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ORIGINAL PAPER

Experimental evaluation of kaolin stabilised with class F fly ash

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Abstract
This study aims to investigate the effectiveness of fly ash (FA) in stabilising a kaolin soil through laboratory tests. Kaolin is an example of moderate plasticity clays that require stabilisation methods for construction purposes. The influence of FA on the improvement of kaolin is studied by varying its dosages in the mixtures (0%, 10% to 20%) as well as the cement content, used as an activator in different percentages (5 and 7%). The influence of the dry unit weight and the curing time of the soil mixture is also analysed through unconfined compressive strength and indirect tensile strength tests. The experimental results show that the strength increases linearly with both FA and cement contents. Moreover, higher initial dry unit weights also yield higher final strengths. To further assess the improvement, the application of the porosity over the volumetric cement content ratio, as the main variable, succeeded in attaining a relationship with the strength and the stiffness of the studied soil. Results for the combined effect of the porosity and the volumetric cement on the secant modulus were also determined. Furthermore, a unique relationship was obtained combining porosity, volumetric cement and FA content.

Keywords Ground improvement · Soil stabilisation · Class F fly ash · Kaolin · Unconfined compressive strength · Tensile strength

Introduction and literature review

Soil stabilisation is a method of improving the performance of a soil to suit the geotechnical requirements of a project, commonly used in soft soils such as clays, silts and organic soils. In recent years, the use of fly ash (FA) for stabilisation of soils has received much attention as an alternative to conventional chemical additives; using FA has a carbon emission factor (i.e. the rate of pollutant released to produce a kg of material) of about 0.027 $kgCO_{2\_equivalent}/kg$, while more conventional methods using Portland cement have values of 0.92 $kgCO_{2\_equivalent}/kg$ (Liu et al. 2015). Hence, FA is an eco-friendly and sustainable material for soil stabilisation. This paper is focused on the utilisation of FA as a soil stabiliser.

FA is a solid waste from coal-fired power plants challenging to dispose of and is profusely produced in about 1.2 billion tonnes per year around the world (Harris et al. 2019). Furthermore, the traditional disposal method by landfill can lead to contamination of arable lands (Mahvash et al. 2017). As soil stabilisation in ground improvement projects requires a large volume of raw materials, utilisation of FA in soil stabilisation has a significant potential to minimise the amount of disposed waste material (Cristelo et al. 2013).

Various studies performed on the influence of FA in stabilising soil showed a positive impact on the strength of the soil for construction purposes. Nonetheless, the type of soil could affect the outcome of FA stabilisation, implying that FA stabilisation with different types of soil needs to be investigated (Mahvash et al. 2017). In particular, there is a lack of previous researches on class F FA stabilisation with kaolin, a material that has low construction quality but is often encountered in geotechnical works. Therefore, in this paper, the influence of stabilisation with class F FA on the strength and stiffness of kaolin is investigated.

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The aim of the research is to examine the effect of various proportions of class F FA and different other factors (namely cement content, curing time and dry initial unit weight) in the strength of stabilised kaolin. In addition to this, the dosage methodology developed by Consoli et al. (2011) will be utilised to assess its validity as a fundamental parameter for stabilisation of this material.

Soil stabilisation

Soil stabilisation is a procedure used in ground improvement and subgrade soil treatment, which consists of modifying the natural soil properties to meet intended engineering standards (Office of Geotechnical Engineering 2008). This is achieved by using stabilising agents (binders), which bind the soil particles together through chemical reactions, improving its geotechnical properties (Makusa 2012). Some of the stabilising agents can be lime, cement, blast furnace slag or FA. Both cement and lime are the most traditionally used soil stabilisers (Jawad et al. 2014).

Cement gains the desired strength once hydration reactions have completely occurred, after which hardened cement paste is produced (Makusa 2012; Cristelo et al. 2013). According to Janz and Johansson (2002), the performance of cement as an improvement additive does not depend on soil mineralogy and it works with any type of soil in the presence of water. The most common cement used for stabilisation is the ordinary Portland cement (EuroSoilStab 2002). As examples, the studies of Arora and Aydilek (2005) and Prusinski and Bhattacharya (1999) can be mentioned (among many others), in which silty sand and clay soils were respectively stabilised with cement, achieving in both cases greater strengths than the ones obtained when the soils were treated with lime instead.

Many authors in the literature report that FA can be reused for soil stabilisation to improve the strength of soils in the construction industry (Baykal et al. 2004). Moreover, Cristelo et al. (2013) concluded that FA is a better stabiliser than cement binders and can be used as a substitute for the cement-based binder. FA is classified into class C or class F based on its calcium content. FA class C has more than 20% calcium oxide, meaning that it forms cementitious compounds with the addition of water. Class F FA contains less than 20% calcium, requiring an activator to form cementitious compounds.

Studies performed on class C FA, applied to various types of soils, can be found in the literature (Cristelo et al. 2012a). The conditions and achieved results varied for each type of material, which led us to conclude that different stabilisation conditions are required for different soil types. Consoli et al. (2001), Arora and Aydilek (2005), Consoli et al. (2011) and Mahvash et al. (2017) have studied the effectiveness of class F FA for soil stabilisation and their results demonstrate a successful application of FA to stabilise soils. Arora and Aydilek (2005) compared cement with lime as possible activators for class F FA stabilisation of sandy soil and concluded that cement is a more successful activator than lime. Consoli et al. (2001) and Consoli et al. (2011) used lime, while Mahvash et al. (2017) used cement as the activator. The comparison of the improvements obtained with class C and class F FA was presented in the research by Cristelo et al. (2012a), concluding that class F FA provides long-term strength three times higher than the one achieved with class C FA. Moreover, Mahvash et al. (2017) showed class F FA activated with cement is the optimum stabilisation approach for most soils.

An increasing number of studies are focusing on class F FA utilisation in different soils. Arora and Aydilek (2005) investigated the stabilisation effect of class F FA on sandy soil; Cristelo et al. (2012a) used marl, a high plasticity clay with high calcium carbonate content. Cristelo et al. (2013) and Cristelo et al. (2012b) studied class F FA soil stabilisation on a low plasticity sandy clay and a granitic residual soil respectively. Furthermore, Sahu (2001) researched various types of soils including sand, black cotton soil, silty sand, intermediate plasticity silt and low plasticity silt. In addition to this, Mahvash et al. (2017) performed experimental research on poorly graded sandy soil. Vukićević et al. (2019) performed oedometer (one-dimensional consolidation) tests on FA stabilised medium and high plasticity clay found in Vojvodina, Serbia. No experiences on the stabilisation of kaolin with Class F FA have been reported. Abdulla et al. (2020) studied stabilisation using kaolin, however, FA based geopolymer was used with high CaO content and this paper focuses on low CaO content Class F FA. Hence, this paper explores the stabilisation of that material with FA class F as an additive and cement as the activator.

Design of laboratory tests

From the literature review, it was found that unconfined compressive strength (UCS) test (Cristelo et al. 2012b; Mehdi et al. 2014; Kolias et al. 2005) and indirect tensile strength (ITS) test (Kolias et al. 2005; Baykal et al. 2004) have been commonly used by previous researchers to examine the performance of soil stabilisation. These tests are employed in the present research.

Baykal et al. (2004) reported that UCS and ITS tests produce similar patterns, where the strength increases with the curing time, the ITS values being around 10% of UCS ones.

From previous researches (Aysen Lav and Hilmi Lav 2014; Kolias et al. 2005), it is noticeable that the ITS values significantly vary for 7 days cured samples for each proportion of cement, whereas for lime, little stabilisation effect was found. This is due to the hydration reaction happening faster than the pozzolanic reactions.

In most research studies (McCarthy et al. 2011; Kolias et al. 2005; Karim et al. 2014, among others), a range between 3 and 10% of cement is employed to activate FA. In the study of Santos et al. (2011), it is suggested that FA-soil mixture with 20% FA shows a clear change in the compressive strength with curing time, whereas little effect in the improvement is observed with FA contents ranging from 40 to 60%. Moreover, submerging samples in water is vital to prevent loss of moisture from soil pores and desiccation causing shrinkage cracks (Hoyos and McCartney 2017).

Mahvash et al. (2017) also demonstrated that strength increases with longer curing times. Curing times of 7, 14 and 28 days are commonly reported in the literature (Reyes and Pando 2007; Kaniraja and Havanagib 1999).

Several studies have been performed to establish a fundamental parameter to assess the strength of a stabilised soil. Findings from Consoli et al. (2007) showed that there is no relation between water/cement ratio and strength of stabilised clayey sand. In Consoli et al. (2007), it was found that porosity over cement content can be used as the normalising parameter for stabilised clayey sand. However, these studies were performed with soil different from the one employed in the present research. Therefore, in this paper, the use of porosity over the percentage of cement content will be used for evaluating the strength of the stabilised kaolin.

Materials and methodology

This work presents the unconfined compressive results of samples of cemented kaolin with different dosages of cement and FA at different densities. All materials and methodologies are described in this section. The cement used was ordinary Portland cement (OPC) following BS EN 1997–1 CEM1 52,5 M (BSI, 2011) and the specific gravity of the cement grains is 3.15.

Kaolin

The kaolin used was obtained from Bath Potters' Supplies located in Bath, UK. Its specific gravity and Atterberg limits are provided in Table 1, and the kaolin is classified as a high plasticity clay (CH), but having a LL of 51, it can be described as moderate plasticity instead.

Fly ash (FA)

Class F FA used here was obtained from the Ratcliffe-on-Soar power plant in Nottingham (UK). The source of the FA used in this study is the same as the FA used in Mahvash et al. (2017), which contained 75% by weight of silicon dioxide + aluminium oxide + iron oxide. According to Sinsiri et al. (2010) and Mahvash et al. (2017), the fineness (percentage by weight of particles with a size smaller than 44 μm, Federal Highway Administration n.d.) of FA can affect the experimental results as pozzolanic activity of FA increases with their fineness. Therefore, before the mixture preparation, the FA was pounded and only particles passing sieve opening 0.425 mm (BS 410:1986 mesh number 36) were used. The specific gravity of 2.3 for the FA was determined using the pycnometer test procedures outlined in BS 1377–2:1990 (BSI, 1990).

Table 1 Properties of kaolin used in this study

Properties	Values
Liquid limit, LL (%)	51.0
Plastic limit, PL (%)	26.6
Plasticity index, PI (%)	24.3
Specific gravity (Gs)	2.6

According to Santos et al. (2011), a greater improvement in the treated soil is achieved when the FA quantity, by weight, is around 20%; therefore, the three selected proportions of FA used in this work are 0%, 10% and 20%. Moreover, the chosen proportions are consistent with other researchers, such as Kolias et al. (2005) and Cristelo et al. (2012a).

Cement contents of 5% and 7% were chosen as the activator for this research, based on previous researches' findings (Arora and Aydilek 2005; Kaniraja and Havanagib 1999).

An analysis of the FA particles was performed using the Morphologi G3 automated particle characterisation system from Malvern. This system uses image technology to scan particles deposited on a flat surface and determine the values of particle descriptors such as circularity, elongation and others. Based on the area of the particle, the system calculates the diameter of a circle of equivalent area (circular equivalent diameter), whilst the volume is calculated assuming the particles are spherical. The results of the particle analysis can be seen in Figs. 1 and 2, where the cumulative distribution of FA particles in terms of aspect ratio (a function of the largest diameter and smallest diameter orthogonal to it) based on the number of particles and volume, are presented. Figure 1 shows that less than 20% of the particles have an aspect ratio lower than 0.6, implying that 80% of FA particles are similar to a circular or square shape. It also shows that there is a small number of particles with an aspect ratio of around 1. However, when the same parameter is plotted against the accumulated volume, it is possible to see that the vast majority of the volume tested has an aspect ratio of 1.

Figure 2 shows that the vast majority of the particles with greater volume have aspect ratios close to 1, with more than 95% of the volume having an aspect ratio higher than 0.8. Sinsiri et al. (2010) show that the particle size distribution

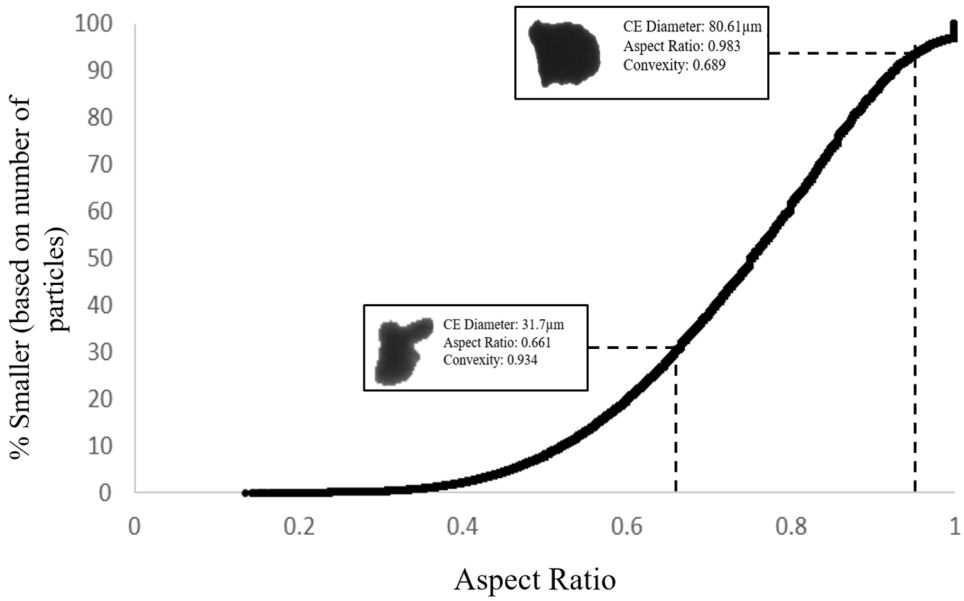


Fig. 1 Cumulative distribution of aspect ratio based on number of particles (obtained with Morphologi G3)

of the FA affects the characteristics of the cemented soil and that the pozzolanic reactivity of the FA increases with the increase in their fineness, as the fineness of FA contributes to a combined effect of a higher degree of packing, the pozzolanic reaction of FA and the hydration of cement, further lowering porosity and permeability of cemented soils.

Dry unit weight and moisture content

The dry unit weight of a mixture is defined as the weight of dry solids per unit of its total volume and moisture content is the percentage of water divided by the total dry weight of the mixture (Da Rocha et al. 2014). In this study, the dry unit weight and moisture content of preliminary samples were chosen considering the findings from previous studies (Saeed et al. 2014). Based on the results of preliminary tests, two dry unit weights (13 kN/m^3 and 14 kN/m^3) were chosen with a target moisture content of 35%.

Sample preparation

The procedure described below was used to create soil samples with different proportions of FA (0%, 10% and 20%), cement content (0%, 5% and 7%) and dry unit weights (13 kN/m^3 and 14 kN/m^3), using the same moisture content (35%). A total amount of 68 samples were created and

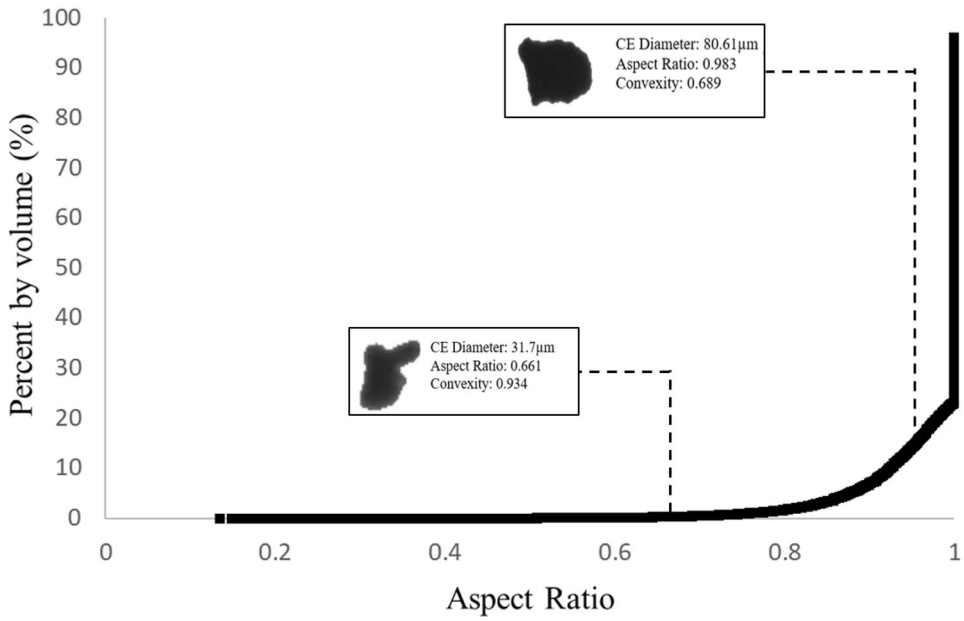


Fig. 2 Cumulative distribution of aspect ratio based on cumulative volume (obtained with Morphologi G3)

tested. Amongst these samples, 16 were employed to decide what dosages should be used and the remaining were used for the analysis shown hereinafter. In addition, untreated soil specimens (0% cement and 0% FA) were prepared to test the strength of the unstabilised soil.

To create a homogeneous sample, enough kaolin was mixed with the appropriate proportions of FA and/or cement, on a zip-lock plastic bag for 5 min (similarly as in Consoli et al. 2001). The mixing was done by shaking and overturning the bag until a uniform colour was visible inside the transparent bag, indicating a well-mixed material. Water was added and the mixing continued for another for 5 min, until a homogeneous mixture was reached and the soil was kept in a covered container covered by a damp cloth until the end of the moulding, to prevent loss of moisture.

The mixture was statically compacted in a lubricated PVC split cylindrical mould, in three layers. The compaction procedure was executed slowly, taking, on average, 10 min per layer, aiming at achieving the intended density on each layer. To guarantee a better adhesion between layers, each previous layer was scarred with a metal tool before adding the correct weight per layer. The compaction of soil samples was performed immediately after the mixing, ensuring that the total preparation time was smaller than the initial settling time (130 min) and final setting time (170 min) of the cement (Santos et al. 2011; Kolias et al. 2005). The static compaction method was used for the compaction of soil samples as the method results in consistent and uniform clay specimens (Venkatarama Reddy and Jagadish, 1993; Sivakumar, 1993). In this study, "Variable peak stress – Constant stroke compaction" defined by Venkatarama Reddy and Jagadish (1993) was used where a monotonic static force is applied at a constant rate until target dry density of the soil is achieved. This was achieved by the vertical movement of the piston of the compaction machine at a rate of 1 mm/min.

Cylindrical samples with 49 mm diameter and 101 mm height were produced in the mould. These samples were stored inside a zip-lock bag with a few drops of water to prevent loss of moisture from the cement hydration. The remaining mixture was oven dried for 24 h to check the moisture content of each sample after preparation. The samples were cured for a total of 7, 14 and 28 (Reyes and Pando 2007; Kaniraja and Havanagib 1999) following the steps below:

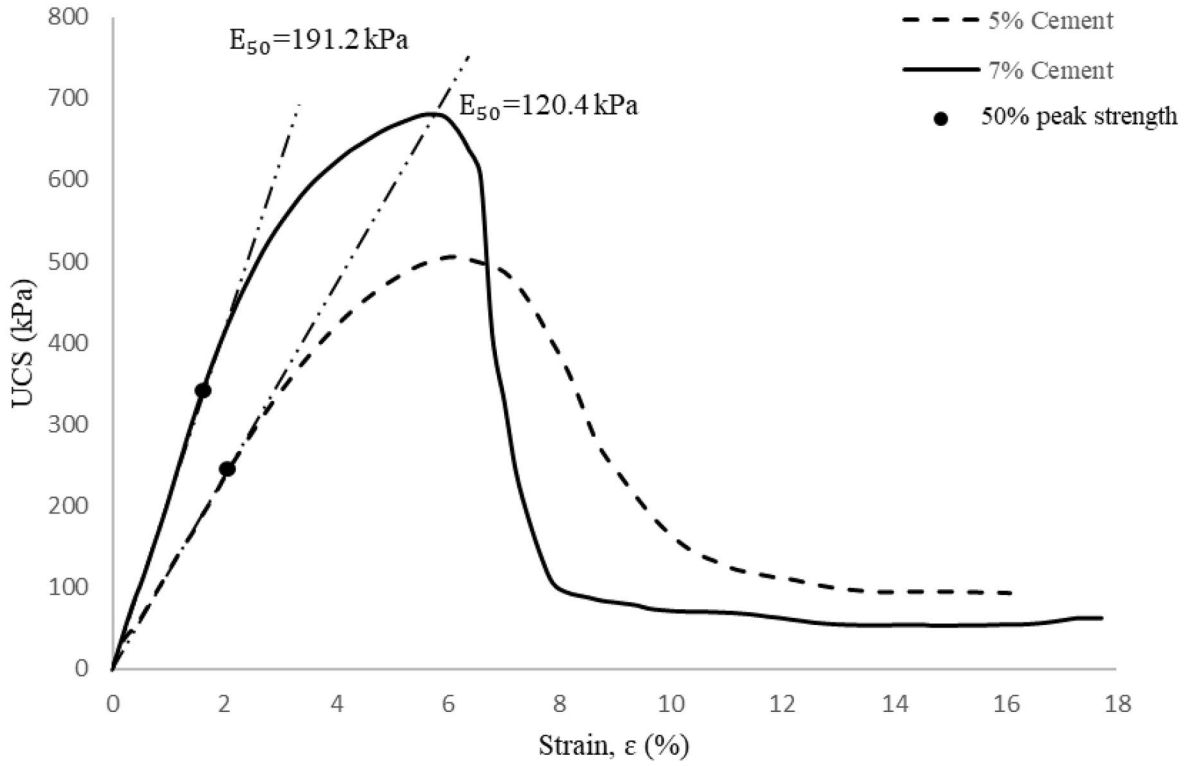
1) Inside the zip-lock bag at room temperature (around 21 °C) in the laboratory to ensure constant humidity until 2 days before testing of soil specimens (Table 2).
2) Water tank: the specimens were submerged in a tank, during the last 2 days of the curing period, to ensure minimisation of suction and full saturation state for the samples before testing. The water temperature was maintained at around 24 °C. In total, 52 samples were produced, 4 for each mixture proportion (13 mixture proportions) mentioned in Table 2, half for UCS tests whilst the other half for ITS testing.

Results

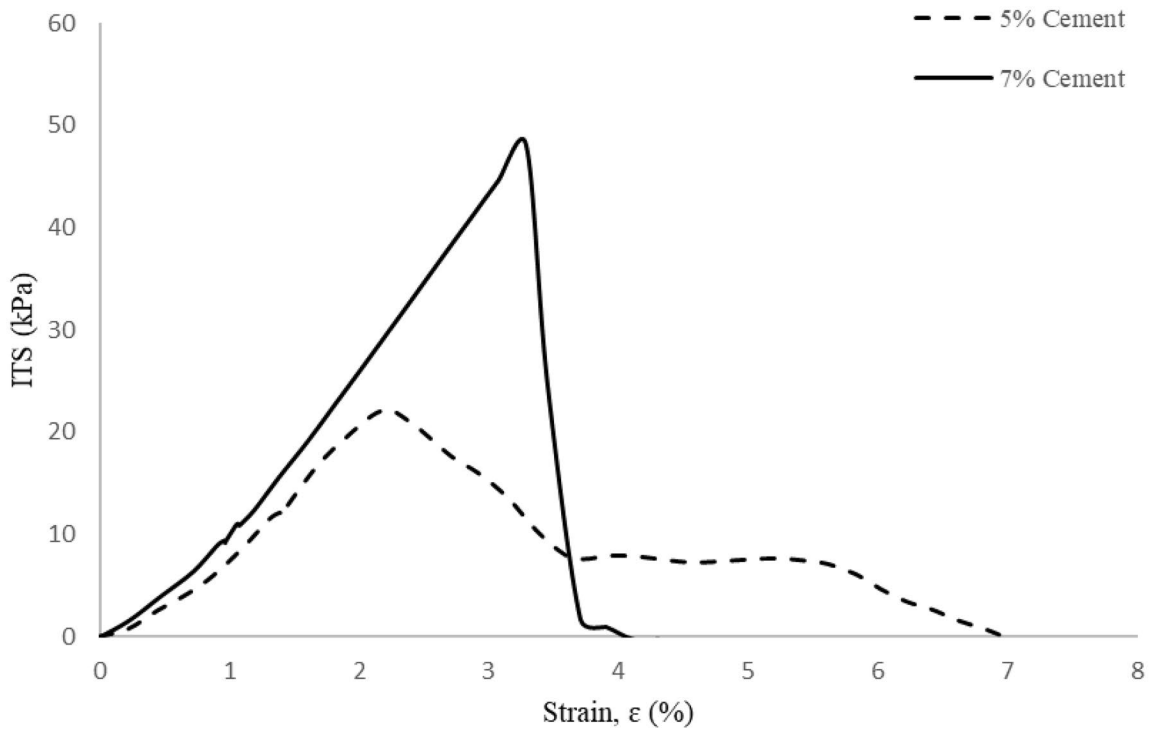
Two sets of soil samples were produced and tested on UCS and ITS apparatus for each mix combination. Table 2 summarises the results of strength obtained from the UCS and ITS tests. UCS results of stabilised soil specimens increased

Table 2 Experimental results for UCS and ITS tests with constant moisture content (moisture content: 35% in all cases). Mixture proportions (%); C, cement; FA, fly ash; d, curing time; D, dry unit weight

Soil sample	Kaolin (%)	FA (%)	C (%)	Curing time (days)	Dry moulding unit weight (kN/m^3)	UCS (kPa)	ITS (kPa)
K-7C-0FA-7d-1.4D	93	0	7	7	14	450.5	27.3
K-5C-0FA-7d-1.3D	95	0	5	7	13	229.3	13.8
K-5C-0FA-7d-1.4D	95	0	5	7	14	386.6	19.7
K-5C-10FA-7d-1.3D	85	10	5	7	13	315.8	19.5
K-5C-10FA-7d-1.4D	85	10	5	7	14	494.8	22.4
K-5C-10FA-14d-1.4D	85	10	5	14	14	593.6	29.8
K-5C-10FA-28d-1.4D	85	10	5	28	14	629.3	33.7
K-7C-10FA-7d-1.4D	83	10	7	7	14	656.4	39.9
K-5C-20FA-7d-1.3D	75	20	5	7	13	405.2	26.0
K-5C-20FA-7d-1.4D	75	20	5	7	14	630.7	32.4
K-7C-20FA-7d-1.4D	73	20	7	7	14	824.2	48.8
K-0C-0FA-0d-1.4D (initial soil state without any additives)	100	0	0	0	14	255.5	13.9



a)



b)

Fig. 3 Stress–strain curve of stabilised soil specimens treated with different proportions of cement while keeping 14 kN/m^3 dry unit weight, 10% FA and 7 days curing, obtained from **a** UCS test and **b** ITS test

by 51.4% up to 222.6% compared to the original soil, implying that the addition of cement and FA can significantly increase the strength of the soil. Comparing the UCS and ITS in Table 2, the values of ITS are in the range of 4 to 6% of the UCS values in all cases.

Analysis of UCS and ITS from the stress–strain relationship of stabilised soil

Figures 3 to 6 illustrate the behaviour of the stress–strain graph of stabilised soil samples with different proportions of cement and FA, dry unit weight and curing times that have been directly obtained from the UCS and ITS tests. The UCS and ITS values presented in Table 2 are the peak stresses of the corresponding stress–strain graph in Figs. 3 to 6. In addition, E_{50} is obtained by taking the secant modulus (ratio of stress over strain) at 50% of peak strength (represented as a dot in the figures) to analyse the stiffness of each soil-FA-cement mixture.

The effect of cement content on the stress–strain behaviour of the soil-FA-cement mixture is represented in Fig. 3. It is clear that the sample with a higher proportion of cement, in the UCS test, reaches peak stress at lower strain, followed by an abrupt reduction. The increased strength, stiffness and brittleness with a higher proportion of cement results from the formation of cementitious compounds, which include calcium silicate hydrate (CSH), calcium aluminate silicate hydrates (CASH) and calcium aluminate hydrate (CAH). The OPC used in the study contains tricalcium and dicalcium silicates (C_3S and C_2S), tricalcium aluminate (C_3A) and tetracalcium alumino-ferrite (C_4AF). In the presence of water, hydrations of these compounds form CSH, CAH and CASH. The stress–strain behaviour observed in the current study is in agreement with the results reported in the literature (Consoli et al. 2001; 2013). For example, in Fig. 3a, the soil samples stabilised with 7% cement content reached a peak (UCS) of 680.8 kPa with higher stiffness (E_{50} = 191.2 kPa) while the specimen with 5% cement attained a maximum strength of 505.8 kPa at a lower stiffness (E_{50} = 120.4 kPa). The sudden drop in stress is clearly seen after the peak stress of the 7% cement specimen, reflecting a brittle behaviour whereas the 5% sample undergoes a plastic deformation with a clear profound strain softening. For cemented soils, the strain-softening can be interpreted as when the bonds between cemented particles are broken, the localised collapse of the structure occurs as the compression progresses.

Similarly, for ITS in Fig. 3b, the peak stress of specimens varies with the cement proportion. However, the maximum stress of 7% cement occurred at strains higher than the sample with 5% cement. This is due to the longer time taken for the cracks to propagate along the specimen with 7% cement.

Figure 4 shows the stress–strain relationship considering 14 kN/m^3 and 13 kN/m^3 dry unit weights. In Fig. 4a, the sample with the highest unit weight shows larger strength for both UCS and ITS test. As expected, the specimen with the highest unit weight (E_{50} = 120.4 kPa) displays higher stiffness than the specimen with the lowest unit weight (E_{50} = 106.9 kPa).

Figure 5 shows the effect of the curing period on the stress–strain curve obtained from the UCS and ITS test. Treated samples with a higher curing time are expected to have a higher strength. This finding is attributable to the samples becoming stronger when cured for a longer period, allowing more time for the pozzolanic reaction and leading to a denser stable structure. This is consistently seen in both UCS and ITS stress–strain curves where the samples cured at 28 days have higher peak stress than the ones cured for a shorter time.

The stress–strain behaviour of untreated kaolin (without any stabiliser), tested at 0-day curing time but following the same procedure as for the treated soil samples, is shown in Fig. 5a. Kaolin reaches its peak strength at 255.5 kPa, a value that, as expected, is lower than those for the stabilised samples. This implies that the FA and cement mixture has a great influence on the strength of a soil. It can be seen that the kaolin curve is increasing continuously with strain. The increase in stress slows down as it approaches the asymptotic value (as previously reported by Amadi and Osu 2016). As the experiment was stopped at the asymptotic line after the strain exceeded 21%, no failure sign in the sample was identified. It is also interesting to highlight that the residual value of the stress is higher in the case of untreated kaolin than for improved material.

Figure 6 demonstrates the effect of FA content (0%, 10% and 20%) on the stress–strain behaviour of the soil-FA-cement mixtures. As seen in Fig. 6 a and b, the peak strength with lower FA content, 0% FA, has a low peak stress (UCS = 392.7 kPa) at lower stiffness (E_{50} = 84.6 kPa). This is observed from the slope of the curve where the sample with 0% FA fails at a high strain. UCS values of samples stabilised with FA and cement are higher than cement-only stabilised samples, which shows the coupled effect of FA and cement additives. The production of hydraulic compounds from cement and FA hydration is increased in the FA-cement-soil compared to the cement-soil mixture, resulting in a more pronounced effect of the FA on the strength of the specimen (Kolias et al. 2005). The silicon dioxide and aluminium oxide from FA react with calcium oxide from the cement in the presence of water to form calcium aluminium silicate hydrates like gismodine ($CaAl_2Si_2O_8 \bullet 4H_2O$), portlandite ($Ca(OH)_2$), etc. The formation of cementitious compounds leads to a denser and more stable structure of the specimen (Arora and Aydilek 2005).

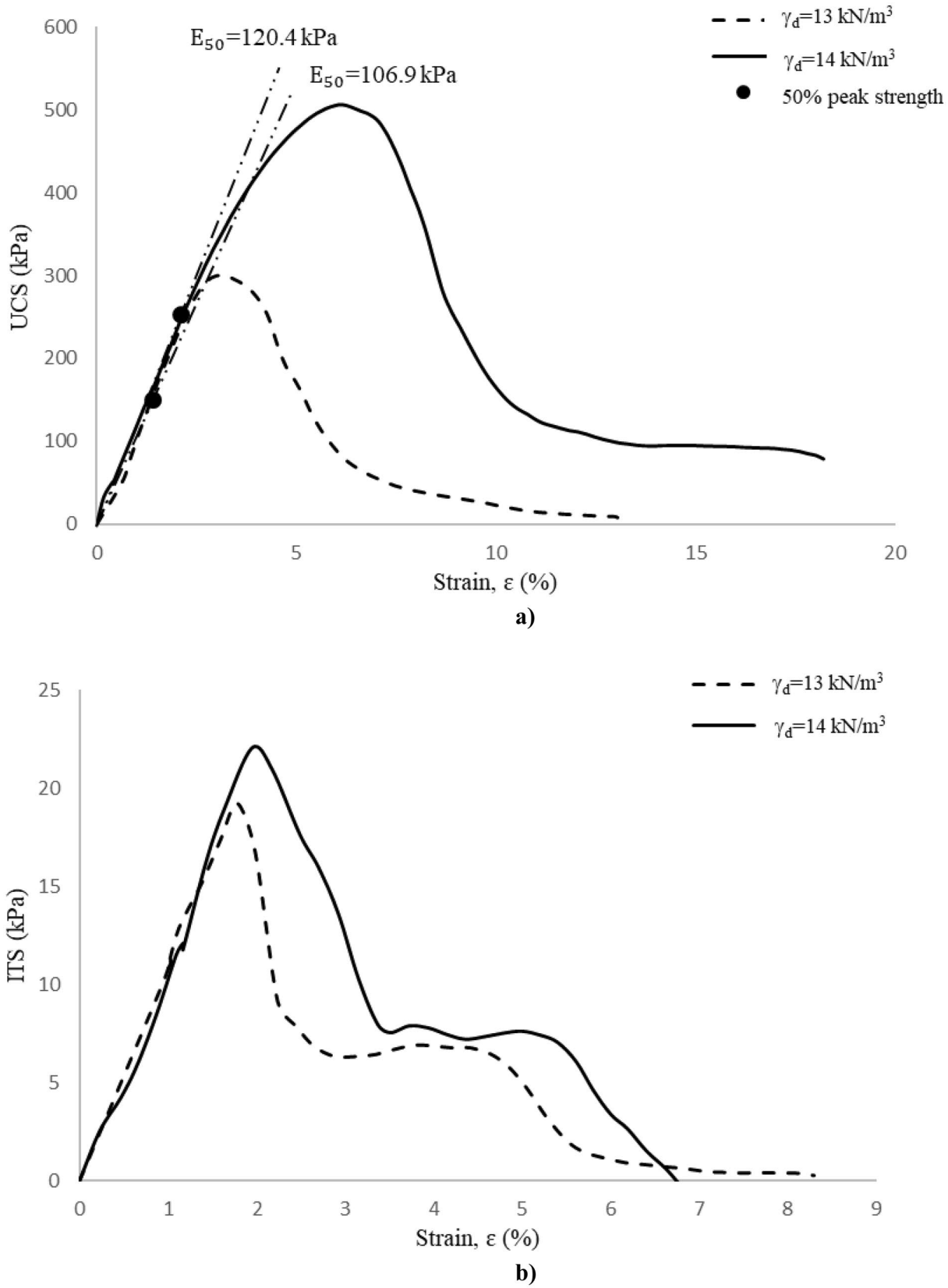


Fig. 4 Stress–strain curve of stabilised soil specimens treated with different dry unit weight while keeping 5% cement, 10% FA and 7 days curing, obtained from **a** UCS test and **b** ITS test

The stress–strain behaviour is in agreement with the behaviour observed in previous studies (Consoli et al. 2001; Kolias et al. 2005). The increased brittleness and reduction in the axial strain at failure of soil-FA-cement mixture (Fig. 6a) is also similar to the behaviour reported by Consoli et al. (2001). Furthermore, the strength results are in the same range as those obtained by Reyes and Pando (2007) for high plasticity clay. Thus, we can conclude that adding FA to the kaolin generates pozzolanic reactions within the sample which aids to produce a stronger and stiffer soil material.

Effect of the curing time

Figure 7a and b show the effect of the curing period on the UCS and ITS values. The results for K-0C-0FA-1 and K-0C-0FA-2 represent the strength of soil without any additives. The strength value of untreated soil is non-zero as it contains some initial shear strength from the undrained pore water pressure that builds up inside the sample. As previously discussed, the samples were tested and cured for 7, 14 and 28 days, respectively, keeping the dry unit weight of 14 kN/m^3 and constant moisture content. From the figures, and as expected, it can be seen that the samples cured for longer periods have greater strength as the longer curing time allow for the hydration reaction to being completed. This behaviour is consistent with the study of Cristelo et al. (2011), Mehdi et al. (2014) and many others.

For both UCS and ITS tests, most of the gain in strength happens within the first 7 days of curing. This behaviour agrees with previous studies (Kamon et al. 2000; Al-Refeai and Al-Karni 1999), where the increase in UCS is smaller from 7 to 14 days curing, and even less from 14 to 28 days curing. Reyes and Pando (2007) state that this effect is related to the initial hydration that takes place within the sample mixture.

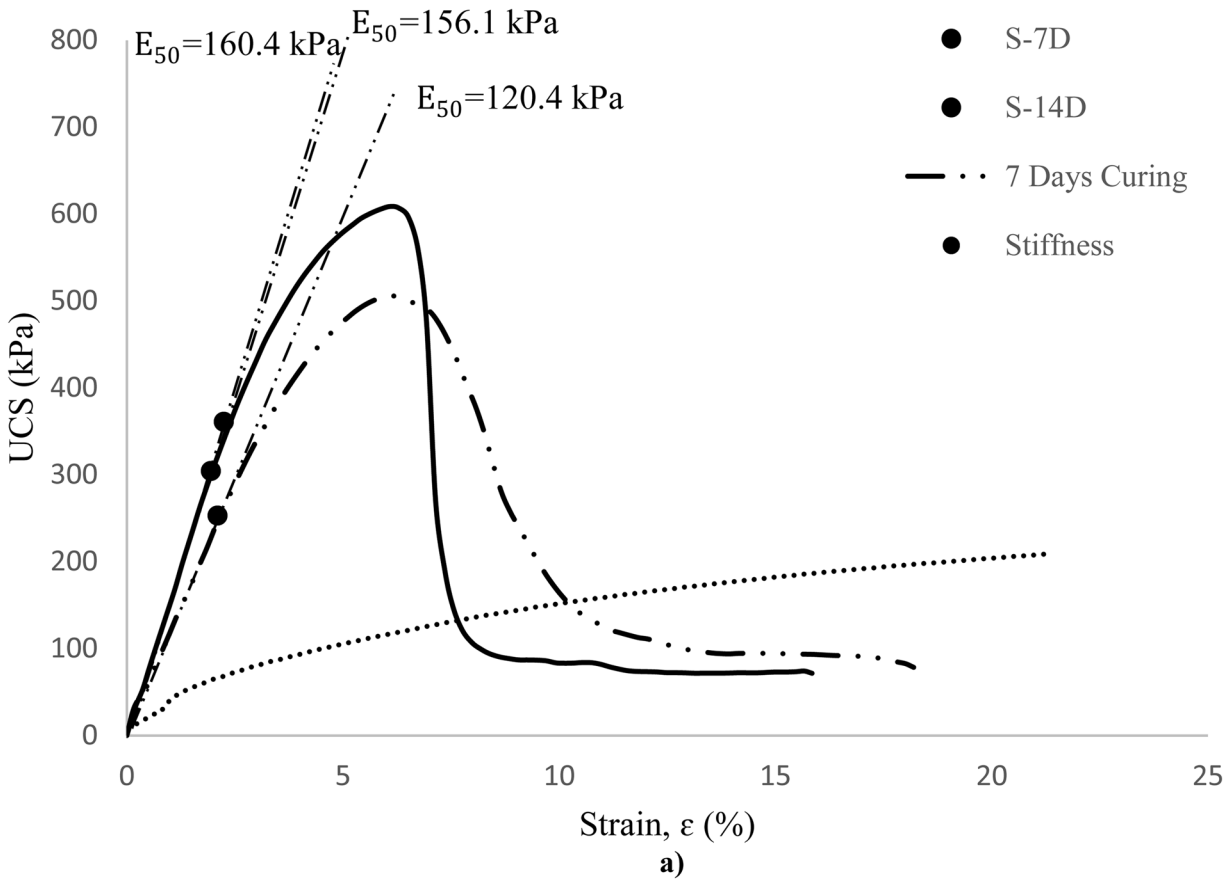
Effect of cement content, FA content and porosity

Figure 8a shows that UCS varies approximately linearly with the proportions of cement and FA. The highest increase of 222.6% in strength is obtained in the soil sample with 20% FA and 7% cement content, implying that the addition of FA enhances the effect of cement in UCS, as previously discussed. Similar behaviour was obtained by Kaniraja and Havanagib (1999), Havanagib, Cristelo et al. (2011) and Kolias et al. (2005) for cemented soil. From Fig. 8a and b, it can be seen that, for each content of cement and both UCS and ITS, the strength increases linearly with the increase in FA content. Santos et al. (2011) reported a similar observation with increasing FA content (20%, 40% and 60%); however, the strength increase was found less substantial when the FA content was increased from 40 to 60%. Furthermore, problems such as transport cost, spreading and mixing problems of large quantities of FA and higher water use arise with the use of high FA content, making it not recommended and impractical (Kolias et al. 2005). Therefore, the determination of the highest level of FA content requires assessment against various criteria in a particular project; an example of such assessment is presented in Table 3.

Figure 9a and b have been plotted to represent the influence of porosity, η (defined as the volume of voids, V_v, over the total volume of the specimen, V_{total}), on the UCS and ITS results, assuming a linear correlation in between those results for which tests for different porosities and identical other conditions were tested. The porosity was determined using the formula given below, where bulk density is the mass of soil over the sample volume and particle density is the mass of soil over the solid only volume. As shown in the formula, η is a function of bulk density (γ_d), % of cement (C), % of fly ash (FA) and % of soil (S) (Da Rocha et al. 2014). Unit weight of each material (soil $\gamma s_s = 26\text{kN/m}^3$, fly ash $\gamma s_{FA} = 23\text{kN/m}^3$ and cement $\gamma s_C = 31.5\ \text{kN/m}^3$) is also considered for calculating porosity.

$$\eta = \left(1 - \frac{bulkdensity}{Particledensity}\right) \times 100 = 100 - \frac{100\left[\left(\frac{(\gamma_d V_{total})\left(\frac{S}{100}\right)}{\gamma s_s}\right) + \left(\frac{(\gamma_d V_{total})\left(\frac{FA}{100}\right)}{\gamma s_{FA}}\right) + \left(\frac{(\gamma_d V_{total})\left(\frac{C}{100}\right)}{\gamma s_C}\right)\right]}{V_{total}} \quad (1)$$

Both Fig. 9a and b show that a decrease in the porosity (η) of the compacted mixture improves the strength. The effect of increasing cement content at lower porosity is more significant, exhibiting the coupled effect of cementation and density. Similar trends were observed by Consoli et al. (2007) where it was demonstrated that greater effectiveness of cement is obtained in more compacted and denser samples as the cement particles appear in a larger number and area of contact to form cement bonds. According to Da Rocha et al. (2014), the relationship between strength and porosity is exponential. The available data plots are limited and more graphs would be required to evaluate if the relationship could be represented by an exponential equation. Consoli et al. (2007) further state that the relationship between porosity and cement content is a very appropriate parameter to evaluate the UCS. Henceforth, the following



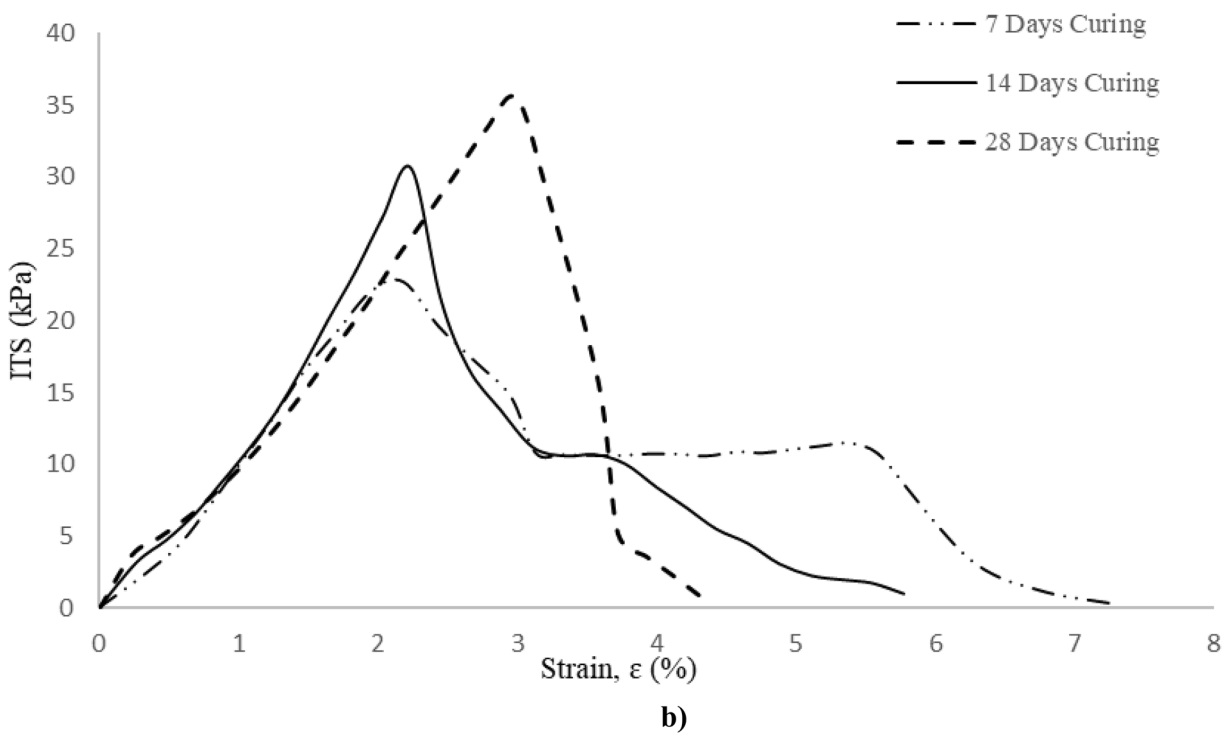


Fig. 5 Stress–strain curve of stabilised soil specimens cured for 0, 7, 14 and 28 days while keeping 14 kN/m^3 dry unit weight, 5% cement, 10% FA, obtained from **a** UCS test and **b** ITS test

section analyses the effect of the relationship between porosity and cement and FA contents.

Relationship between porosity/cement ratio and porosity/(cement) ratio with compressive strength

To analyse the relationship between strength, porosity and cement content, the porosity divided by the proportion of cement in volume, as defined by Eq. (2) (Consoli et al. 2007), will be used.

$$\frac{\eta}{C_{iv}} = \frac{\frac{V_v}{V_{total}}}{\frac{V_c}{V_{total}}} = \frac{V_v}{V_c} \tag{2}$$

where η is the porosity of the sample, C_{iv} denotes the volumetric cement content which is the volume of cement (V_c) over the total volume of the specimen (V_{total}), whilst V_v is the volume of voids.

Figure 10 represents the combined effects of both variables (η and C_{iv}) on UCS for 10% FA-cement soil specimens at a curing period of 7 days. This means that although η and C_{iv} have distinct effects on the UCS, a change in η could be counteracted by varying the C_{iv} proportionally.

Figure 10a–d enable us to understand the effect of raising the power of the parameter C_{iv}. The coefficient of correlation between UCS and η/C_{iv} in Fig. 10a is reasonable ($R^2 \sim 0.82$) since rates of change of UCS with η/C_{iv} were distinct. However, the use of $\eta/(C_{iv})^{0.038}$ provides a better fit of the UCS values by enhancing the scale of effects of η while reducing the scale of effects of C_{iv}. According to Consoli et al. (2009), to remove substantial variations in rates of η/C_{iv} and normalise the effects of the variation on the strength, power on the inverse of the parameter C_{iv} is applied ($1/(C_{iv})^{0.038}$). In this case, power of 0.038 resulted in a better coefficient of correlation $\left(R^2 \sim 0.96\right)$ and is plotted as shown in Fig. 10b. It is worth highlighting that other correlations were attempted, all of them yielding worse correlation coefficients.

Figures 11 and 12 show the combined effects of 3 different proportions of FA on the UCS and ITS of the soil specimens, respectively. In Fig. 11, for the same $\eta/(C_{iv})^{0.038}$, but consisting of a different combination of porosity and cement content, the strengths achieved are different. This signifies that an optimum combination of porosity and cement content can be obtained according to strength and cost requirements.

From the calibrations represented in Figs. 11 and 12, the following equations can be obtained:

$$UCS(0\%FA)(kPa) = 1.0 \times 10^{22}\left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95} \tag{3}$$

$$UCS(10\%FA)(kPa) = 1.2 \times 10^{22}\left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95} \tag{4}$$

$$UCS(20\%FA)(kPa) = 1.5 \times 10^{22}\left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95} \tag{5}$$

$$ITS(0\%FA)(kPa) = 1.9 \times 10^{7}\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521} \tag{6}$$

$$ITS(10\%FA)(kPa) = 2.4 \times 10^{7}\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521} \tag{7}$$

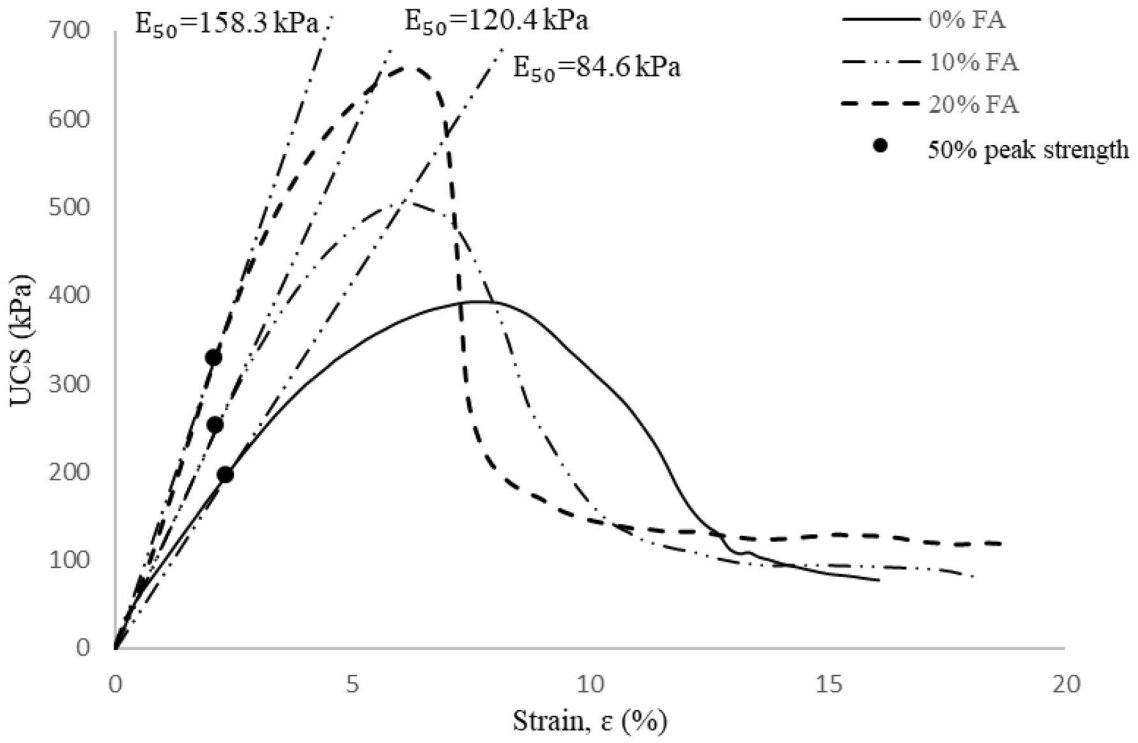
$$ITS(20\%FA)(kPa) = 3.0 \times 10^{7}\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521} \tag{8}$$

The coefficient of correlation (R^2) between UCS and η/C_{iv} is 1,0.96 and 0.96, respectively for 0%, 10% and 20% FA. Similarly, the coefficient of correlation between ITS and η/C_{iv} is 0.97,0.94 and 0.999 respectively for 0%, 10% and 20% FA. Comparing Eqs. 2–7 in Figs. 13 and 14, UCS is proportional to $\left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95}$ and ITS is proportional to $\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521}$. Consequently, a unique relationship can be attained relating the UCS with η, C_{iv} and FA content (percentage by weight of total volume), as shown in Figs. 13 and 14 and Eqs. 9 and 10**.** In those figures, for the UCS results, the expression employed in the y-axis is $UCS/\left\{10^{22}\bullet\left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95}\right\}$, while for the ITS it is $ITS/\left\{10^{7}\bullet\left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521}\right\}$. Linear correlations between those respective values and the FA content have been found in both cases, yielding the final following expressions:

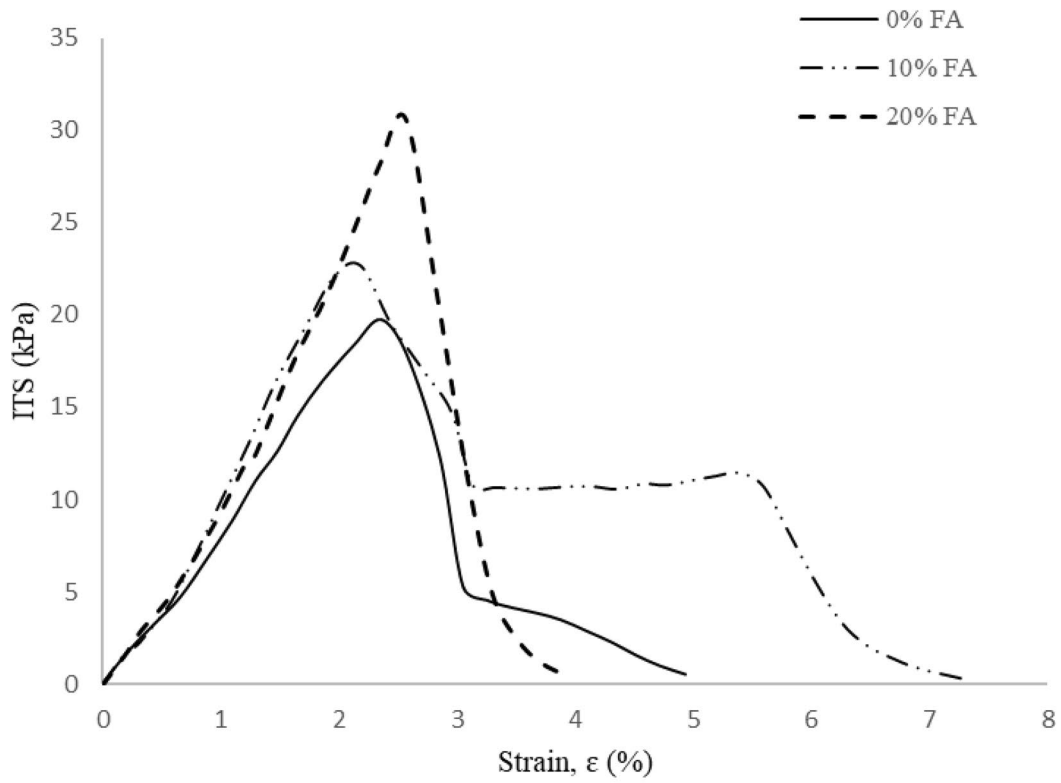
$$UCS(kPa) = [2.3 \times 10^{20}(\%FA) + 0.9582 \times 10^{22}] \times \left[\frac{\eta}{(C_{iv})^{0.038}}\right]^{-10.95} \tag{9}$$

$$ITS(kPa) = [6.14 \times 10^{5}(\%FA) + 1.7974 \times 10^{7}] \times \left[\frac{\eta}{(C_{iv})^{0.28}}\right]^{-3.521} \tag{10}$$

From Figs. 13 and 14, it can be concluded that the explicit relationship is suitable for the mixtures analysed in the present study. Furthermore, the equation in Fig. 13 allow linking UCS with η, C_{iv} and FA content. Equations 8 and 9 are valid for a range of porosities (59.5 to 63.3%), cement contents (5 to 7%), FA contents (0 to 20%) and moisture content (35%) studied here. The suitability of the methodology is in agreement with



a)



b)

Fig. 6 Stress–strain curve of stabilised soil specimens treated with different proportion of FA while keeping 14 kN/m^3 dry unit weight, 5% cement, 7-day curing period, obtained from **a** UCS test and **b** ITS test

findings from past studies (Consoli et al. 2007, 2009, 2011; Da Rocha et al. 2014). Further studies would be required on the use of η/C_{iv} in evaluating UCS for different moisture contents. Furthermore, studies on a wider range of porosities would also need to be carried out to assess the possibility of generalisation of the findings from this research and improve the calibration of the empirical equations to a wider range of additive dosages and porosities.

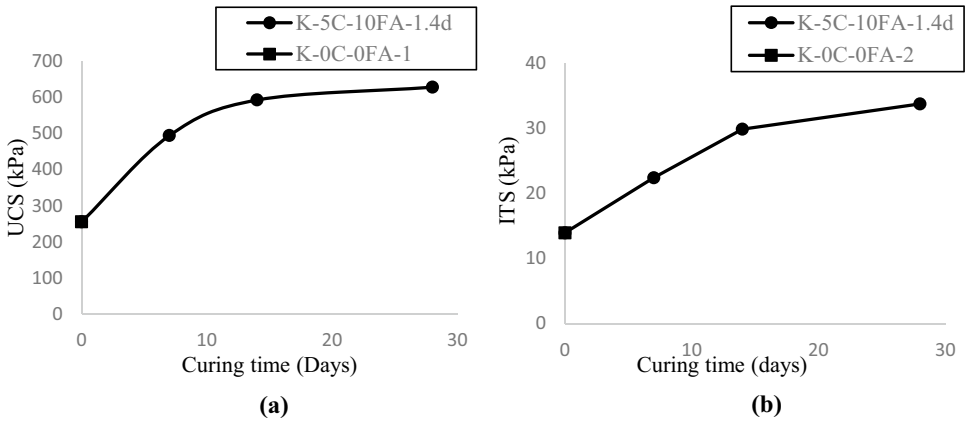


Fig. 7 Effect of curing times on **a** UCS values and **b** ITS values

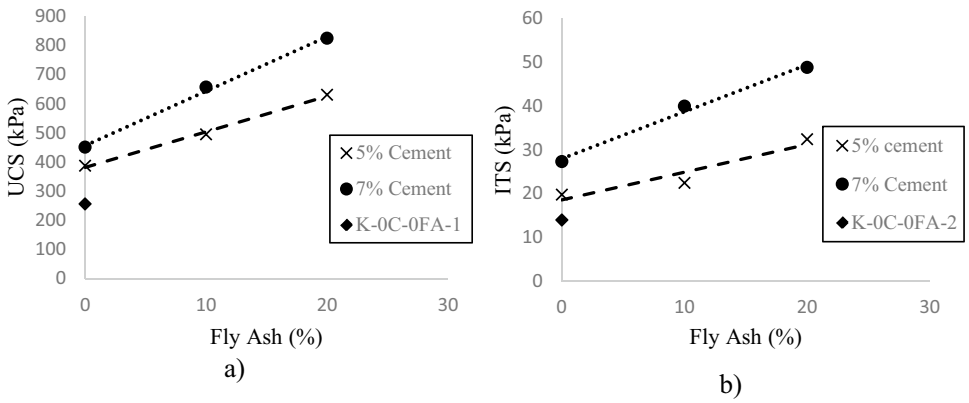


Fig. 8 Effect of varying cement and fly-ash content on **a** UCS and **b** ITS, keeping dry unit weight of 14 kN/m^3 and 7 days curing

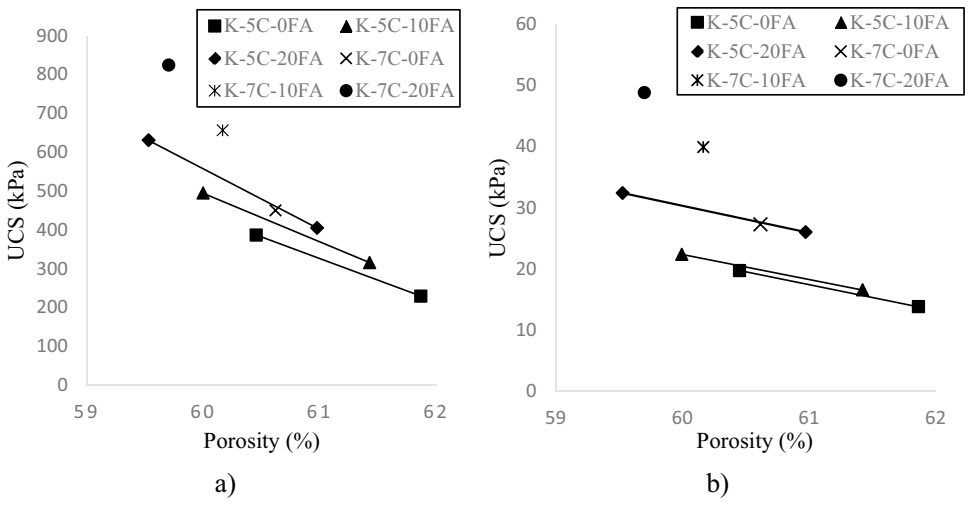


Fig. 9 Variation of strength with porosity for different FA content. **a** UCS test and **b** ITS test

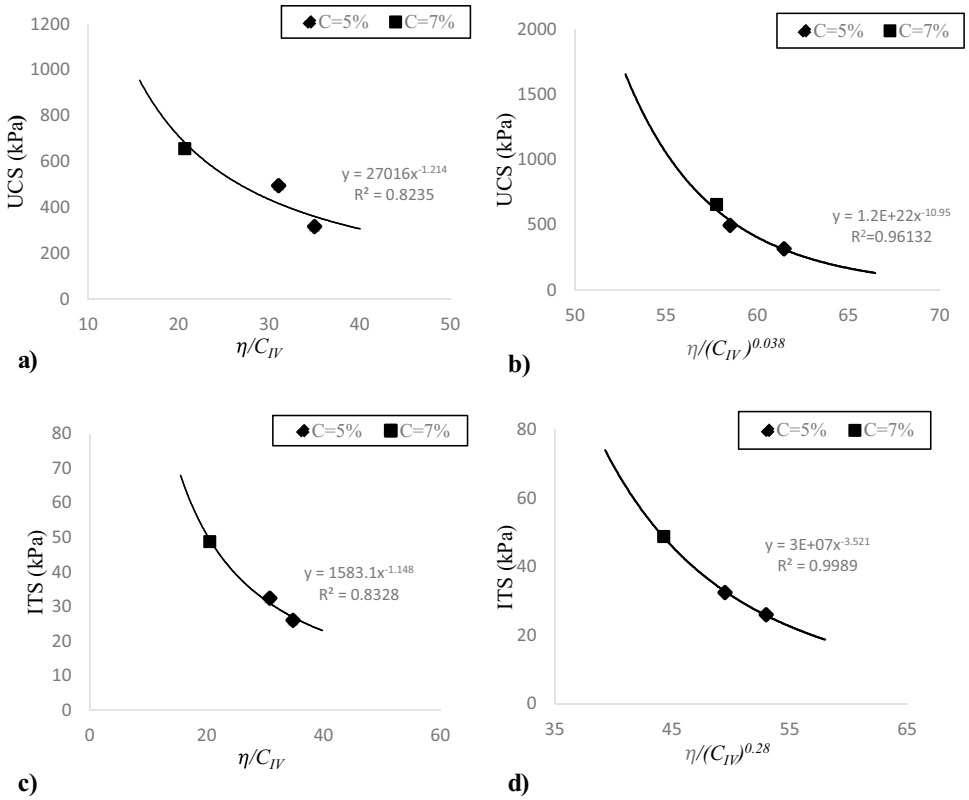


Fig. 10 Comparison of the effect of adjusted porosity over volumetric cement ratio on the coefficient of correlation between the strength of soil and the parameters (η and Civ) for 7 days curing. **a** UCS with porosity/cement ratio [η/C_{iv}] for 10% FA-cement. **b** UCS with porosity/cement ratio[$\eta/(C_{iv})^{0.0385}$] for 10% FA-cement. **c** ITS with porosity/cement ratio [η/C_{iv}] for 20% FA-cement. **d** ITS with porosity/cement ratio [$\eta/(C_{iv})^{0.28}$] for 20% FA-cement

Relationship between porosity/cement ratio with E_{50}

Figure 15 shows the combined effect of variables η and C_{iv} on secant modulus, E_{50}. It can be observed that the increase in the normalised η/C_{iv} *ratio* causes a reduction on E_{50}. Separate trend lines are drawn in the graph to show the relationship between η/C_{iv} and the elastic modulus of soil for various proportions of FA. Good correlation between E_{50} and the η/C_{iv} *ratio* is achieved when applying the power of 0.35 on the parameter C_{iv} for 0, 10 and 20% FA. The figure combines the E_{50} results of two cement contents (5% and

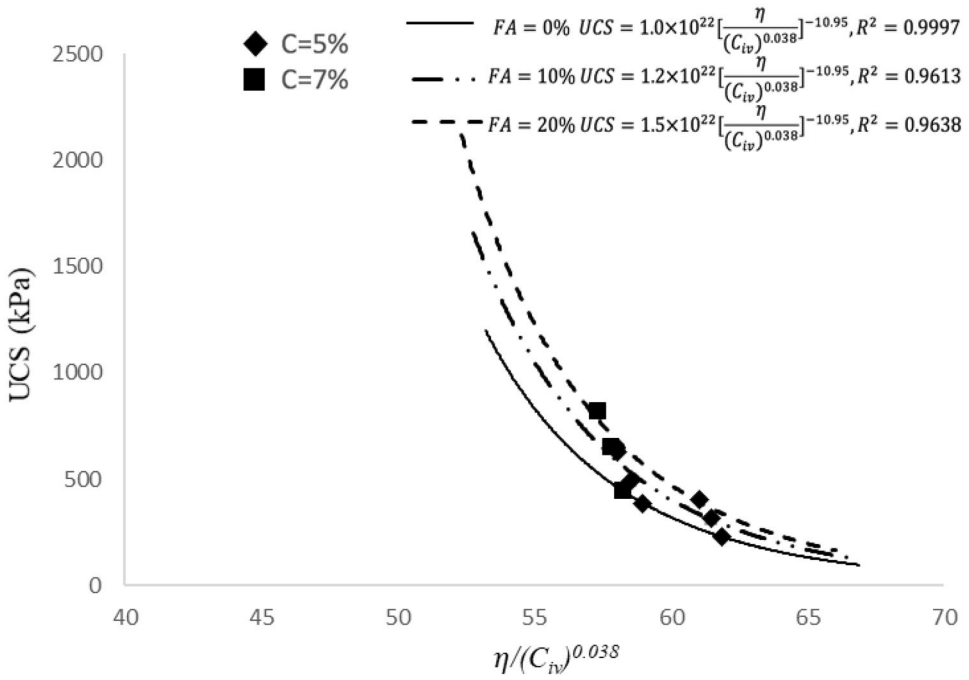


Fig. 11 Variation of UCS with adjusted porosity/cement ratio [$\eta/(C_{iv})^{0.038}$] for 0%, 10% and 20% FA content

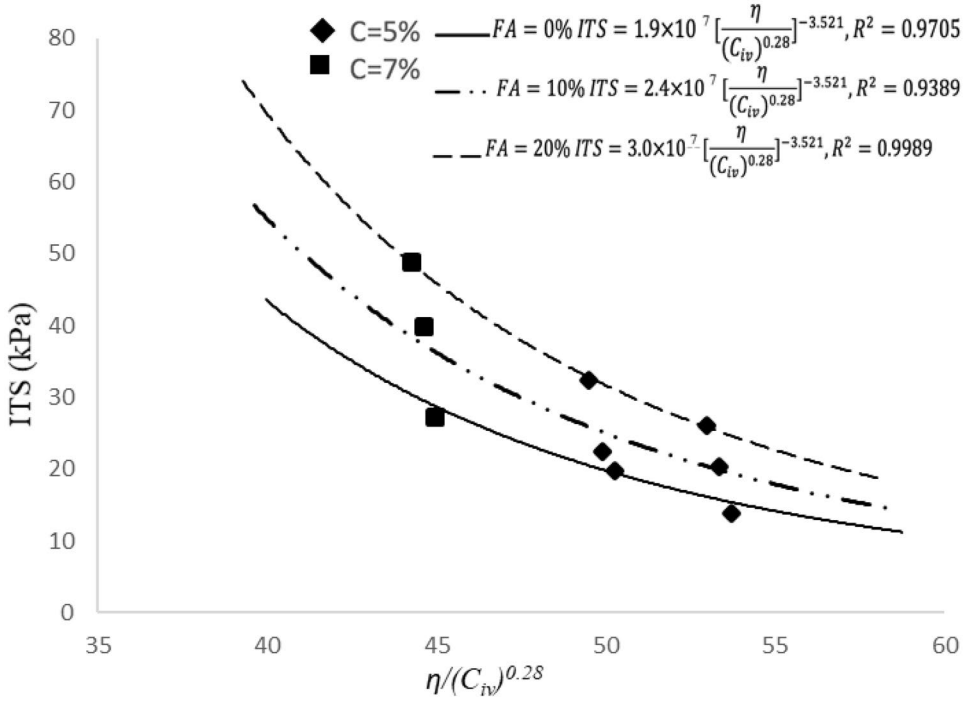


Fig. 12 Variation of ITS with adjusted porosity/cement ratio $[\eta/(C_{iv})^{0.28}]$ for 0%, 10% and 20% FA content

7%) and two dry unit weights (13 kN/m^3 and 14 kN/m^3) with the corresponding FA content. As shown in Fig. 15, the higher the FA content, the greater the elastic modulus of the soil and the presented results demonstrate that there seems to be a distinct relationship between FA content, cement content, porosity and E_{50} for the curing period being studied.

Implications of the equations

In order to illustrate the application of the proposed equations, Table 3 shows each dosage option with its performance against the sustainable consumption of resources. The dosage options are developed to obtain a target UCS strength of 0.8 MPa, which is the strength of the stabilised soil targeted in Kolias et al. (2005) for application to pavement structures. Using Eq. 8, FA content (the unknown variable) is calculated by assigning the target strength (UCS), cement content and dry unit weight with 7 days as the curing period. The assessment of each dosage option is based on Da Rocha et al. (2014)'s three criteria: maximum FA content for maximisation of resources recycling, minimum dry unit weight for minimisation of energy consumption and minimum cement content for minimisation of raw materials consumption. Each dosage option causes a different environmental impact. Option A meets all three criteria of the assessment of the dosage. However, Kolias et al. (2005) suggest that very high quantities of FA would cause problems of transport and feasibility of mixing and spreading of large FA quantities. In option B, increasing dry unit weight (reducing porosity) of stabilised soil requires lesser quantities of cement and FA. Da Rocha et al. (2014) suggest that minimisation of cement content by reducing porosity is more environmentally sustainable as the embodied energy and percentage of cement required to achieve an increase in the UCS is higher than the compaction energy required to achieve the porosity to produce that same increase in the UCS. Moreover, compared to option D, option B requires

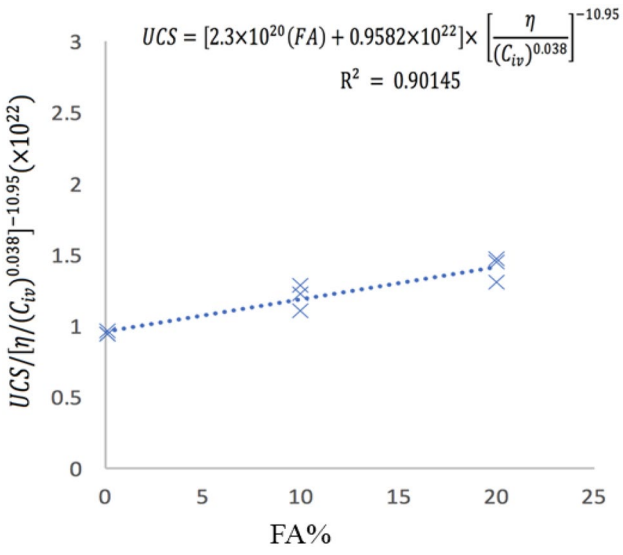


Fig. 13 Relationship combining the variation of UCS with η, C_{iv} and FA content

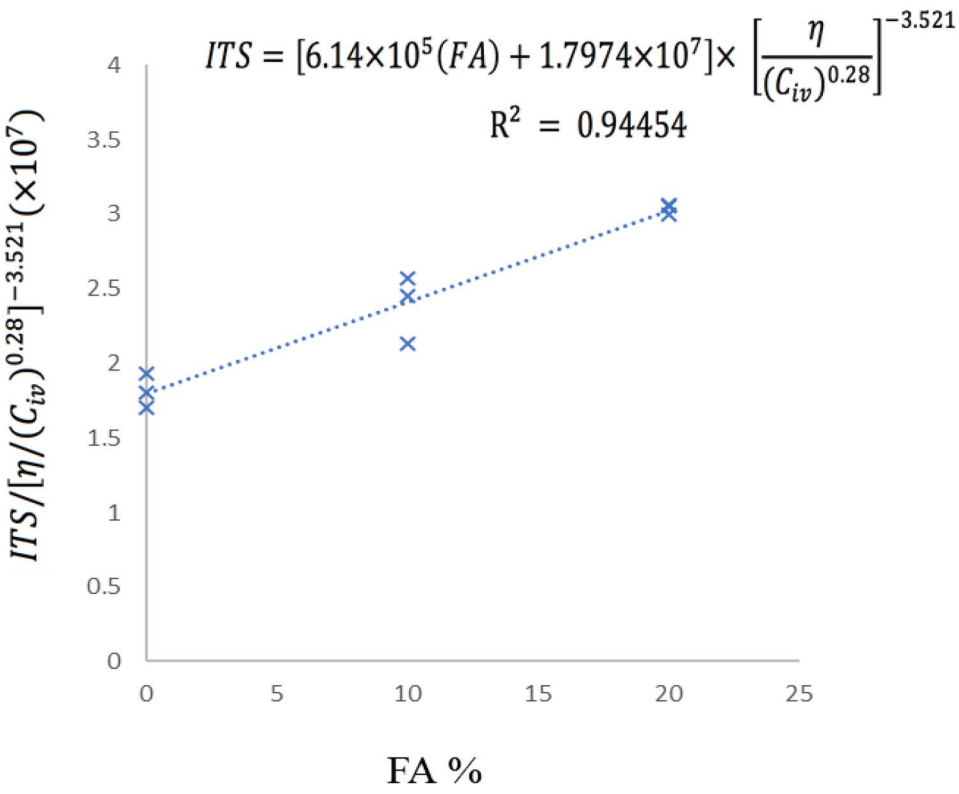


Fig. 14 Relationship combining the variation of ITS with η, C_{iv} and FA content

lesser cement content and higher FA content, meeting the criteria of maximising waste resource reuse. Therefore, option B is the best one for project locations where FA is vastly available without proper waste disposal. This is only one of the possible applications of the equations. The designers can use the equations to devise and assess the dosages according to the project criteria.

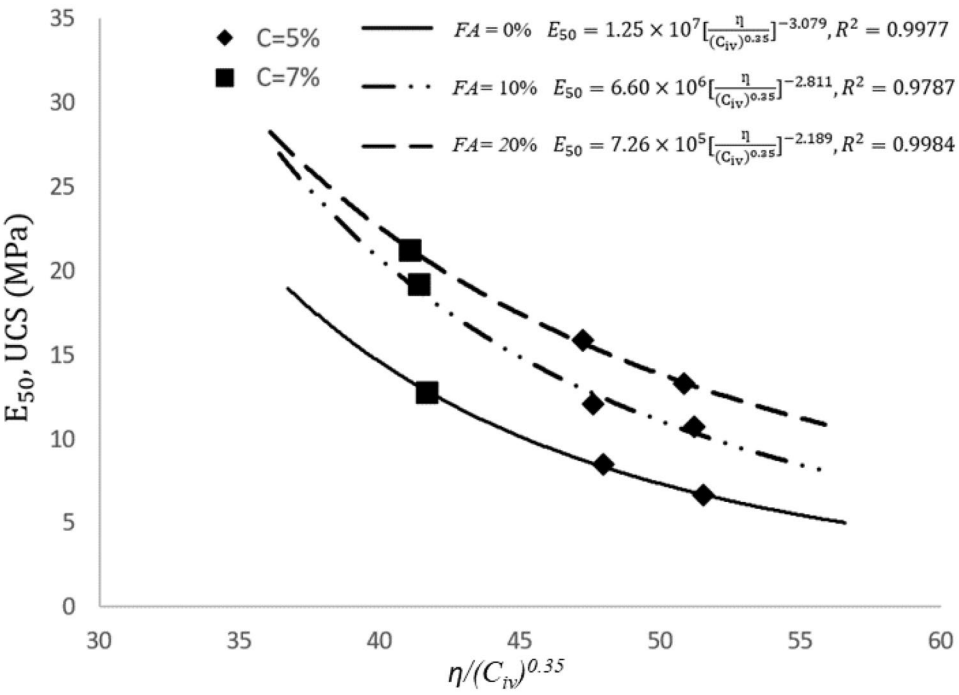


Fig. 15 Variation of E_{50} (UCS) with adjusted porosity/cement ratio $[\eta/(C_{iv})^{0.35}]$ for FA-cement-treated soil at 7 days curing

Table 3 Dosage options for attaining a 0.8 MPa UCS

Dosage option	FA content (%)	Cement content (%)	Dry unit weight (kN/m^3)	Curing period (days)	Critical appraisal
A	82	5	13	7	This option requires the lowest cement content and dry unit weight but requires high FA content to meet the target strength
B	30	5	14	7	As compared to options A and C, the increase in dry unit weight can reduce a substantial amount of FA while lowering or keeping the cement content constant
C	61	7	13	7	Compared to option A, a reduced amount of FA is required when the cement content is increased; however, the reduction is not as substantial as option B
D	20	7	14	7	Worst option as it requires high cement content and dry unit weight with the lowest FA waste reuse

Conclusions

The experimental study of kaolin improved with class F fly ash (FA), activated with cement, was carried out to investigate the effectiveness of reutilising this waste material (FA), as a soil stabiliser in the construction industry. Based on the results and analysis, the following observations and conclusions can be summarised:

- The results show an increase in strength with the increase in FA percentage. The same was noticed when the percentage of cement increases from 5 to 7%. However, the highest increase in strength is observed when the cement percentage is increased. A similar trend is seen in the calculated values of stiffness.v
- As expected, the strength of the treated soil cured at 28 days is higher than 7 or 14 days curing, with the majority of the gain in strength occurring in the first 7 days.
- The methodology using porosity over the percentage of cement content (η/C_{iv}) ratio to evaluate the UCS and ITS was successfully applied for FA-cement-kaolin soil mixture. The ratio provides a better correlation than only the dry unit weight or the cement content used alone.
- The E_{50} values calculated from the stress–strain curves, soil stiffness parameters, decrease with the increase in η/C_{iv} ratio. The correlation has a good agreement with 0, 10 and 20% FA.

The results show that the use of class F FA can successfully be used, together with cement, to improve the strength of kaolin clay soils. FA contains pozzolanic properties that lead to an increase in strength, the results show that the addition of 20% FA roughly doubles the strength of kaolin reinforced with either 5 or 7% cement.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10064-021-02373-5.

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