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Suitability of Fly Ash-Cement Kiln Dust Columns for Stabilizing Expansive (Black Cotton) Soils

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Abstract: The paper focuses on the potential use of industrial wastes, which are fly ash (FA) and cement kiln dust (CKD), to stabilize expansive soils like black cotton (BC) soil for construction purposes. Although many soil stabilization methods exist, the placement of columns consisting of industrial wastes has yet to be tested. Knowing the pozzolanic action and mechanism between the waste product and the soil, this method of placing the industrial waste as a remedy should be trialled. Therefore, this paper proposes and investigates the placement of FA-CKD columns into the soil via a series of laboratory experiments using myriad mixtures and combinations of placement of such columns. The effect of molding water content and curing time on the BC soil's consolidation and strength behavior was also assessed here. Through the experiments, it is found that the optimum mixture of FA-CKD for the columns is at 90–10%, respectively. This column mixture has been evidenced to improve the unconfined compressive strength of the soil significantly, where its performance improves with curing time. The highest strength improvement can be found at optimum moisture content, followed by wet of optimum and dry of optimum, respectively. By placing the columns in the soil with 4.5D spacing, better consolidation behavior with a reduced swelling potential of BC soil can be found. Based on the above findings, using FA-CKD columns can improve the BC soil's engineering behavior, contributing to waste-to-wealth and sustainable soil stabilization approaches.

Keywords: ground improvement, molding water content, swell pressure, swell potential, unconfined compressive strength (UCS)

1. Introduction

Black cotton (BC) soils, which are a type of expansive soil, are one of the key soil deposits in India, covering an ample space of about 3,00,000 km^2 [1]. These soils extend over the states of Madhya Pradesh, Karnataka, Andhra Pradesh, Tamil Nadu, and other provinces. Construction of structures on such soil becomes challenging where necessary changes are required to be implemented within the planning of the structure, or application of appropriate soil treatment needs to be done before the development in such soils. Improving the engineering properties of the weak and problematic soil becomes imperative in many cases to reduce the distress on the building and maintain its serviceability under varying climatic conditions. From an economic standpoint, this is crucial as ground remediation can be costly and challenging. Hence, feasible ground treatment must be resorted to before constructing any structures on them. Many researchers have conducted extensive studies to produce simple, sustainable, economical, environmentally friendly, and effective methods for ground improvement [2–6]. Since then an extensive range of ground improvement techniques have been developed to improve poor ground conditions. These techniques include compaction using vibro-replacement, vibro-flotation, preloading with and without vertical drains, dynamic consolidation, grouting, soil stabilization, soil reinforcement, and the installation of sand or stone columns [7]. The latest improvement among these methods is the study of in situ columns. Numerous research studies have studied the in situ columns' effectiveness using different fill materials like broken stones, lime, and fly ash (FA). It is well-known that the pozzolanic activity of lime is well known to significantly improve the long-term strength performance of stabilized soil [8]. This meant a further improvement of the shear strength, California Bearing Ratio, and reduced expansive characteristics of the expansive soil could be achieved via the addition of lime. The addition of carbide lime and salts has proven to show a denser environment compared with untreated soil, as the mixture binds the particle with hydrated gel. Nonetheless, the use of FA-cement kiln dust (FA-CKD) mixture as a fill material in soil remediation has yet to be studied extensively.

CKD is a fine powder that consists of partially calcined and unreacted raw feed, clinker dust, and ash. It also contains high levels of alkali sulfates, halides, and other volatile compounds [9]. The CKD in small quantities supplemented to the clayey soil improves its compaction characteristics and stress–strain behavior [10]. Therefore, it can be considered an effective stabilization material [11]. With a lower CKD amount, there is less calcium available for the formation of cementing products and exchange

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with other cations. This is because the higher availability of calcium (Ca), silicon (Si), and aluminum (Al) make it futile as a measure of ground improvement. At higher CKD content, however, the migration of calcium ions through the pore fluid is limited due to the presence of FA, even though there are plenty of Ca^{2+} ions available. Nonetheless, FA aggregate may be effectively utilized as column material instead of conventional coarse aggregate to improve soft clay [12]. The interaction and mechanisms between FA-CKD and expansive soils, as highlighted above, indicate the importance of selecting an optimal dosage of admixture to stabilize these soils effectively. This paper, as a result, details an experimental investigation of the effect of various parameters on the vertical FA-CKD columns in expansive soil.

2. Materials and Methodology

The materials used in this study were FA, cement-kiln dust (CKD), and expansive BC soil. The BC soil is collected from Raichur, India. FA, on the other hand, is collected from Raichur thermal power plant in Karnataka and is classified as class C FA by the ASTM standards. CKD was obtained from a cement factory located in Wadi, Gulbarga. Table 1 shows the index properties of soil and its classification, while Table 2 indicates the chemical properties of CKD and FA. The composition of FA can vary depending on how the coal is burned. FA has pozzolanic properties due to the presence of siliceous materials [13]. CKD is a mixture of fine dust particles that are made up of cement raw materials, partly processed cement components, and volatile components that have adhered to their surfaces. It can contain calcium carbonate, silica, and calcium oxide (“free lime”), despite the variation in composition. Other minor components like alkali sulfates and chlorides can be found in CKD too. Most CKD, when mixed with water, tend to have a relatively high pH level. CKD has some characteristics that make it a promising material for soil stabilization. As CKD contains free lime (CaO), have high alkali content and high fineness, it can improve the strength of soil.

Table 1
Index properties of black cotton soil

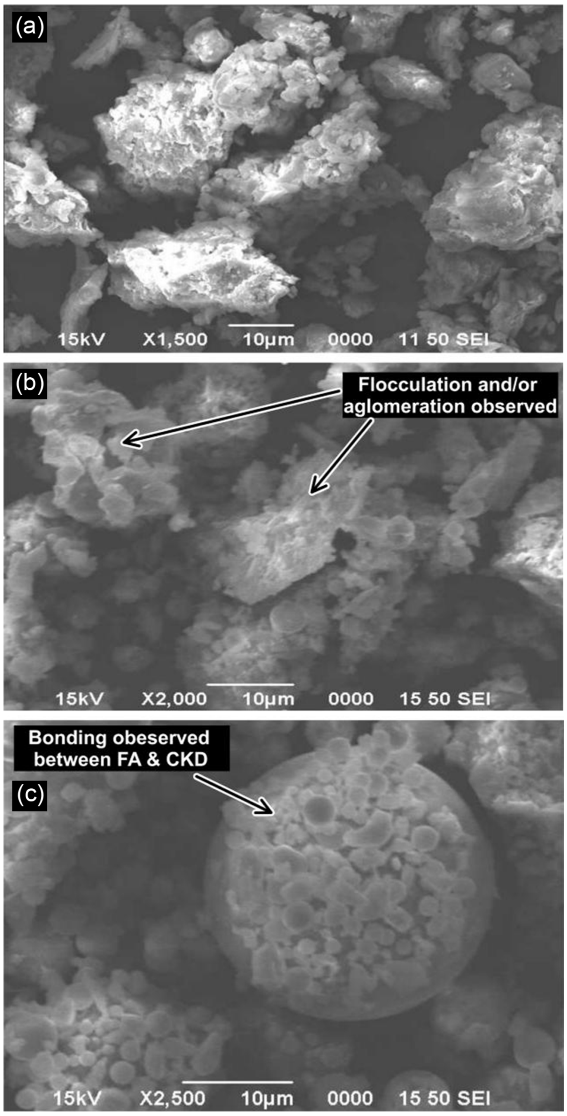
Properties	Unit	Test method	Values
Color	–	–	Grey
Specific gravity	–	IS 2720 (Part 3), 1980	2.58
Liquid limit	%	IS 2720 (Part 5), 1985	82
Plastic limit	%	IS 2720 (Part 5), 1985	36
Shrinkage limit	%	IS 2720 (Part 6), 1972	8
Plasticity index	%	IS 2720 (Part 5), 1985	46
Maximum dry unit weight	kN/m^3	IS 2720 (Part 7), 1980	14.95
Optimum moisture content	%	IS 2720 (Part 7), 1980	27
IS soil classification	–	IS 1498 (1970)	CH
USCS soil classification	–	ASTM D2487, 2017	CH
Free Swell Index	%	IS 2720 (Part 40), 1977	80

Figure 1(a) shows the scanning electron microscope (SEM) testing results of untreated BC soil. The soil has a smooth plane with a flaky structure, which suggests that the microstructure of the soil is dispersed, undulated, and film-like. The voids (micropores) present in the BC soil are visible due to the disintegrated flocculation of BC soil caused by the cohesion in the montmorillonite present in the BC soil. Figure 1(b) portrays the SEM results of BC soil supplemented with FA-CKD column at 28 days of curing. Due to chemical treatment, the soil structure has been altered to a more flocculated composition, which enhanced the cementation property in BC soil. The presence of binders is prominent in the SEM images of stabilized soil due to the binding agents produced from pozzolanic reactions. Figure 1(c)

Table 2
Chemical compositions of FA and CKD

Chemical composition	Unit	FA	CKD
Calcium oxide	%	0.88	49.4
Aluminum oxide	%	20.18	4.4
Silicon dioxide	%	66.4	17.6
Magnesium oxide	%	0.6	2.4
Ferric oxide	%	5.28	2.28
Loss of ignition	%	4.0	9.6

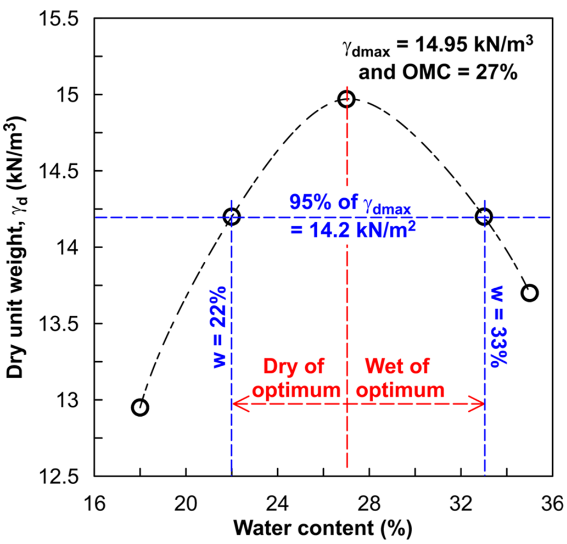
Figure 1
Scanning electron micrographs of (a) untreated black cotton soil, (b) black cotton soil supplemented with FA-CKD column cured for 28 days, and (c) FA-CKD column at 28 days curing



shows the SEM results of a dense matrix of FA-CKD column mix in a 90-10 ratio that has been cured for 28 days. When CKD reacts with water via hydration, it forms a dense layer of reaction products around the CKD particles. Bonding between FA and CKD can be found as scrappy blurred mass adhered in the interface of the particles. This phenomenon, in turn, decreases the voids (micropores) between soil particles. SEM observations further validate the role of cementitious gel, where the increase in the amount of cementitious gel with curing time led to an increase in strength.

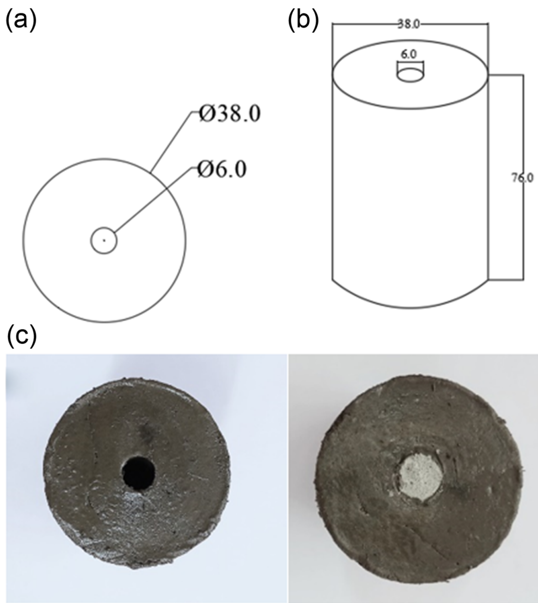
Unconfined compressive strength (UCS) and 1-D consolidation tests based on Indian Standards (IS) are conducted in this study to determine the influence of FA-CKD columns on expansive clay's strength and swelling properties. The specimen is prepared by hand-mixing oven-dried soil with particle size < 4.75 mm at the required water content. Compaction tests based on IS: 2720 (Part 7) – 1980 have been conducted to determine the maximum dry unit weight (γ_{dmax}) and optimum moisture content (OMC). Figure 2 indicates the result of the compaction test.

Figure 2
Compaction curve for black cotton soil



Next, the specimens prepared are subjected to UCS tests. The UCS tests were conducted per IS: 2720 (Part X) – 1973 at a 1.5 mm/min strain rate. Readings are obtained at every 0.2 mm deformation until five or more consecutive readings of the load dial show a decreasing or constant load has been achieved, or a deformation strain of 20% of the specimen has been reached, whichever condition is first fulfilled. The samples for the UCS test are prepared as follows. Using an extruder to extract the soil sample, a 6 mm diameter hole was made through a hollow metal rod. Figure 3 shows the sample prepared for UCS testing. Columns with different mixtures of FA-CKD cured at seven days, with a relative density between 80% and 85%, have been tested. The optimum combination of FA-CKD can be obtained after the strength tests of the soil column cured for seven days. Furthermore, the role of molding water content is also being studied using the UCS tests. Specimens at 95% γ_{max}, which have moisture wet of optimum and dry of optimum, respectively, are prepared using the same methodology above. Samples with curing times of 7, 14, and 28 days are prepared and subjected to the UCS test.

Figure 3
UCS specimen used for testing (a) top view (b) front view (c) test specimen (*all dimensions are in mm*)



1-dimensional (1-D) consolidation test based on IS: 2720 (Part XV) – 1986 (Reaffirmed 1997) are conducted to determine the compressibility characteristics of the soil. The expansive soil's swell pressure and swell potential are determined based on IS: 2720 part XV1965. The 76 mm diameter and 25 mm height soil samples are prepared at γ_{max} and OMC. 1-D consolidation test makes it possible to investigate the compressibility of expansive soils with different distance between soil columns. Various column spacing (3 and 4.5 times the column's diameter (D)) is tested in this study. Figure 4 indicates the presence of 4 mm diameter columns prepared using the methodology described above, where Figure 4(a) indicates the placement of columns with a spacing of 3.5D, and Figure 4(b) indicates the placement of columns with spacing of 4D instead. Vertical holes into the compacted soil specimen have been made using a metal rod of 4 mm diameter. Care is to be provided when making holes for columns to avoid disturbing other holes. A dried filter paper is then placed at the bottom of the soil specimen. With that in place, holes are filled with the optimum mixture of FA-CKD obtained from the UCS test at a relative density of 80% to 85%, using a paper cone with a small opening at the bottom. Like the above methodology, the CKD is oven dried at 100°C for an hour before being sieved through a 425 µm sieve. After the specimen is filled, a dried filter paper is placed on top of it and left for seven days to cure. Similarly, the role of curing towards the compressibility of soil is also being investigated in this study as well.

3. Results and Discussion

3.1. Optimum FA-CKD combination using UCS test

Figure 5 shows the variation of BC soil's UCS using a variety of combinations of FA-CKD soil columns after curing for seven days. FA column, when supplemented to the BC soil, has found to have increase the compressive strength and stiffness of the soil. This is

Figure 4
Top view of the specimens used in the consolidation test (a) at 3D spacing, (b) at 4.5D spacing, (c) test specimen with 4.5D spacing (*all dimensions are in mm*)

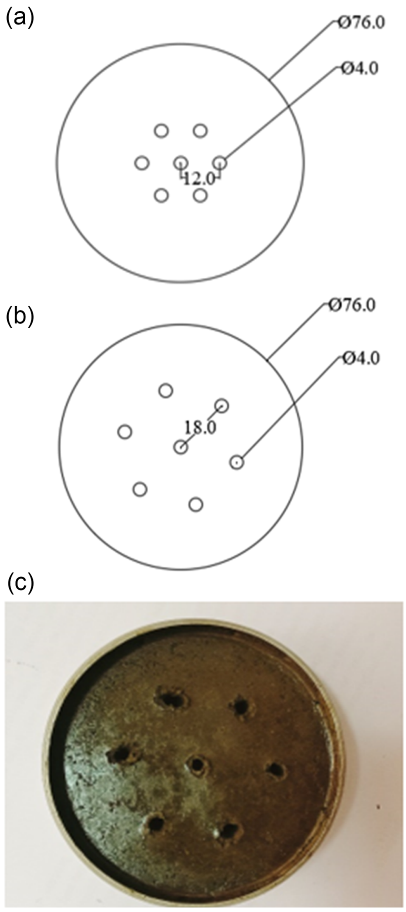
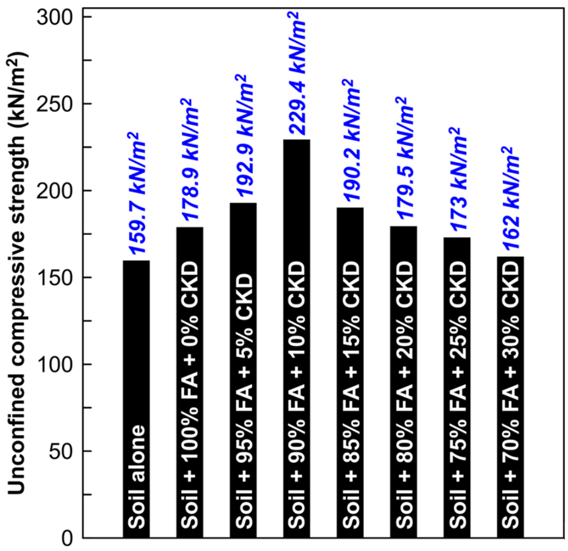


Figure 5
Variation of BC soil's UCS treated with different mixture combinations of FA-CKD column



caused by the presence of calcium hydroxide from the FA dissolves into the soil, which dissociates in pore water and increases its pH [10]. The silica and alumina particles found in the clay particles dissolve as the pore water becomes more basic. These naturally pozzolanic silica and alumina particles would then react with calcium ions present in the soil to form calcium silicate hydrate gel (C-S-H gel) and calcium aluminate silicate hydrate gel (C-A-S-H gel) with the soil matrix [14].

On the other hand, the BC soil's UCS treated with FA-CKD column was significantly higher than that of soil only. This is because the presence of soil column has caused the formation of C-S-H, C-A-H, and C-A-S-H gel, which are all strong cementitious materials [15]. The strength development of the soil up to optimum lime content is exceptionally high. The C-S-H formation will then fill up the void space between the BC soil particle, which results in denser and stronger soil that allows a higher compressive strength [16]. An increase in CKD content from the FA-CKD column can improve the stiffness of BC soil [17]. The compressive stress increases linearly with higher CKD content up to the combination of 90-10. This has led to the highest value of UCS, reaching 229 kN/m^2, an increase of strength by 1.47 folds. Any further increase in the CKD content beyond the optimal ratio leads to a decline in the soil's compressive strength. With increasing CKD content in the soil, the calcium ions in the pore water increase, which will react with hydroxyl ions present in the soil to form free lime and further reduces soil strength. Hence, based on the stress–strain behavior of BC soil treated with various combinations of FA-CKD filled in the column for a curing period of 7 days, the optimum combination of FA-CKD column to be used for BC soil was found to be 90-10. This mixture combination is then used in the subsequent tests.

3.2. Effect of FA-CKD column on BC soil strength with curing

The optimum ratio of FA-CKD soil columns cured at various periods of 0, 7, 14 and 28 days are supplemented into BC soil and tested. Figure 6 presents how the stress–strain behavior of BC soil improves when it is treated with FA-CKD column and cured for different lengths of time. The increase in UCS at 0 days of curing is marginal compared to the results obtained when samples are cured for seven days. The pozzolanic reaction found in the soil sample is found to be the cause, which has increased with the curing period [18]. Since both the development of hydrate gels within the soil and the intrusion of calcium ions is a time-dependent behavior, minimal improvement in strength is shown at the immediate testing of soil with minimal curing, which mainly is due to the addition of stiffer FA-CKD additive into the weak plastic soil [10]. The compressive strength of the soil continues to increase with curing time as more hydrate gels that are formed have hardened, which aligns with the literature [19, 20]. This is represented by the stress–strain curve of the soil, which became linear with an increase in strength, representing a noticeable improvement in the stiffness of the soil samples.

3.3. Effect of BC soil molding water content with FA-CKD column and curing on soil strength

FA-CKD column at optimum ratio were applied to treat the BC soil with different molding water content. After undergoing various curing periods of 0, 7, 14, and 28 days, the specimens are subjected to a UCS test. Figure 7 reveals the decrease of BC soil's UCS with increasing moisture content at 0 days of curing. The UCS values

Figure 6
BC soil's stress–strain curve treated using soil columns with optimum FA-CKD combination at different curing periods

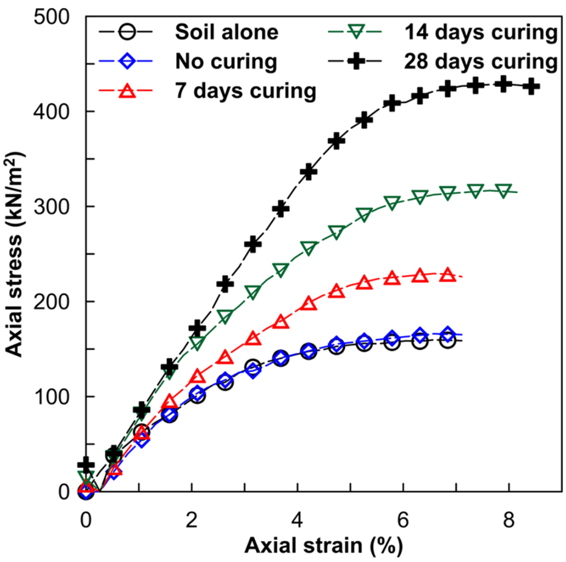
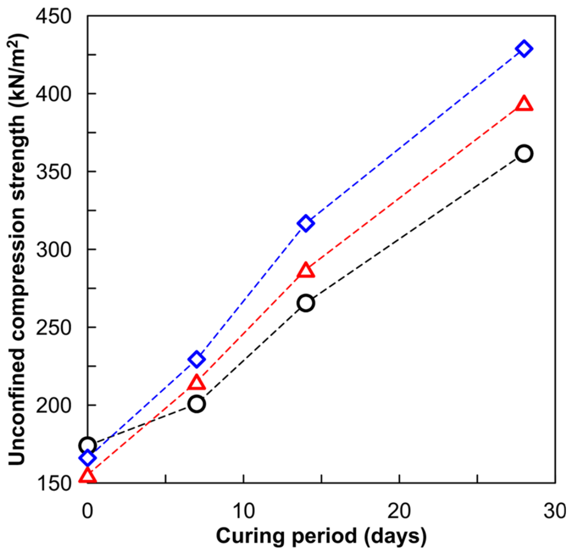


Figure 7
Variation of BC soil's UCS treated with FA-CKD column at different molding water content with various curing periods



are then evolved with curing time, where the highest strength is found at OMC, subsequently at wet of optimum and dry of optimum. The increasing strength due to curing time, as observed previously, can be found here despite the variation in moisture content of BC soil as well. With an increased presence of free water in the soil mixture, the dissociation of calcium hydroxide ($Ca(OH)_2$) along with the creation of C-S-H and C-A-S-H would have increased soil strength. Specimen with moisture content at dry of optimum specimen has the least increase in strength as the formation of pozzolanic activity is limited by the free water present in the soil mixture, which inhibits the complete dissociation of $Ca(OH)_2$ and the release of calcium ions that contributes to gaining in soil strength.

3.4. Effect of column spacing on the swelling behavior of BC soil treated with FA-CKD columns

Using the optimum combination of FA-CKD columns, the effect of column spacing on soil specimens is identified. Figure 8 describes the variation of swell potential with increasing soil column spacing. Figure 8(a) describes the reduction of swell potential with the increase in soil column spacing, while Figure 8(b) describes the reduction of swell potential with increasing curing time. The increase in spacing assisted in the migration of calcium into the soil due to the addition of CKD. Figure 9 describes the swell pressure of the soil influenced by the presence of FA-CKD columns, where Figure 9(a) describes the reduction of swell pressure with increasing soil column spacing.

Figure 8
BC soil's swell potential when treated with FA-CKD columns (a) at different column spacing (b) at various curing periods

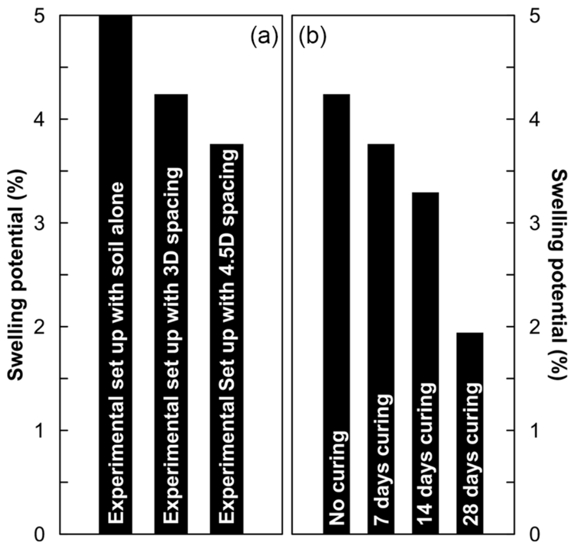
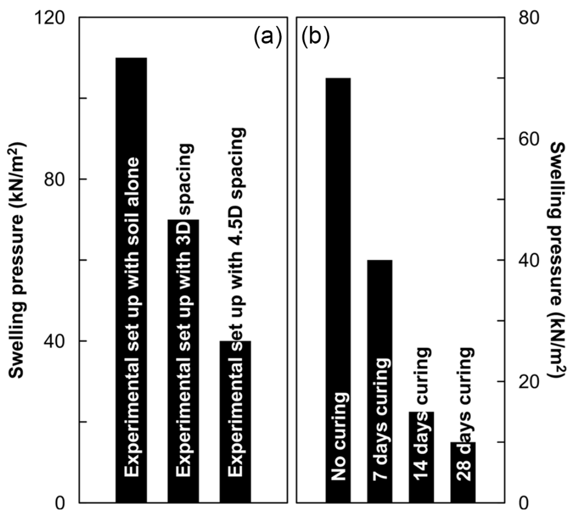


Figure 9
BC soil's swell pressure when treated with FA-CKD columns (a) at different column spacing (b) at various curing periods

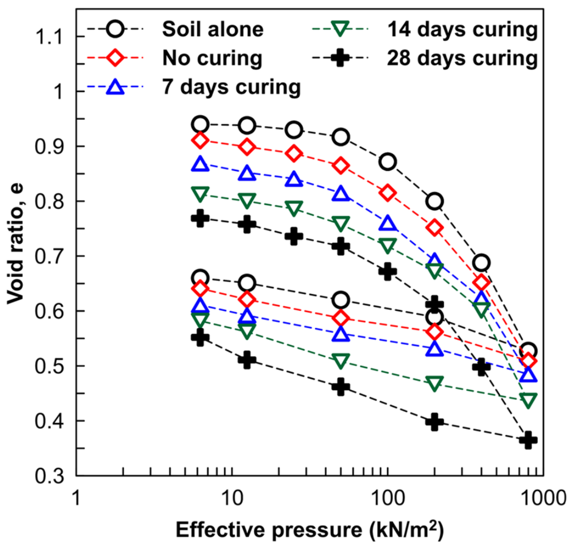


In contrast, Figure 9(b) describes the decrease of swell pressure with increased curing time.

3.5. Effect of FA-CKD columns on the compressibility behavior of BC soil

Based on the outcome of the previous section, a column space of 4.5D is adopted for this study. Figure 10 shows how the pressure and void ratio for BC soil change when it is treated with cured FA-CKD columns. As shown in previous sections, the initial void ratio of BC soil reduced with increasing curing time due to the replacement of weakened plastic soil with the stiffer FA-CKD. The compression index of the void ratio with pressure curve shows that the compressibility reduced with increasing curing time of the optimum composition of FA-CKD columns. This lower compressibility is caused by an increase in the formation of hydrated gels, which has also been mentioned in previous sections [21].

Figure 10
1D consolidation behavior for BC soil treated with FA-CKD columns at various curing periods



4. Conclusion

Expansive soils are often problematic due to the significant changes in soil volume with changes in soil moisture. This can be problematic to structures and can be costly to remedy. Therefore, this paper presents research on the practicality of implementing FA-CKD columns to improve the strength and compressibility of the BC soil. The behavior of the optimum mixture of an FA-CKD column is determined by conducting UCS test and 1-dimensional (1-D) consolidation tests. At the ratio of 90% FA and 10% CKD, the UCS of BC soil supplemented with this combination of soil columns has found an increase in soil's strength due to pozzolanic reaction. With the addition of the curing period, the soil strength has improved significantly with higher pozzolanic activities. BC soil prepared with the highest unit weight (γ_{max}) at the OMC is discovered to have the highest strength improvement of expansive soil, followed by soil prepared at wet and dry of OMC, respectively. This is due to the presence of free water, aiding the formation of C-A-S-H and C-A-H gels as also highlighted in the literature.

Through 1-D consolidation and swell potential tests, expansive soil's swelling and compressibility behavior reduced significantly when FA-CKD columns at optimum ratio were placed at a spacing of 4.5D. This is due to the increased formation of hydrated gels with increased spacing between columns as it assisted with the migration of calcium into the soil.

Nonetheless, the application of waste products shown in this paper is evident to be effective in improving the engineering properties of expansive soil. In this paper, columns filled with industrial waste products, such as FA and CKD, can improve the strength and compressibility of soil. This allows for deeper sections of the soil to be stabilized, which can avoid extra costs in ground remediation. By practising the waste-to-wealth principle, it will assist in achieving sustainable development goals 9 and 11.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

B. S. Pankaja: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **N. H. Ranjita:** Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **H. N. Ramesh:** Conceptualization, Formal analysis, Investigation, Writing – review & editing, Visualization, Supervision. **Jun Cheng Kho:** Formal analysis, Investigation, Writing – review & editing. **Mavinakere Eshwaraiah Raghunandan:** Conceptualization, Formal analysis, Investigation, Writing – review & editing, Visualization, Supervision.

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