very distinct as shown in Fig. 13b-d. Fig. 13b is the SEM micrograph after 28-days curing for the sample treated with 10 %CPSA and AL/P of 0.45 at a molarity of 12 M. The presence of some N-A-S-H and C-A-S-H gel-coatings can been seen
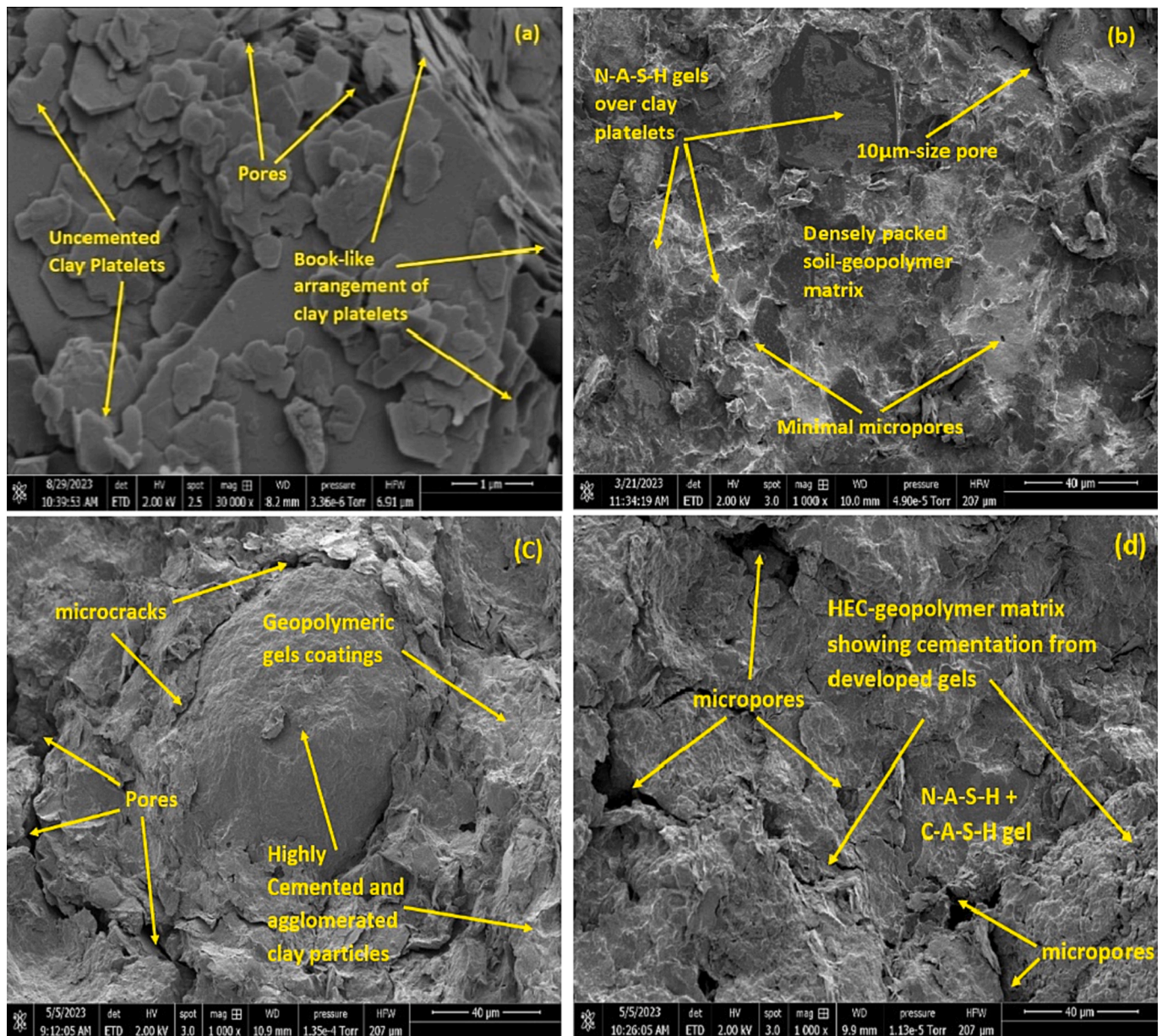
Fig. 13. Scanning electron micrographs of stabilised HEC treated with 12 M activator at AL/P of 0.45 (a) Untreated HEC (b) 10 wt% of CPSA-geopolymer (c) 20 wt% of CPSA-geopolymer (d) 30 wt% of CPSA-geopolymer.

on the platelets with some traces of crystals of the alkaline solution sparsely distributed over the dense surface of the stabilised soil matrix, corroborating lower pore volume. This reduced pore volume and increased compactness confirms the source of the higher density of the samples containing 10 %CPSA at AL/P ratio of 0.45. The increase in microcracks and pores at higher AL/P ratios supports the idea that more alkaline solution was detrimental due to the low precursor content at 10 %CPSA. Higher CPSA content resulted in a more cemented matrix with reduction in microcracks for the same AL/P ratios as shown in Fig. 13c and d.

Although significant absorption of the activator liquid at AL/P of 0.45 for the 20 and 30 %CPSA contributed to reducing the density of the samples due to lower lubrication of particles, the 0.45 activator liquid ratio appeared to provide the required activator content for the formation of sufficient N-A-S-H gels resulting in higher capacity to bind the clay platelets. Similar observation has been made by others [104]. This higher binder capacity for the 30 %CPSA samples at AL/P of 0.45 was highlighted in the compressive strength performance of the treated

subgrades and is also the reason for the brittle nature of these samples, particularly 30 %CPSA. As more CPSA is made available, the treated matrix is transformed from a weak and loose state into a highly cemented microstructure with reduced plastic behaviour. Therefore, it is imperative that the geopolymer constituents are synthesized using the OAC for optimisation of the precursor contents. The morphological and microstructural characteristics of the treated samples are consistent with previous observations from stabilised samples both for traditional binders and geopolymers [107,93].

Fig. 14a-d shows the SEM and EDX results for the samples treated with 20 %CPSA. Fig. 14a and b represent the SEM and EDX results of the sample treated with 20 %CPSA and 8 M alkaline solution, whereas Fig. 14c and d is for the 15 M counterpart. The micrographs are included to compare the effects of the molarity on the microstructure of the CPSA-geopolymer treated soils. The results of EDX analysis identifies peaks for Na, Si and Al as expected with a fair amount of calcium as shown in Fig. 14a-d. A greater peak for Na and Si is observed for the 15 M version of the 20 %CPSA sample due to higher amount of the activator liquid at
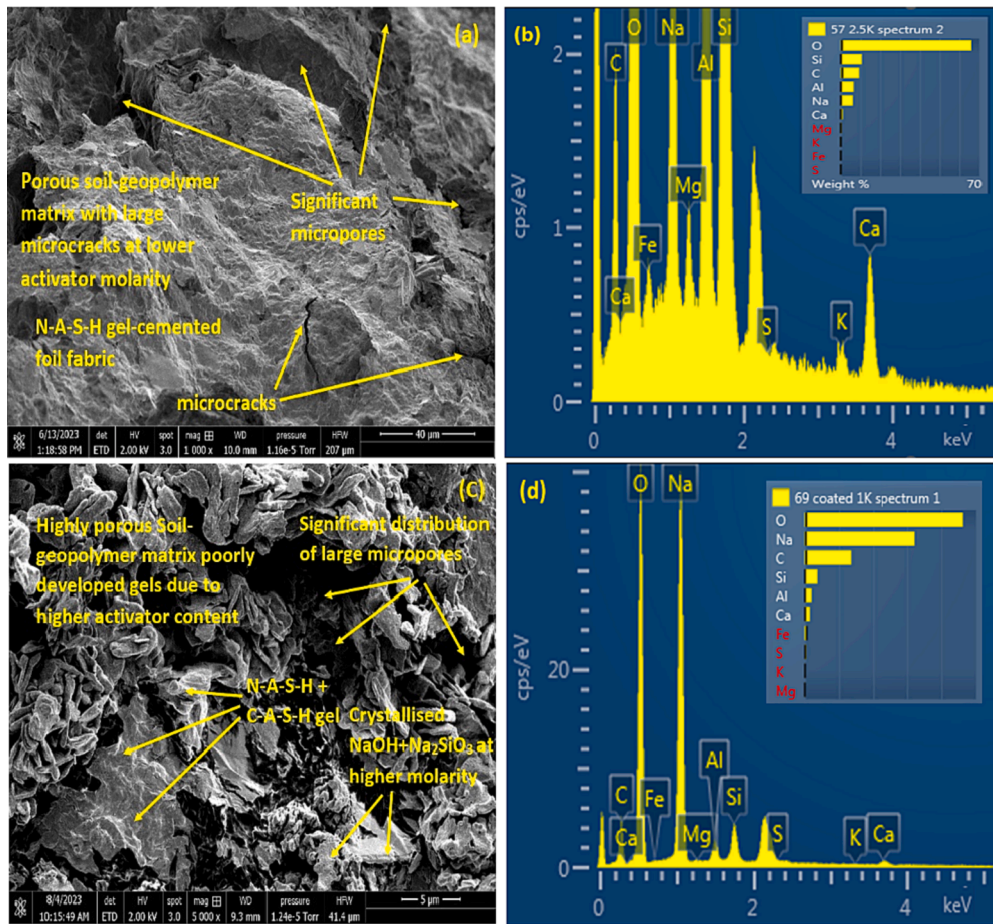
Fig. 14. Scanning electron micrographs and EDX results of CPSA-geopolymer treated HEC. (a) SEM of treated HEC containing 20 %CPSA and 8 M activator at AL/P of 0.5 (b) EDX of treated HEC containing 20 %CPSA and 8 M activator at AL/P of 0.5 (c) SEM of treated HEC containing 20 %CPSA and 15 M activator at AL/P of 0.55 (d) EDX of treated HEC containing 20 %CPSA and 15 M activator at AL/P of 0.55.

AL/P of 0.55 which supplied more silica ions within the sample. The SEM micrograph in Fig. 14a also shows wider pores and cracks for the 8 M when compared with the 15 M version. Some flakes of crystallised activator liquid can be seen on the surface of the platelets at higher molarity and activator content as shown in Fig. 14c.

Higher molarity is expected to increase the cementation effect and enhance compactness of the microstructure. Although samples treated with higher molarity still performed better even at higher activator liquid contents, the high activator liquid content at AL/P of 0.55 which was above OAC negated some of the gains of the 15 M solution by causing agglomeration and swelling, resulting in lower density for the same compaction effort. This is seen in the distribution of micropores as well from less cementation. Fig. 15a-d shows the SEM and EDX results of the CPSA-geopolymer treated samples containing 30 %CPSA. The microstructure is quite compact with reduced pores at AL/P of 0.55 compared to that of 10 and 20 %CPSA. Also, very few and shorter microcracks are observed which is line with the UCS results in section 3.1.1 and 3.1.2, resulting in higher strength at 30 %CPSA across all AL/P ratios. Greater formation of N-A-S-H gel and C-A-S-H coatings was seen virtually over the entire surface area of the sample, sealing up the interparticle boundaries.

Substantial clusters of crystallised activator liquid were found within the pores of the sample and around the clay platelets. It is important to state that the presence of the crystals of the activator liquid suggest that elevated temperature curing could enhanced the strength of the treated samples by keeping the activator in liquid state for longer, allowing a stronger N-A-S-H network to develop at higher temperatures. Overall, the CPSA-geopolymers have shown to enhance the strength of the

treated clay by modifying the soil-binder matrix at the micro level and hence changing the engineering behaviour of the expansive clay from a highly compressible and low strength material which is unsuitable for road pavement construction to a high strength subgrade material with reduced affinity for water and enhanced resistance against swell and water absorption which meets the requirements for use as a road pavement subgrade construction material.

Conclusion

The performance of CPSA-based geopolymers as a viable solution in engineering the properties of expansive clays have been studied. Amongst several factors, the CPSA content, molarity of the activator liquid, and the ratio of the activator liquid to soil and binder content have shown immense influence on the behavior of the treated soils. The HEC is modified to a non-expansive material with significant strength enhancement and meets the requirements of subgrade materials. HEC instead of being carted away from site, could be treated with CPSA-geopolymer using mix proportions predicted from developed curves in this study to obtain desired strength for 7 and 28-days curing periods. Based on the results of this study, the following conclusions can be drawn.

- CPSA-geopolymer has been shown to be viable sources of alumina-silica resource which could be explored as a replacement for OPC.
- The application of CPSA-geopolymers significantly enhances the strength of highly expansive clays by transforming the microstructural characteristics of the treated clay through the development of
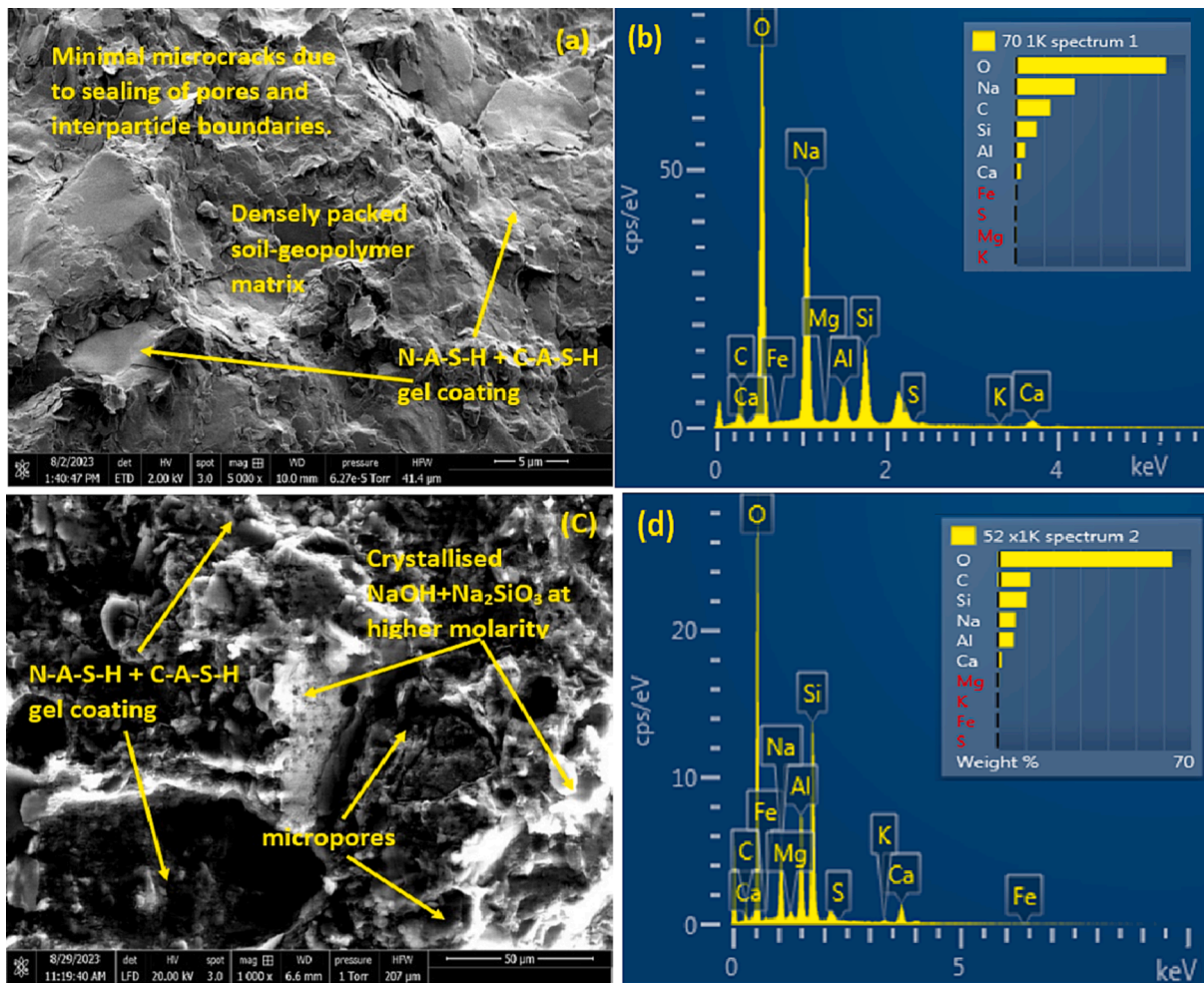
Fig. 15. Scanning electron micrographs and EDX results of CPSA-geopolymer treated HEC. (a) SEM of treated HEC containing 30 %CPSA and 15 M activator at AL/P of 0.55 (b) EDX of treated HEC containing 30 %CPSA and 15 M activator at AL/P of 0.55 (c) SEM of treated HEC containing 30 %CPSA and 12 M activator at AL/P of 0.55 (d) EDX of treated HEC containing 30 %CPSA and 12 M activator at AL/P of 0.55.

N-A-S-H cementitious gels thereby increasing the UCS of the soil up to a maximum value of 220 % over OPC treatment.

- Stabilisation of expansive clay with CPSA-geopolymer results in improved resistance against water ingress into the fabrics of the stabilised clay thereby reducing the risks of heaving and shrinking during seasonal fluctuations in moisture content. A significant reduction in swell and water absorption of 95 % and 97 % respectively were recorded following treatment with CPSA.
- CPSA-geopolymer proves to be a viable alternative in response to the rising quest for low-carbon binders in place of OPC and lime. It is possible to achieve high strengths in subgrade soils even with weak clays while scoring lower carbon emissions below that of OPC. A reduction in carbon emissions of up to 36 % was recorded at 2250 kPa target 7-day strength when compared to OPC.

CRediT authorship contribution statement

Jeremiah J. Jeremiah: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Samuel J. Abbey:** Writing – review & editing, Supervision, Software, Resources, Project administration, Investigation, Data curation, Methodology, Conceptualization. **Colin A. Booth:** Supervision, Software, Resources, Project administration. **Eyo U. Eyo:** Visualization, Resources, Project administration.

Declaration of competing 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.

Data availability

Data will be made available on request.

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