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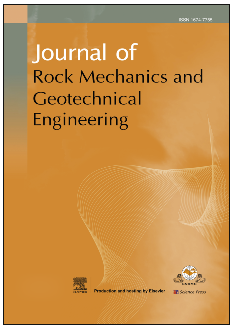

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Incorporation of a nanotechnology-based additive in cementitious products for clay stabilisation

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Abstract: The mechanical performances and water retention characteristics of clays, stabilised by partial substitution of cement with by-products and inclusion of a nanotechnology-based additive called RoadCem (RC), are studied in this research. The unconfined compression tests and one-dimensional oedometer swelling were performed after 7 d of curing to understand the influence of addition of 1% of RC material in the stabilised soils with the cement partially replaced by 49%, 59% and 69% of ground granulated blast furnace slag (GBBS) or pulverised fuel ash (PFA). The moisture retention capacity of the stabilised clays was also explored using the soil-water retention curve (SWRC) from the measured suctions. Results confirmed an obvious effect of the use of RC with the obtained strength and swell properties of the stabilised clays suitable for road application at 50% replacement of cement. This outcome is associated with the in-depth and penetrating hydration of the cementitious materials by the RC and water which results in the production of needle-like matrix with interlocking filaments – a phenomenon referred to as the 'wrapping' effect. On the other hand, the SWRC used to describe the water holding capacity and corresponding swell mechanism of clays stabilised by a proportion of RC showed a satisfactory response. The moisture retention of the RC-modified clays was initially higher but reduced subsequently as the saturation level increased with decreasing suction. This phenomenon confirmed that clays stabilised by including the RC are water-proof in nature, thus ensuring reduced porosity and suction even at reduced water content. Overall, the stabilised clays with the combination of cement, GGBS and RC showed a better performance compared to those with the PFA included.

Keywords: cement; ground granulated blast furnace slag (GBBS); fly ash; RoadCem (RC); swell; stabilisation; unconfined compressive strength; soil-water retention curve (SWRC)

1. Introduction

The present rising trend in world population has made land development activities on areas having an abundance of weak soils unavoidable. Engineers have often recognised that the construction of vital infrastructures on very soft soils is a challenging task. Besides, the physical damage caused to building properties by weak expansive soils and the resultant estimated costs are well-known around the globe (Magdi, 2015; Mezhoud et al., 2017). Chemical treatment or soil stabilisation introduced several decades ago has proven to be a very cost-effective technique amongst the potentially available methods used to improve the engineering performances of weak soils (Petry and Armstrong, 1989; Ahnberg et al., 1995; Uddin et al., 1997; Bergado et al., 1999; Nalbantoglu and Tuncer, 2001; Horpibulsuk et al., 2004; Al-Rawas et al., 2005; Seco et al., 2011; Khemissa and Mahamedi, 2014; Tran et al., 2014; Abbey et al., 2017; Eyo et al., 2017, 2018). Stabilising agents such as lime and cement have been used traditionally over the years as binders to improve the engineering qualities of soft soils. However, the significant environmental impacts associated with their production are a global concern. It is estimated that 1 tonne of cement produced could lead to 5000 MJ of energy consumed, 1.5 tonnes of non-renewable resources released and 1 tonne of CO_2 emission (i.e. 8% of the total global CO_2 emissions) (Higgins, 2007; European Commission, 2010; Olivier and Peters, 2018). Apart from the above-mentioned health and environmental concerns, soil-cement stabilisation could in some cases cause the growth of ettringite which is a deleterious expansive mineral (Rao et al., 2008; Verástegui-Flores and Di Emidio, 2014).

Developments in knowledge and research are currently shifting from an over-dependence on cement and lime to the production and usage of waste materials, industrial by-products, organics, polymers, etc., in engineering applications (Obuzor et al., 2011; Celik and Nalbantoglu, 2013; Ganjian et al., 2015; Al-Swaidani et al., 2016; Sharma and Sivapullaiah, 2017; Behnood, 2018). Two examples of industrial by-products considered in ground improvement works are ground granulated blast furnace slag (GGBS) and pulverised fuel ash (PFA or fly ash). GGBS and PFA are desirable in soil stabilisation projects not only because of their pozzolanic effects but also because they are cost-effective, energy-saving and environmentally friendly (Wild et al., 1999; Higgins, 2005, 2007; Mohamad et al., 2016; Ghadir and Ranjbar, 2018). However, the replacement of cement with industrial by-products is in most cases limited to low quantities of the later; therefore, the environmental impact of cement still remains a concern (Deka, 2011; Abbey et al., 2016; Keramatikerman et al., 2016; Abbey and Olubanwo, 2018; Zhang et al., 2018).

It is suggested that the engineering properties achieved by partial replacement of cement with industrial by-products could be further enhanced by incorporating minimal quantities of a nanotechnology-based additive called 'RoadCem (RC)' (Ventura and Koloane, 2005; Marjanovic et al., 2009; Ouf, 2012; Wu, 2015). RC is a fine-grained additive that is based on synthetic zeolites, alkali earth metals and complementary complex activator to enhance its unique properties. Just like most by-products, RC has been tested and found to possess excellent environmental credentials and macro-economic prospects (Montero et al., 2012; Blass, 2017). It is manufactured majorly by PowerCem Technologies in Moerdijk, the Netherlands, who has designed it primarily for applications in road construction and stabilisation. In spite of its potential merits as a cement improver, only limited research has been carried out to ascertain the effect of incorporating RC in soils stabilised by replacement of cement with GGBS or PFA on engineering properties. Moreover, several regions of the world, especially the UK, are slow in the adoption of this product in vital road and railway infrastructures. Wu (2011, 2015) carried out some studies to evaluate the mechanical and shrinkage behaviours as well as the crack susceptibility of cement/RC-stabilised soils. The influence of RC was observed in the reduced drying shrinkage (up to 50% at 28 d) of the cement-stabilised soils. Reductions in the tensile stresses and the potential of transverse cracks (by 50%) were also attributed to the effect of RC addition. Faux (2015) proposed a design method for working platforms by comparing the influence of using

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cement bound material (CBM) and cement/RC combination in the stabilised soil. The use of cement/RC ensured a satisfactory reduction in the platform thickness occasioned by an increase in unconfined compressive strength (UCS) and elastic modulus (E_{mod}) as compared to the design based on CBM. Ouf (2012) experimentally assessed the strength and free swell index of a soil stabilised by cement/RC and cement/RC/lime/GGBS combinations in different mix proportions. They concluded that while the UCS and E_{mod} increased, the free swell index reduced with increases in the total binder content and the curing duration. Ventura and Koloane (2005) examined the addition of 1% of RC to cement replaced by fly ash in both fine-grained sand and fine-grained clayey sand. The studied engineering properties (California bearing ratio, UCS, durability, erodibility and flexibility/stiffness) showed a satisfactory performance thus complying with the standards used.

It is evident from the foregoing that the swelling potential and the moisture encapsulation properties of soils stabilised by addition of RC have been rarely reported. Therefore, investigation into the firmly-established sustainability credentials of GGBS and PFA in addition to the potential impact of RC on the volume change and soil-water retention behaviour of cement-GGBS/PFA stabilised soil is the main motivation in this context.

2. Materials and methods

2.1. Clay

Two model clays having extreme plastic properties are used in this research for purpose of comparison after stabilisation. Preliminary studies were performed as outlined in Eyo et al. (2019) after which a low plastic kaolinite (china clay) and a highly plastic clay composed essentially of 25% kaolinite and 75% bentonite were considered. The kaolinite and bentonite are materials processed in powdered form and supplied commercially by Mistral Industrial Chemicals Company in Northern Ireland, UK. The chemical tests from X-ray fluorescence (XRF) to obtain the main oxide compositions of the kaolinite and bentonite minerals used are presented in Table 1.

2.2. Cement

The cement binder (CEM I) utilised in this study was sourced from the Hanson Heidelberg group in the UK. The properties of this cement comply with the requirements of BS EN 197-1 (2011) CEM I Portland cement with a strength class of 52.5 N. This Portland cement type ensures rapid setting and rapid hardening which makes it very suitable for urgent works in cold climatic conditions. The major chemical compositions of the cement are shown in Table 2.

2.3. Ground granulated blast furnace slag (GGBS)

The GGBS used was produced and tested following the methods outlined in BS EN 196-2 (2013) by the Hanson Heidelberg Cement Group, UK. The results of chemical analysis are given in Table 2.

2.4. Pulverised fuel ash (PFA)

The used PFA is manufactured to comply with the standard BS EN 450-1 (2012) (loss on ignition (LOI) Category B and Fineness Category S) and was sourced from CEMEX Cement Limited, UK. Table 2 presents some of the relevant properties of the used PFA as obtained from the supplier.

2.5. RoadCem (RC)

RC additive was supplied by PowerCem Technologies in Moerdijk, the Netherlands. The chemical properties of this additive are also given in Table 2.

Table 1. Chemical composition of clay minerals.

Material	Oxide composition (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	Na_2O	SO_3	Mn_2O_3	LOI
Kaolinite	49	36	0.75	0.06	0.3	1.85	0.02	0.1	-	-	12
Na-bentonite	57.1	17.79	4.64	3.98	3.68	0.9	0.77	3.27	0.11	0.06	7.85

Table 2. Chemical composition of binders and additive.

Binder/additive	Oxide composition (%)											Method
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	Na_2O	SO_3	Mn_2O_3	LOI	
CEM I	20.7	4.6	2.3	64	1.7	0.4	0.3	0.1	2.9	0.1	2.9	BS EN 197-1 (2011)
GGBS	34.1	13	0.51	39	9.5	0.5	1.3	0.3	0.3	0.7	1.9	BS EN 196-2 (2013)
PFA	52.1	30.1	4	3	1	2.1	1	2.1	1.2	-	4	BS EN 450-1 (2012)
RC*	21.2	1.7	0.63	47.1	4	7.46	-	-	-	-		PowerCem Technologies (2015)

* The oxide component not included in the table is H_2O which is 17.9% for RC.

2.6. Material combination programme and preparation

The clays were sampled in their natural state and thoroughly mixed in dry state with the binders. In keeping with the primary objective of this research, cement is utilised as the reference binder or stabiliser that needs to be partially replaced or substituted in the stabilised soils. 8% of the cement binder calculated by dry weight of the clays was added to the clays. This predetermined cement quantity was chosen based on some already established procedures and recommendations in the literature for the enhancement of the engineering qualities considered in this study (Chen, 1975; Broderick and Daniel, 1991; PCA, 1992; Ouhadi et al., 2014; Abbey et al., 2016; Behnood, 2018). The 8% cement (determined by dry weight of the clay soil) was then subsequently replaced by 50%, 60% and 70% of GGBS or PFA each calculated by the actual dry weight of the cement mass. In order to understand the influence of RC, the clay-binder mixtures were prepared by substituting either the GBBS or PFA in their respective mixes with 1% of the RC also determined by dry weight of the cement. This percentage of the RC is generally recommended by its manufacturers as the designed quantity for soil stabilisation (Marjanovic et al., 2009; Faux, 2015; PowerCem Technologies, 2015; Wu, 2015). Hence, the total binder or stabiliser content in the clay did not exceed 8% of the clay mass in each of the stabilised soil mixtures. For the sake of brevity, the cement-GGBS/PFA-RC proportions are represented in terms of the mixture ratio of their percentages by weight (wt%) with their respective notations, as presented in Table 3. A total of 20 different combinations of the stabilisers in their various proportions were produced based on the two model soils used. The proportions of the stabilisers added to the clays are comprehensively enumerated in Table 4.

Table 3. Cement replacement mix proportions.

Mix phase	Cement/GGBS	Cement/GGBS/RC	Cement/PFA/RC

	Mix proportion (wt%)	Designation	Mix proportion (wt%)	Designation	Mix proportion (wt%)	Designation
1st mix	30:70	C30/GGBS70	30:69:1	C30/GGBS69/RC1	30:69:1	C30/PFA69/RC1
2nd mix	40:60	C40/GGBS60	40:59:1	C40/GGBS59/RC1	40:59:1	C40/PFA59/RC1
3rd mix	50:50:0	C50/GGBS50	50:49:1	C50/GGBS49/RC1	50:49:1	C50/PFA49/RC1

Table 4. Soil-stabiliser combinations.

Sample notation	Total stabilizer (wt% of soil)	Percentage of stabiliser (wt% of cement)				Total percentage of stabilisers (wt% of cement)
		Cement	GGBS	PFA	RC	
Soil I	0	-	-	-	-	0
Soil I + C100	8	100	-	-	-	100
Soil I + C30/GGBS70	8	30	70	-	-	100
Soil I + C40/GGBS60	8	40	60	-	-	100
Soil I + C50/GGBS50	8	50	50	-	-	100
Soil I + C30/GGBS69/RC1	8	30	69	-	1	100
Soil I + C40/GGBS59/RC1	8	40	59	-	1	100
Soil I + C50/GGBS49/RC1	8	50	49	-	1	100
Soil I + C30/PFA69/RC1	8	30	-	69	1	100
Soil I + C40/PFA59/RC1	8	40	-	59	1	100
Soil I + C50/PFA49/RC1	8	50	-	49	1	100
Soil II	0	-	-	-	-	0
Soil II + C100	8	100	-	-	-	100
Soil II + C30/GGBS/70	8	30	70	-	-	100
Soil II + C40/GGBS/60	8	40	60	-	-	100
Soil II + C50/GGBS/50	8	50	50	-	-	100
Soil II + C30/GGBS69/RC1	8	30	69	-	1	100
Soil II + C40/GGBS59/RC1	8	40	59	-	1	100
Soil II + C50/GGBS49/RC1	8	50	49	-	1	100
Soil II + C30/PFA69/RC1	8	30	-	69	1	100
Soil II + C40/PFA59/RC1	8	40	-	59	1	100
Soil II + C50/PFA49/RC1	8	50	-	49	1	100

2.7. Experimental procedure

2.7.1. Index property testing

Atterberg limits testing were conducted on the samples by following the procedure as set out in ASTM D4318-17 (2017), while their specific gravities were determined in accordance to the procedure in ASTM D854-10 (2010). The Malvern Mastersizer 2000 which uses the technology of laser diffraction was utilized to analyse the grain sizes of the samples in their dry states (Fig. 1). The moisture contents of the samples used in the subsequent performance of the engineering testing were determined at optimum conditions as derived from the compaction tests in accordance to ASTM D1557-12e1 (2012). However, the moisture contents of the stabilised samples were calculated based on the optimum moisture contents of the samples in their natural states with at least 2% more water added. Following the compaction test, the sample mixes were appropriately removed from the moulds using suitable extractors, wrapped in a cling film and further sealed in zip-lock type bags and preserved under room temperature (22 °C) to cure for a period of 7 d before carrying out further engineering testing. Table 5 presents the relevant geotechnical properties of the natural clays used.

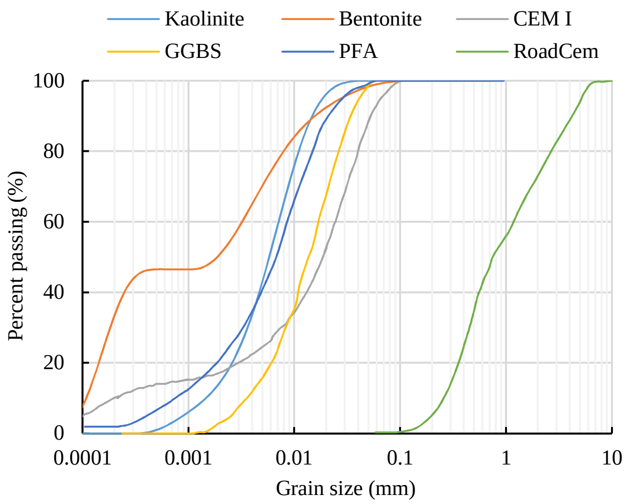


Fig. 1. Analysis of material grain size.

Table 5. Geotechnical properties of the clays.

Clay property	Value		Test standard
	Soil I (K100/B0)	Soil II (K25/B75)	
Liquid limit	58	285	ASTM D4318-17 (2017)
Plastic limit	30	72	
Plasticity index	28	213	
Silt content (%)	74	48	ASTM D422-63 (2007)
Clay content (%)	26	52	
Specific gravity	2.6	2.76	ASTM D854-10 (2010)
Modified activity	0.67	4.06	

MDD (kN/m^3)	15	12.9	ASTM D1557-12e1 (2012)
OMC (%)	17	30	
USCS classification	CL	CH	
UCS (kPa)	190	220	ASTM D2166-00 (2000)
Maximum swell percent (%)	12.6	37	ASTM D4546-14e1 (2014)

Note: K and B represent the kaolinite and bentonite, respectively; MDD and OMC represent the maximum dry density and optimum moisture content of the clay, respectively; USCS means the unified soil classification system; CL is the lean clay; and CH is the clay of high plasticity.

2.7.2. Unconfined compression test

The unconfined compression test was carried out according to ASTM D2166-00 (2000) on the natural and stabilised clay samples of 76 mm in height and 38 mm in diameter after 7 d of curing, and the average value of UCS was determined from at least two of the tested samples. The rate of axial deformation maintained through unconfined compression testing was 1 mm/min.

2.7.3. Swell-deformation test

The conventional one-dimensional (1D) oedometer testing was utilized to determine the free swell-strain of the samples in accordance to ASTM D4546-14e1 (2014) after 7 d of curing. The samples were placed in the oedometer apparatus having a ring of 20 mm in thickness and 76 mm in internal diameter and were made to sit in between two porous stones lined with filter papers. The automated linear variable displacement transducer (LVDT) was set to zero after recording the initial compression under the seating load of 5 kPa. Water was then gradually introduced into the oedometer and the samples were soaked or inundated and then allowed to undergo free vertical swelling for a minimum time period of 24 h until equilibrium was reached. The swell percent was then calculated as the increase in sample height (Δh) divided by the original height (H).

2.7.4. Suction test

Suction measurement ASTM D5298-16 (2016) utilizing the filter paper method was applied in this research to measure a wide range of suctions of the compacted specimens for subsequent determination of the soil water retention properties using the Whatman Grade No. 42 qualitative type filter paper with 55 mm in diameter. Samples prepared as per ASTM D1557-12e1 (2012) were used in the experiment. In order to obtain suctions upon wetting (Dineen, 1997; Melgarejo Corredor, 2004; Jotisankasa, 2005), multiple identical compacted samples were allowed to absorb controlled quantities of water using a syringe. The water was added to increase the degree of saturation by ensuring that the moisture increments were in multiples of 2 g but with an initial addition of 1 g. The saturated samples were then wrapped in transparent cellophane bags and a time period of about 1 h was allowed to ensure adequate penetration and absorption of moisture after which the filter was introduced to measure the total suctions (used as a surrogate for matric suction in this study with the osmotic suction or salt concentration ignored) after a minimum period of 10 d (Nelson et al., 2015). The calibration methods used in the present research for suction measurement are those in following equation for the initially dry Whatman 42 filter paper (Leong et al., 2002):

$$\varphi = \begin{cases} 10^{2.909-0.0229w_\mathrm{f}} & (w_\mathrm{f} \geq 47) \\ 10^{4.945-0.0673w_\mathrm{f}} & (w_\mathrm{f} < 47) \end{cases}$$

where φ is the suction, and w_f is the water content of the filter paper.

2.8. Mathematical models for soil-water retention curve (SWRC)

Laboratory suction data were subjected to a nonlinear regression fitting process to obtain the soil-water retention curve (SWRC) using the models proposed by Fredlund and Xing (1994) and van Genuchten (1980), both which are widely used in engineering practices and presented in Table 6. The soil module function of SoilVision program (version 5.4.08) was utilized to enable an effective nonlinear fit of the suction data using the in-built fitting models.

2.9. Micro-structural examination

Image analysis of selected natural and stabilised clays was carried out to support the description of the mechanism of change occurring in the fabric of the samples. Scanning electron microscope (SEM) observations using the Zeiss apparatus were conducted on the cured, dry and fully vacuumed samples working at a voltage of acceleration of up to 5 kV, minimum distance of 2 µm and minimum degree of magnification of 900×.

Table 6. SWRC fitting models.

Notation	Mathematical model	Source
FX	$\frac{w}{w_\mathrm{sat}} = \left[1 - \frac{\ln\left(1+\frac{\varphi}{h_\mathrm{r}}\right)}{\ln\left(1+\frac{10^6}{h_\mathrm{r}}\right)}\right] \frac{1}{\left\{\ln\left[\mathrm{e}+\left(\frac{\varphi}{a}\right)^n\right]\right\}^m}$	Fredlund and Xing (1994)
vG	$\frac{w}{w_\mathrm{sat}} = \frac{1}{\left[1+\left(\frac{\varphi}{a}\right)^n\right]^m}$	van Genuchten (1980)

Note: w is the gravimetric water content (%); w_sat is the saturated water content (gravimetric water content at soil suction φ = 0); h_r is the fitting parameter, which is a function of the suction at the residual water content; e is the base of natural logarithm; a is the fitting parameter, which relates to the air entry value of the soil (kPa); n is the fitting parameter, being a function of the slope of the SWRC; and m is the fitting parameter, being a function of the residual water content.

3. Testing results

As would be generally observed subsequently in this study, the values of the engineering properties (UCS and swell potential) of the natural clays (Table 5) were much improved when treated with different compositions and quantities of the binders used. However, in keeping with the primary objective of this study, a comparison of the engineering behaviour of the clays stabilised with cement (C) alone and the clays stabilised by C/GGBS, C/PFA/RC and C/GGBS/RC combinations will be mostly considered in the sections following with some interest on the resulting effect of RC.

3.1. Unconfined compressive strength (UCS)

The UCS of soil I treated with cement (C) alone is lower than those treated with all the proportions of C/GGBS/RC combinations considered (Fig. 2a). It could also be noticed that the inclusion of RC in soil I enabled a progressive increase in strength until the highest strength was obtained with 50% cement used in the soil mixes containing C/GGBS/RC in comparison with those of C/PFA/RC and C/GGBS contents. Hence, the mixes containing GGBS seem to perform better than those containing PFA from Fig. 2a. Also, the effect of inclusion of RC in producing the highest strength values is typically seen in Fig. 2b at 50% replacement of cement.

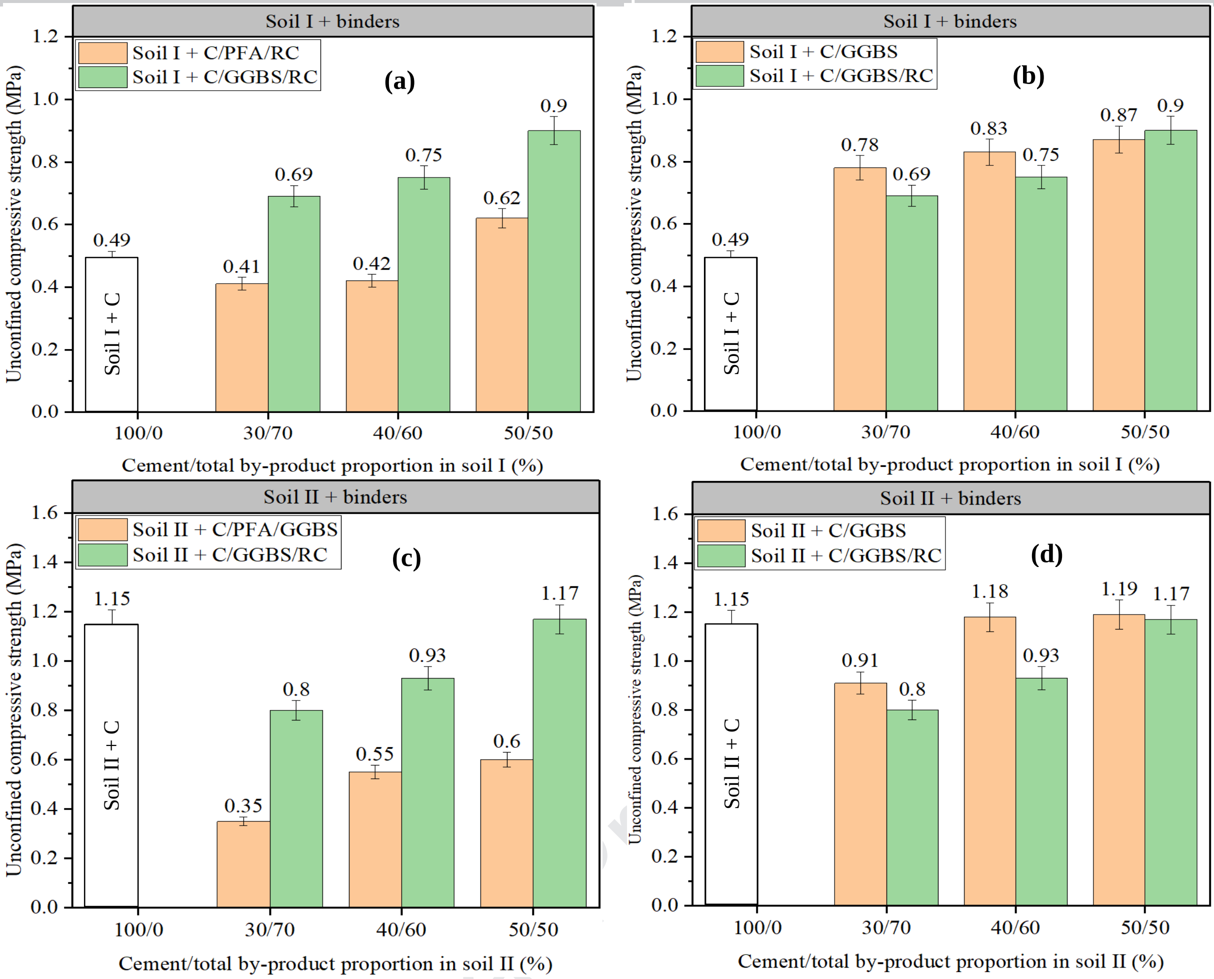


Fig. 2. Unconfined compressive strength (UCS) of stabilised clays: (a) Comparison between cement used alone and by-products binders in soil I; (b) Binder combination comparison showing effect of RC in soil I; (c) Comparison between cement used alone and by-products binders in soil II; and (d) Binder combination comparison showing effect of RC in soil II.

Similar trend does seem to occur as is the case in soil I when considering the effect of treatment on the UCS of soil II. It should be noted that soil II has a much higher plasticity and higher compaction moisture content than soil I as a result of the bentonite present in the former. There is a significant gain in strength brought upon by addition of the binders and their various proportions and combinations. The soil-binder mix with the C/GGBS/RC combination does seem to have higher strength values as compared with mixes containing C/PFA/RC (Fig. 2c). Unlike soil I, the influence of RC in the stabilisation process as the C/GGBS/RC mixes seems to slightly fall below the strength of the stabilised soil without RC at 50% cement content (Fig. 2d).

Having established the positive influence of the RC on the strength properties, a further investigation of the behaviours of the stabilised clays by comparing the mixtures containing C/PFA/RC and C/GGBS/RC combinations and those with cement alone shall be carried out.

3.2. Swell potential

This section explores and compares the degree of swelling of stabilised mixtures containing C/PFA/RC and C/GGBS/RC combinations and those with cement alone. Fig. 3a and b demonstrates the remarkable effect of cement on the reduction of the swelling (lowest values) of soils I and II as compared to the mixes containing the by-products. The stabilised cement/by-product mixes containing GGBS does act to reduce the swelling more than those with the PFA included. The claims of swell reduction are further substantiated by the observations of Fig. 3c and d which shows the strain or deformation path followed during the 1D oedometer swell. The stabilised mixes with the cement/by-product combination at 30% replacement seem to exhibit greater water absorption with a corresponding increase in swelling at the initial and primary phases.

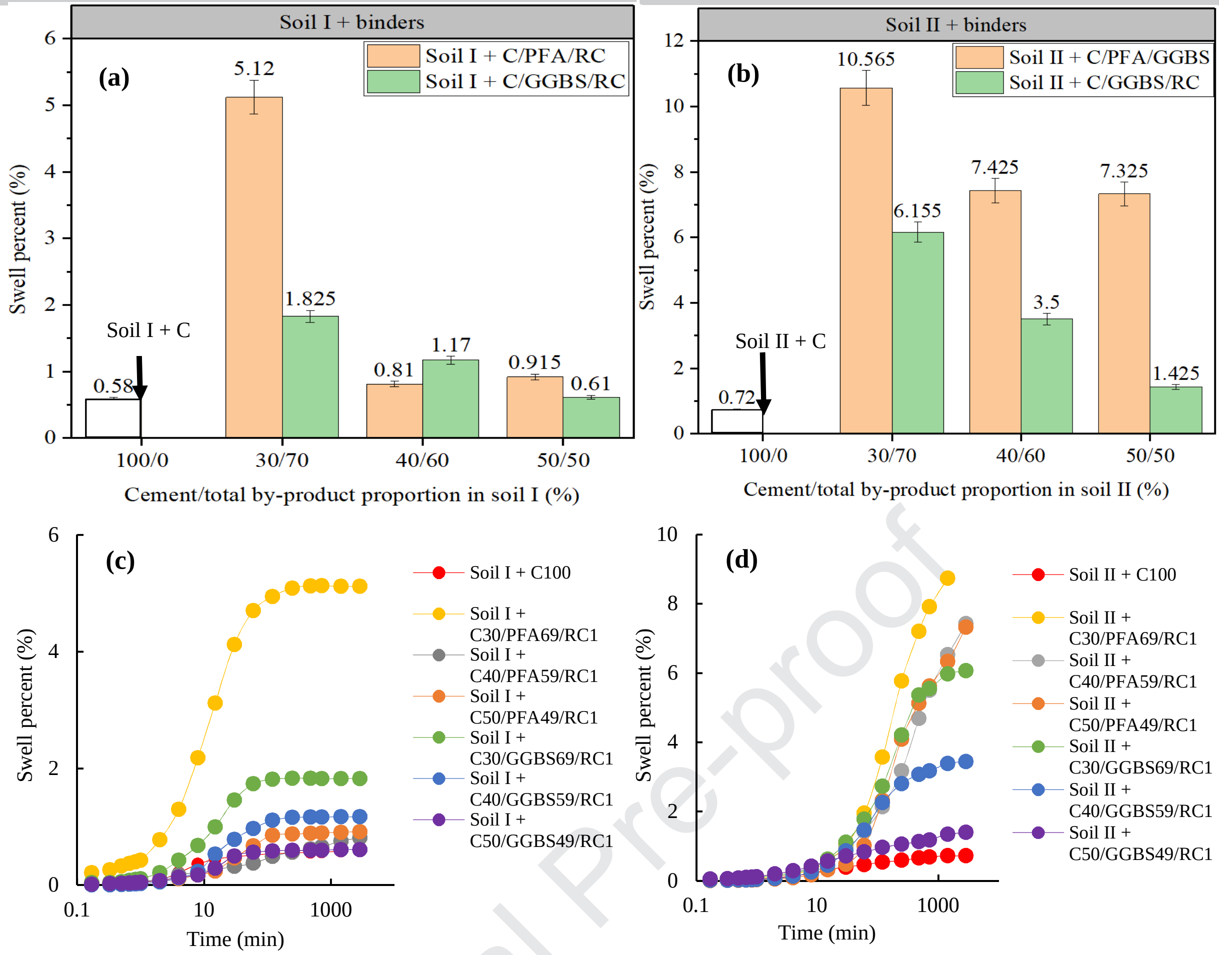


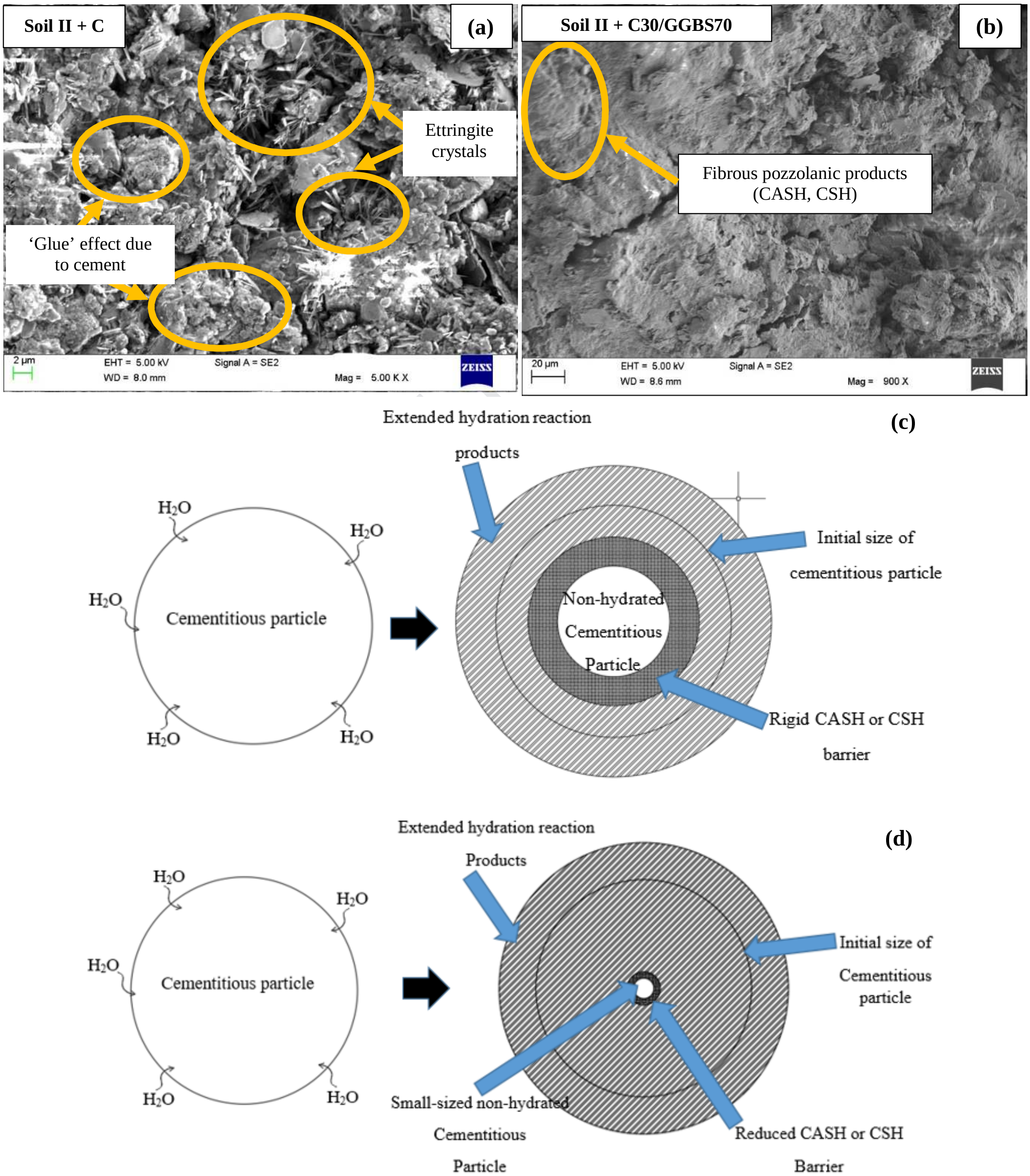
Fig. 3. Swelling potential of stabilised clays: (a) Comparison between cement used alone and by-products binders in soil I; (b) Comparison between cement used alone and by-products binders in soil II; (c) Differences in the swell path followed and water absorbed by stabilised soil I; and (d) Differences in swell path followed and water absorbed by stabilised soil II.

4. Discussion of strength and swell properties of stabilised clays

The change in the engineering properties of clays stabilised by cement alone and C/GGBS or C/PFA combinations are well established (Kaniraj and Havanagi, 2001; Sariosseiri and Muhunthan, 2009; Horpibulsuk et al., 2010; Sarkar and Islam, 2012; Ouhadi et al., 2014; Pourakbar et al., 2015; Wu et al., 2016; Mengue et al., 2017; Por et al., 2017; Zhang et al., 2018). The UCS is often used as an index to quantify the improvement of soils due to chemical treatment. The standard guide for evaluation of the effectiveness of binders used in soil stabilisation as contained in ASTM D4609-08 (2008) sets a minimum target of UCS of 0.345 MPa (50 psi) for treatment to be considered as effective. Moreover, the recommended strength for stabilised layers in practical applications may vary extensively from agency to agency. For example, the methods proposed by Ingles and Metcalf (1972), ACI C230 (1990), and U.S. Army Corps of Engineers (2004), for cement-stabilised soils at 7 d of curing, suggest a range of UCS between 0.7 MPa to 1.4 MPa to be suitable for road sub-base and subgrade under light and heavy traffic. As compared to soil II, soil I treated with cement alone may not meet most requirements for pavement construction. Similarly, soil I stabilised by replacement of cement with all the proportions of by-products containing PFA/RC may not also be suitable for road construction. However, soils I and II stabilised by replacing up to 60% and 70% respectively of the cement with GGBS and GGBS/RC seem sufficient for applications as road sub-base and subgrade.

An investigation of the stabilised soils I and II indicated reductions of their maximum swell potentials as compared to the natural clays given in Table 5. The French standard NF P94-100 (1999) for instance suggests a minimum of 5% swell as an acceptable limit for construction. Meanwhile, Ingles and Metcalf (1972) suggested a minimum of 2% swell for cement-treated soils at 7 d of curing. The Ohio Department of Transport (2011) recommended swell of 1.5% for chemically treated soils. Soils I and II treated with cement meet the above requirements. Unlike their unsatisfactory strength criteria stated above, the stabilised soil I with cement replaced by up to 60% of PFA/RC and GGBS/RC seems to satisfy the swell requirements. However, for the treated soil II, replacement of cement in the mixes by all the proportions of the by-products (PFA/RC and GGBS/RC except at 50% replacement) seems to fall short of the above-recommended values for swelling. It could be seen that even though the UCS of stabilised soil II is very promising with cement replacement, the swell performance on the other hand seems undesirable.

During hydration of cementitious materials, calcium silicate hydrate (CSH) or calcium alumino silicate hydrate (CASH) gels are formed. If cement alone is used in stabilisation of soil having some amount of sulphates (i.e. soil II), ettringite crystals may be formed in some cases (Fig. 4a). However, with the cement partly replaced with GGBS by-product for instance, the ettringite crystals capable of causing expansion are further reduced or eliminated (Fig. 4b) (Wild, 1996; Wild et al., 1999; Celik and Nalbantoglu, 2013). Moreover, the reaction mechanism of cement, GGBS or both could result in production of even more complex hydrates (with complete spherical barrier, as shown in Fig. 4c) that prevents further reaction of the binder materials (Rahimi-Aghdam et al., 2017). However, addition of RC to the cementitious binders enables further and deeper penetration of it and water of hydration by breaking the CSH or CASH barrier, causing most of the cementitious materials to react with increased pH value (Fig. 4d). A larger proportion of water is then converted to crystalline water with more crystals growing into the spaces left in the hydration process. The extended crystallisation process coupled with a drastic decrease in the evolution of heat of hydration influences the soil-stabiliser binding mechanism which at this time would change from just the 'gluing' effect (occurring if only cementitious binders are used as in Fig. 4a) to 'wrapping' effect (matrix with interlocking filaments), a phenomenon which is only made possible by the presence of the RC additive as an agent in the stabilisation process (Fig. 4e). The 'wrapping' and encapsulation effects associated with formation of the crystalline reaction product in the hydration process are also responsible for the modified cementitious product to bind very heavy clays together, a result which is nearly impossible when using cementitious binders alone. A decrease in the porosity during the initial hydration process and an increase in the structural crystalline matrices can lead to increase in the compressive strength, reduction in the swelling properties and increase in the durability of the mixed product. The composition of RC (mainly alkali and zeolites) also enables other processes to occur simultaneously in the clays and probably other similar materials through ionic exchanges, modifications, charge neutralization and replacements.



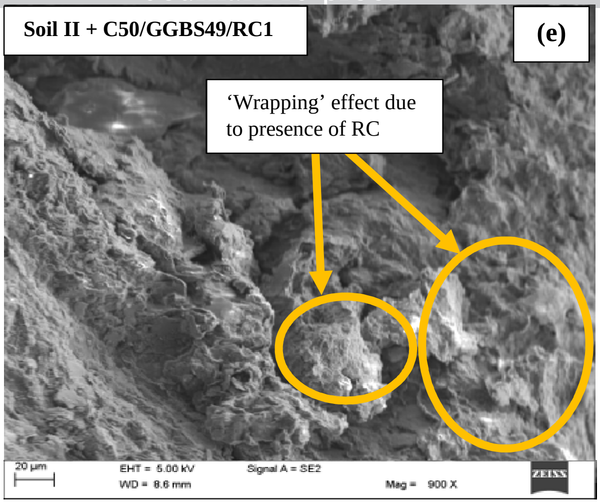


Fig. 4. Mechanism of cement and by-product modified soil: (a) Needle-like ettringite crystals due to cement in stabilised soil; (b) Formed pozzolanic products caused by cement and GGBS addition; (c) Mechanism of stabilisation without inclusion of RC; (d) Mechanism of stabilisation with inclusion of RC; and (e) Transformed stabilised product showing wrapping effect due to RC.

5. Soil-water retention property

Stabilised soils used as materials in roadworks are intended to be above the groundwater table or near the surface of the ground (active zone) and as such, they are considered to exist essentially in an unsaturated state. Hence, their hydraulic characteristics interpreted through the SWRC enable a description and understanding of the corresponding mechanical behaviour under unsaturated condition. The SWRC describes the relationship between the mass of moisture presented in a soil and the corresponding energy state or suction within the pore water. The behaviour of the SWRC is herein used to forge an understanding of the effect of stabilisation on the two model soils used. The moisture retention behaviour of the samples stabilised with 50% replacement of the cement is studied in this section, since these appear to provide the most acceptable performance in terms of the studied strength and swell properties above. Furthermore, the SWRC of the stabilised samples are analysed irrespective of the curing condition given that the relatively shorter duration of curing adopted in this study has been proven to have very minimal and in most cases no effect on the stabilised curve (Stoltz et al., 2012; Elkady and Al-Mahbashi, 2013; Zhang et al., 2014, 2017).

5.1. SWRC models for natural and stabilised clays

The variations of air entry value (AEV) with the stabilised soils are plotted in Fig. 5. AEV is that value of suction at which air will begin to penetrate the largest void structure and this occurs at the transition zone from unsaturation to saturation or vice versa. As it could be seen, the FX fitting model seems to provide a lower-bound AEV compared to the vG model. Since the soil's treatment mechanism (mainly the production of hydration or pozzolanic products) by calcium-based binders (e.g. cement, GGBS, PFA or class C fly ash) would ultimately lead to a closely-packed and well-bound treated soil particles, it therefore follows that the AEV should rise as displayed in Fig. 5 when compared with the natural soil due to the binding effect that is occasioned by the used stabilisers (Khattab and Al-Taie, 2006; Puppala et al., 2006; Elkady et al., 2015). Cement-stabilised soils I and II seem to produce the largest AEV compared to the natural soils and those stabilised by a combination of cement and the other by-products. This indicates that greater suction (capillary behaviour) tends to occur in the soil-cement samples (as compared to the samples having the by-products) due to a preponderance of smaller pore spaces as the wetting progresses. Moreover, the AEVs of soil II stabilised by cement partly replaced with the by-products are generally higher than those of the stabilised soil I. Besides the high amount of clay particles contained in soil II, the availability of more water (i.e. higher optimum moisture plus added water during saturation) could have probably enhanced the formation of more pozzolanic products with more and more soil voids filled by the by-product stabilisers used, and hence higher AEV could be obtained. It should also be noted that the same reason was earlier suggested for the higher UCS values of stabilised soil II as compared to stabilised soil I.

On the other hand, Fig. 6 indicates that both the vG and the FX models seem to predict almost identical SWRC with the only differences observed as the values of suction become higher. However, it could be said that the best fit is generally obtained using the FX model as seen from the coefficient of determination (R^2) for the SWRC and is thus recommended for the stabilised medium-to-high plasticity clays.

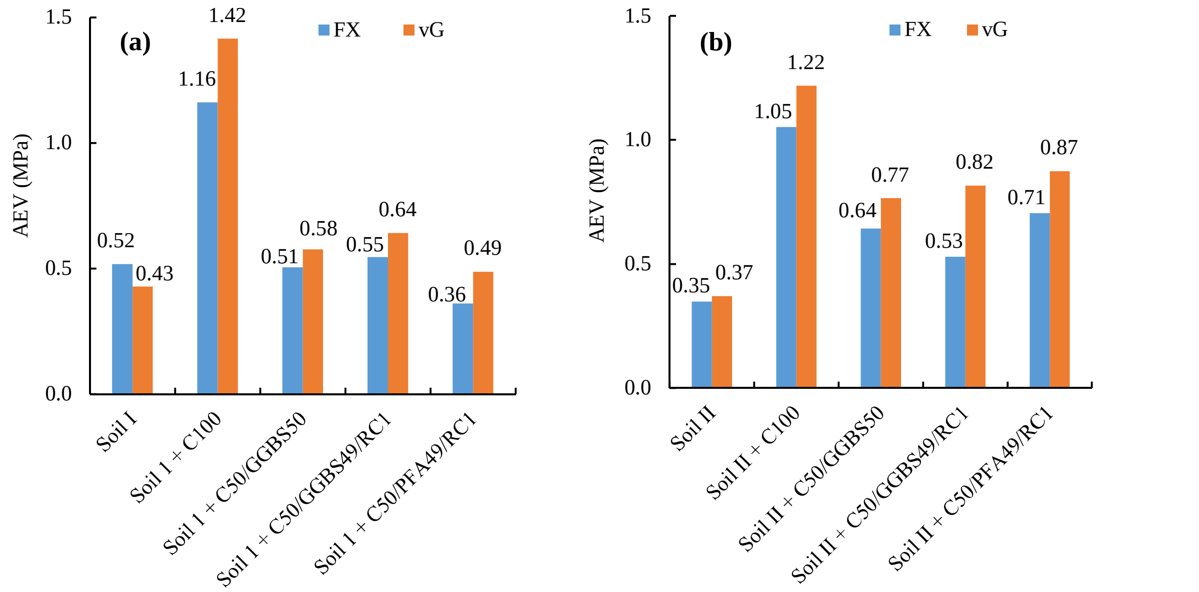
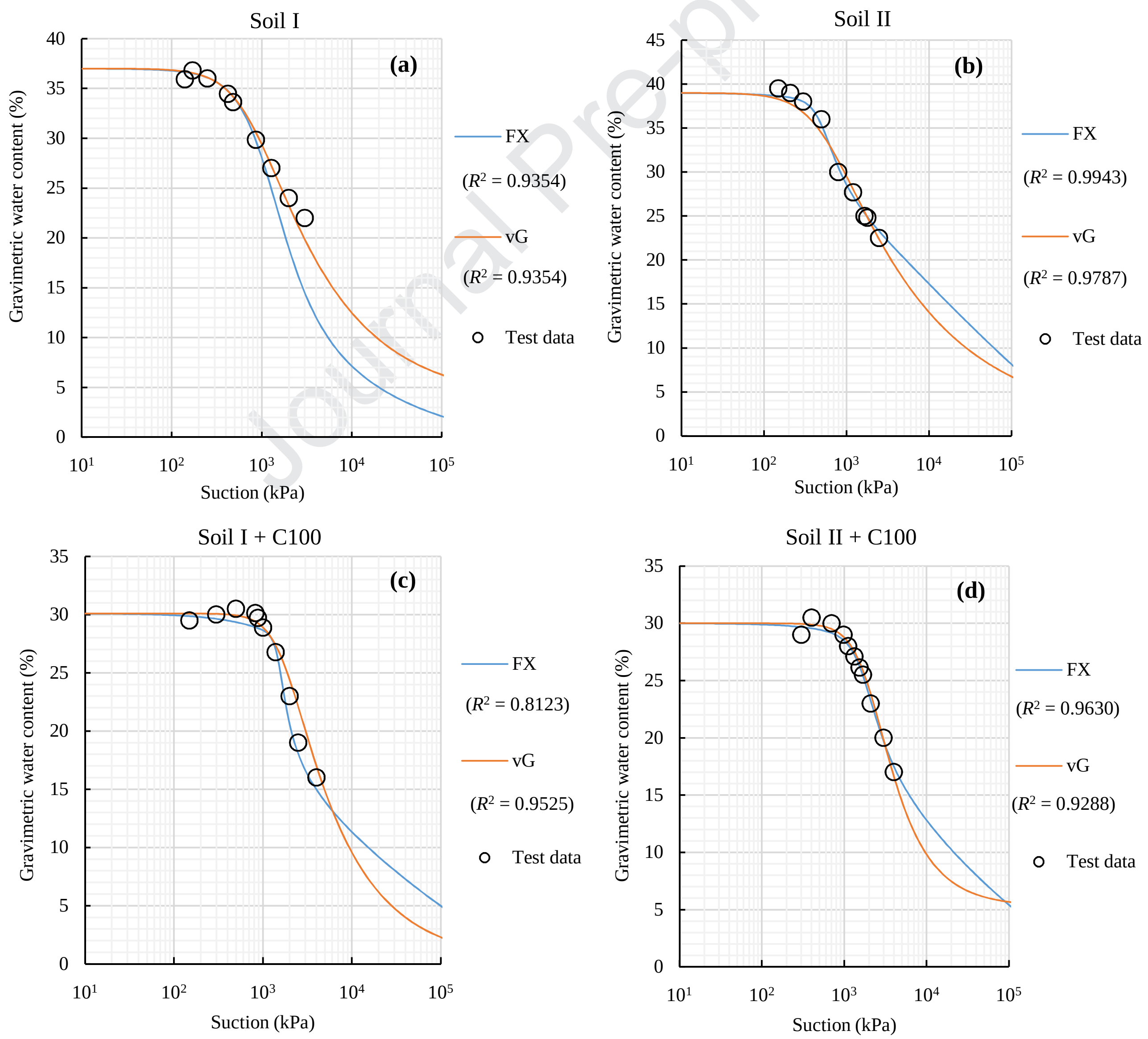


Fig. 5. Air entry value (AEV) for natural and stabilised clays: (a) Comparison between FX and vG AEVs for soil I; and (b) Comparison between FX and vG AEVs for soil II.



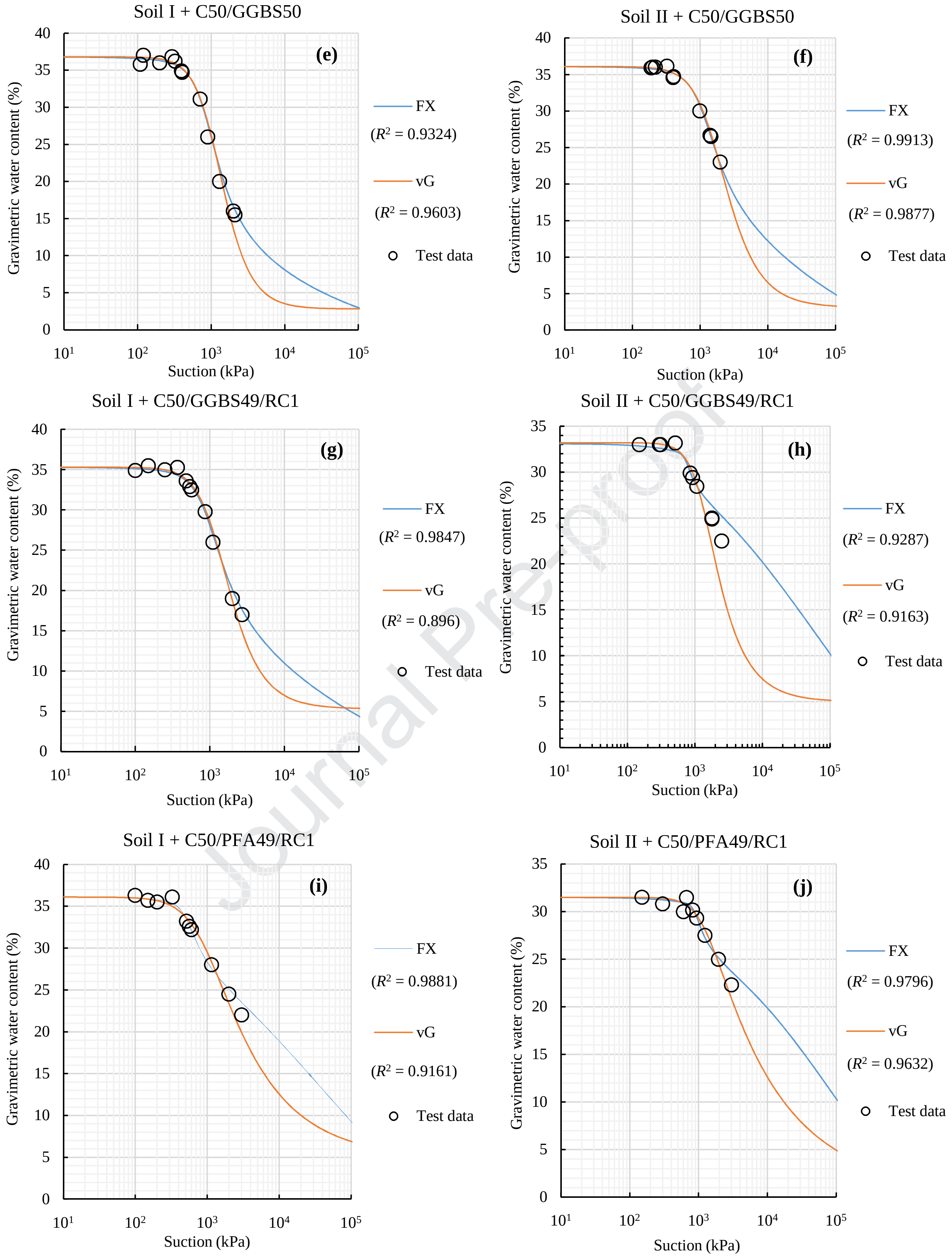


Fig. 6. SWRC model comparisons for natural and stabilised clays: (a) Soil I; (b) Soil II; (c) Soil I + C100; (d) Soil II + C100; (e) Soil I + C50/GGBS50; (f) Soil II + C50/GGBS50; (g) Soil I + C50/GGBS50/RC1; (h) Soil II + C50/GGBS50/RC1; (i) Soil I + C50/PFA50/RC1; and (j) Soil II + C50/PFA50/RC1.

Further comparison of the effects of by-product addition in stabilised samples is carried out by relying on the FX model. As could be observed in Fig. 7a, the stabilised as-compacted soil I samples tend to exhibit greater moisture retention capacity during the initial stages (water entry phase with suction approximately above 1000 kPa) of the wetting process as compared to the natural soil. This is incidentally within the range of osmotic suction. Hence, this phenomenon should be expected given a modification of the physicochemistry and microstructure of the soil caused by treatment with binders. The exchangeable calcium ions from the binders alter the electrical charge (double diffused layer) that surrounds the clay, enabling the formation of flocs (particles being attracted to one another) and increase in the moisture content of the compacted mixed product (Bell, 1996; Chew et al., 2002; Tedesco and Russo, 2010). However, as the suction reduces further (especially below 1000 kPa) upon saturation progress, the stabilised soil I using cement alone tends to possess the lowest gravimetric moisture. It has been suggested that at reduced suction levels, the moisture storage mechanism is determined mostly by capillarity and the retention curve is thus influenced by soil fabric (Tedesco, 2006). Accordingly, it is presumed that cement replacement by either GGBS or PFA should lead to more pores being filled and a more reduced gravimetric moisture as compared to cement used alone (Keramatikerman et al., 2016; Zhang et al., 2018). However, it seems that the presence of RC may have distorted this phenomenon slightly for the stabilised soil. It is also interesting to note the similar moisture retention behaviour of cement-stabilised and C/GGBS/RC-stabilised soil I at the higher suction range (above 1000 kPa).

The stabilised soil II seems to exhibit almost the same phenomenon as those of the treated soil I except for the slightly reduced water retention of the cement-stabilised clay as compared to the natural clay during the initial stages of the wetting process (Fig. 7b). This could suggest a less pronounced effect of the cement used alone on a soil with higher amount of the clay fines at relatively higher suctions as compared to the by-products added. It could also be noticed that regardless of the higher plasticity of soil II and its higher initial moisture content at optimum, the gravimetric moisture contents (at the low suction ranges) of stabilised soil II do not vary as much from those of stabilised soil I for all the binder combinations considered. Hence, beyond the AEV and as the suction gradually decreases on the wetting curve, the difference in soil's initial properties (such as plasticity, optimum moisture and MDD) of both stabilised soils I and II seems to bear little effect on the amount of moisture absorbed. This claim may need some more validation using clays having different properties as those given in this study. However, it should be borne in mind that the AEVs of the stabilised soil II are generally higher than those of the stabilised soil I (Fig. 5), which could be partly due to the reduced pore sizes (hence lower permeability) of the compacted soil II brought about by the production of more hydration products (CASH and CSH) as a result of more available water (higher optimum moisture and water for saturation or wetting) as mentioned earlier.

Overall, it can be inferred from Figs. 5 and 7 that much smaller void spaces are available for the penetration of the added water during the saturation process in the stabilised soil when only the cement is utilised compared to the combined cement/by-product materials used, especially at suctions below about 1000 kPa. In other words, the fast reacting cement used alone in the stabilisation of the soils seems to thrive relatively more in the presence of sufficient hydration moisture. This further substantiates the lowest swelling potential value obtained (at zero suction) with the clays stabilised by cement only (Fig. 3).

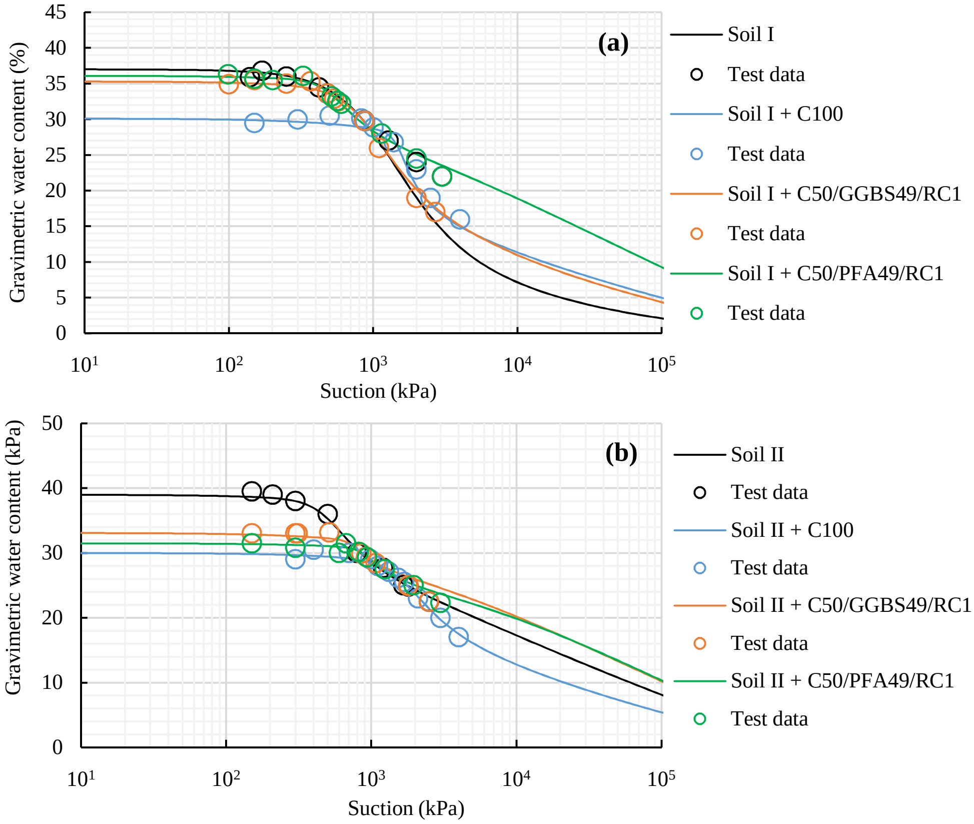


Fig. 7. SWRC depicting the effect of cement and by-product binders on the stabilised clays: (a) Soil I; and (b) Soil II.

Table 7. FX fitting model parameters.

Sample	*a* (kPa)	*n*	*m*
Soil I	990	2.17	0.87
Soil I + C100	2322	12.8	1.74
Soil I + C50/GGBS50	746	3.53	0.55
Soil I + C50/GGBS49/RC1	488	6.99	0.11
Soil I + C50/PFA49/RC1	467	5.69	0.14
Soil II	1114	4.81	0.1

Soil II + C100	1529	4.17	0.3
Soil II + C50/GGBS/50	963	3.19	0.41
Soil II + C50/GGBS49/RC1	706	12.31	0.06
Soil II + C50/PFA49/RC1	854	10.26	0.08

5.2. Effect of RC on SWRC

A comparison to depict the effect of addition of RC to the stabilised mixes is plotted in Fig. 8. The main observation is that the SWRCs of the stabilised samples (soils I and II) with RC content become relatively 'flatter' (demonstrated by the higher *n* values of Table 7), which thus clearly demonstrates the effect of RC in retaining moisture as claimed earlier. Initially though, the water-holding capacity of the stabilised soils having the proportion of RC is higher but tends to reduce as the saturation level increases with decreasing suction. Hence, further hydration may have possibly occurred with more saturation leading to the formation of a water-proof structure with reduced porosity at reduced suction. The greater moisture retention property is promising for contaminant encapsulation during dredging activities as suggested by Zhang et al. (2018) while the relatively reduced porosity (compared to the combination without RC) at low suctions is desirable for swell reduction in the subgrade of pavement structures. But it should be recalled that at reduced suction levels, the rapid hardening cement used solely to stabilise the clays does possess slightly more reduced porosity as compared to the stabilised clays with the RC included. This further supports the claim made previously that cement replacement with the by-products considered in this research is more likely to give more satisfactory outcome in terms of strength improvement than reducing swell.

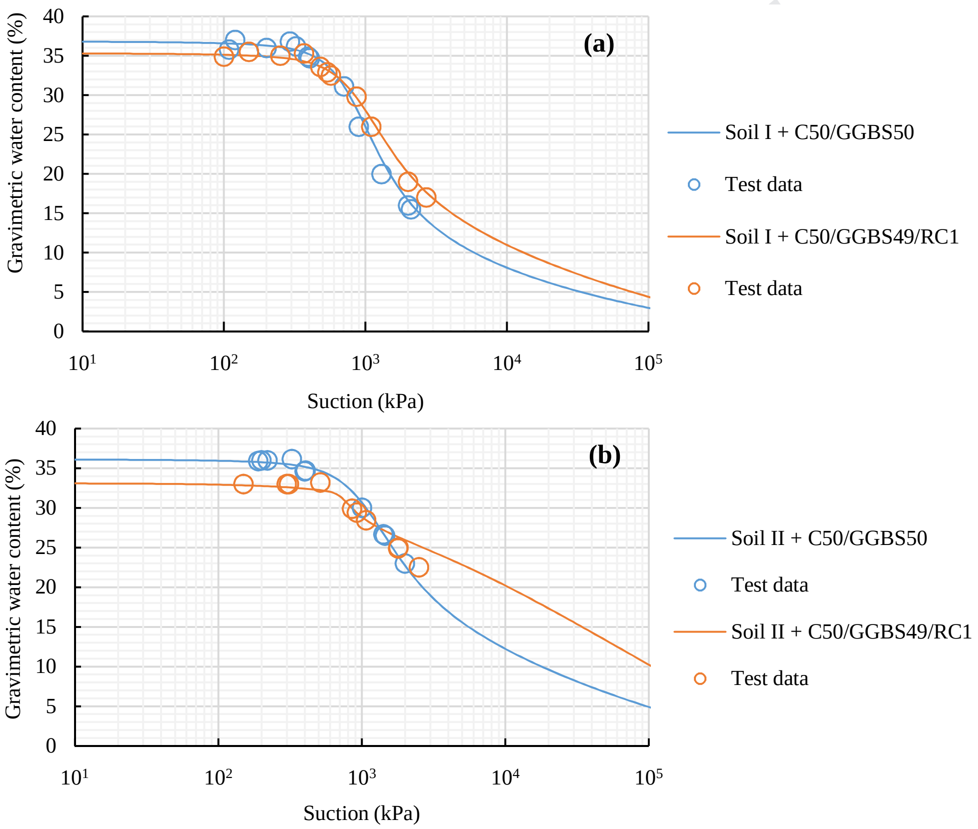


Fig. 8. Effect of RC addition on the stabilised clays: (a) Soil I; and (b) Soil II.

5.3. Relationship between fitting model and engineering properties of stabilised clays

Some of the fitting parameters proposed by FX model have been known to bear important relationships with properties such as strength and swell of natural clays at least empirically (Thakur and Singh, 2005; Thakur et al., 2005; Rao et al., 2011). However, with the clay stabilised by binders, the mechanism of hydration and production of pozzolanic products (CASH or CSH) does intrinsically alter the behaviour, not least the pore size structure and distribution (Puppala et al., 2006; Lin and Cerato, 2012; Zhang et al., 2018). The FX model parameter *n* is one of the shaping functions of the SWRC that depends on the rate of extraction (for desorption curve) or imbibition (for adsorption curve) of water from or into the soil particles. It determines the slope portion of the SWRC, the portion of the curve that also invariably influences the nature of the void structure of the soil. A semi-empirical relationship between the FX model parameter *n* and the stabilised engineering properties is shown in Fig. 9. The best correlation occurs with the swelling potential indicating the dependence of this property on the pore morphology of the stabilised clays. An increase in the parameter *n* which may be invariable suggests a better retention property of the stabilised soils and eventual reduction in swelling as the suction reduces to zero is clearly depicted in Fig 9. On the other hand, the parabolic fitting line seems to give the best fit even though this is still a rather unsatisfactory relationship between the parameter *n* and the UCS as seen in the reduced coefficient of determination (R^2). No clear description of this poor trend can be given except that unlike swelling, the stress path followed for determination of the UCS is due to external compressive loading instead of wetting.

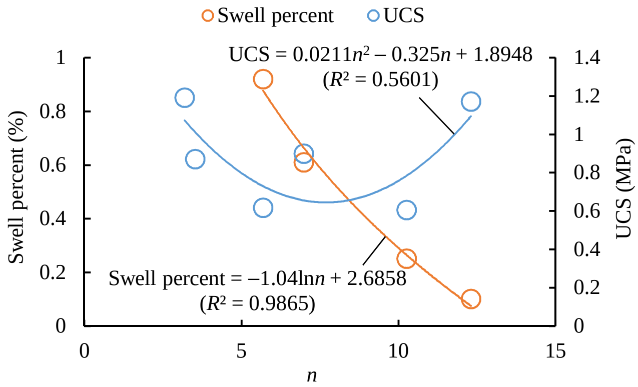


Fig. 9. Relationship between FX parameter and the studied stabilised clay properties (UCS and swell percent).

6. Conclusions

The engineering properties and moisture encapsulation capacity of stabilised clays involving the partial replacement of cement (C) with by-products such as GGBS and PFA and the inclusion of RC were investigated in this study. Overall, the stabilised clays with the C/GGBS/RC combination showed better performance compared to those with the PFA included. The major findings are drawn as follows:

(1) The UCS increased progressively until the highest strength was obtained with 50% of the cement used in the clay mixes containing C/GGBS/RC in comparison with the clays stabilised by using cement alone. The effect of using RC on the strength was confirmed by comparing with the mixtures without RC. Overall, the obtained UCS of the stabilised material with the cement replacement satisfies the requirements for road construction.

(2) A gradual reduction in the swelling potential of the stabilised clays with the cement replaced by 70%, 60% and 50% of the by-products which included 1% of the RC was observed. However, both clays stabilised using cement alone showed greater reduction. Notwithstanding, swell potential value at 50% cement replacement with the by-products was adjudged to have met standard requirements.

(3) Beyond the AEV and as the suction gradually decreases on the wetting curve of the moisture retention curve, the difference in soil properties (such as plasticity, optimum moisture and MDD) of both stabilised clays seemed to bear little effect on the amount of moisture absorbed.

(4) The moisture retention of the RC-modified clays was initially higher but reduced subsequently as the saturation level increased with decreasing suction. This phenomenon confirmed that the clays stabilised by including the RC are water-proof in nature, which ensures reduced porosity and suction even at reduced water content.

Declaration of Competing Interest

The authors wish to confirm that there are no known conflicts of interests associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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Highlights

- RoadCem (RC) inclusion in stabilised clays ensures satisfactory standard performance
- 50% cement replacement by RC, GGBS and PFA satisfies requirements for road application
- RC-modified clays produce reduced porosity and moisture even at reduced suction
- Stabilised clays with cement-GGBS-RC combinations ensures better performance.