

Research Article

Effectiveness of Bagasse Ash Incorporating Limestone Calcined Clay Cement (LC³) in Improving Shear Strength and Durability Properties of Black Cotton Soils

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This study aims to investigate the capacity of bagasse ash (BA) incorporating limestone calcined clay cement (LC³) for stabilisation of black cotton soil (BCS) in Shire Valley, Malawi, in terms of shearing and durability properties. First, BA and LC³ were developed, and their physiochemical properties were investigated. Specimens were created of BA incorporating LC³ in mix ratio of 2:1, respectively. BA incorporating LC³ specimens were blended into BCS at mix proportions of 0% to 12%. The mixtures were subjected to 3, 7, 15 and 30 curing days, and 10°C and 32°C curing temperatures, under confining pressures of 150, 300 and 450 kPa for direct shear test. Effect of simulated whether condition of wetting–drying cycles (WDCs) on behaviour of treated BCS was investigated through durability test. The results showed that the shear strength of 12% treated BCS increased above 70% on average, with higher values at 450 kPa confining pressure, and that the shear strength of treated BCS cured at 10°C was lower than that cured at 32°C. Durability test results illustrated that the 4% treated BCS collapsed upon immersing in water. The 8% treated BCS reduced against WDC. The 10% and 12% treated BCS specimens displayed an increasing trend against WDC, indicating both short- and long-term hydration stabilisation reaction. This study shows the feasibility of BA incorporating LC³ for BCS stabilisation relevant to geotechnical construction in tropical climatic regions, and further promotes the reuse of by-products and wastes as cementitious materials for BCS stabilisation practice.

Keywords: bagasse ash; BCS treatment; durability performance; LC³ system; shearing performance

1. Introduction

Escalation of carbon footprint and economic challenges due to the utilisation of conventional binders such as ordinary Portland cement (OPC) for black cotton soil (BCS) stabilisation has stemmed environmental and financial limitations [1–4]. Sugar industry and milling places from Shire Valley in Malawi, produce more than 2,000 tonnes of bagasse ash (BA) per month during processing stages [5]. Most of these BA wastes are dumped on open spaces as landfill and they create serious environmental challenges. Shire Valley also experiences problems of BCS that covers a large area such that it is not feasible to avoid or replace it. This BCS is

derived from the Shire River (largest river in Malawi) and the river's tributaries throughout its flood plains. Damages to geotechnical constructions such as highways, railways and buildings founded on such BCS in the area have been reported in various places, and have resulted in significant economic losses. Problematic nature of this BCS is related to its weak structure [4, 6]. Whenever inadequate attention is paid to treat its properties, the result is usually undesirable infrastructural failures [6–9]. The treatment of this BCS is presently one of the priorities of Malawi nation.

Stabilisation process is among significant treatment methods applied to solve unacceptable geotechnical behaviour of BCS, and various research works have been performed to treat

this BCS over several decades through either mechanical or chemical techniques [7–10]. Mechanical improvement involves processes such as reinforcement, dewatering and densification, while chemical improvement incorporates binders as additives [10, 11]. Effectiveness of chemical improvement option is shown through low-cost requirement compared to high-cost mechanical techniques [11]. It involves soil mixing with binders which react chemically through pozzolanic and hydration means to enhance engineering properties of the soil in ideal cases [11–16]. The most frequent chemical cementitious binder employed for BCS treatment to remediate its damaging impact globally is the OPC [17]. However, regardless of its universal acceptance, there is an increased trend to substitute it with by-products and waste materials because of resource limitations and its extensive demand [2, 13]. Moreover, carbon footprint has stemmed from its energy-intensive manufacturing process, which contributes to at least 9% of global carbon anthropogenic emissions [1, 2]. Where bulk BCS stabilisation is needed, OPC consumption is quite high and expensive [8, 15], considering the prevailing poor economic conditions of countries such as Malawi. Hence, a need for alternative binders is critical to substitute OPC and minimise its negative impacts to the environment and its high BCS stabilisation cost requirement.

One of those alternative binders is from sugar industry that produces BA wastes. The widespread and inapplicability of these wastes are resulting in problems of disposal and on environment in Shire Valley, Malawi. Sugar producing industry may burn bagasse wastes, which is obtained from sugarcane after extracting juice, as a fuel in a combined generator to produce electricity, and BA becomes the final waste during that process [16]. Thousand kilograms of bagasse waste may yield approximately 30–45 kg of BA [18]. Many research works have shown that BA can be employed as cementitious material to replace OPC in BCS stabilisation [6, 9]. Similar to industrial by-products, BA maintains or improves the performance of treated BCS due to its pozzolanic reaction and may yield benefits both environmentally and economically [16]. Besides, BA is produced continuously, making its application as a cementitious material in BCS stabilisation a promising research direction [9, 18]. On the contrary, BA has been widely used as a fertiliser and is reported by several studies to yield a very minimal nutritional value and to cause soil pollution risks when used as a fertilising material [19]. To date, several attempts have been made to use BA in many areas, such as production of ceramic materials [20, 21], sintered aggregates (lightweight) [22] and silica aerogel [23]. Other attempts have employed BA as a cementitious material such as in ordinary, self-compacting and pavement concretes [24–27], and improved strength, durability and interface compactness properties have been reported. These studies justify the practicability of the use of BA as a cementing material. In terms of BCS treatment, the adoption of BA as stabilising material has been broadly reported by several studies [6, 9]. However, the sole examination of BA to fulfil serviceability and strength criteria of treated BCS implies that BA alone is not suitable for stabilising BCS subgrades for geotechnical constructions [16]. When BA was solely applied

to stabilise BCS, vertical displacement increase was reported [9]. Many studies assessed the incorporation of addition materials such as propylene fibre, lime, fly-ash and dolime to BA for stabilisation of BCS [28–30]. These studies discovered that such incorporations curtailed the plasticity index (PI) of the treated BCS, although increase in California bearing ratio of treated BCS was insignificant. Incorporating BA with OPC improved unconfined compressive strength (UCS) of BCS and managed BA disposal concerns through BA waste reduction [6, 14]. Application of BA incorporating OPC exhibited significant decline in PI and free swell potential of treated BCS [16, 17]. Himani, Kitendra and Biswajit [9] assessed the reduction in heave due to the addition of BA incorporating OPC content in BCS samples and significant improvement of the treated BCS samples was reported. These previous studies verify the capacity of BA incorporating OPC on the improvement of engineering behaviour of BCS. However, the utilisation of OPC as an incorporating material to BA might raise the carbon footprint environmental concerns and significantly increase the BCS stabilisation costs as compared to the related benefits [1, 3, 31].

Limestone calcined clay cement (LC³) offers high prospects of carbon footprint reduction and cost effectiveness when used as an additive material to BA and is currently an emerging technique in geotechnical construction [32–35]. LC³ is made from calcined clays [33]. With calcining kaolin clay, metakaolin is produced, which demonstrates good hydration reaction when combined with the filler of limestone [34]. Moreover, its manufacture does not require new technologies, making it inexpensive and easy to introduce to the geotechnical construction industry [32]. With 0.3 calcined clay factor and 0.15 limestone filler factor, its performance is relative to or better than OPC at 0.5 and 0.05 clinker and gypsum factors, respectively [33, 35]. Compared to OPC, the LC³ notable features lie in being able to decrease consumption of clinker by almost 50%, while facilitating the dense rheological formation just as OPC, leading to enhanced mechanical strength and improved durability [33, 34]. Thus, LC³ is currently one of the solutions for combating the climate emergency and high costs associated with OPC industry in geotechnical construction sector [32, 35]. Several studies have been published so far with regard to the use of LC³ as a substitute of OPC. For example, Kafodya et al. [36] analysed the impacts of calcined clay on performance of LC³ concrete. Akindahunsi, Avet and Scrivener [33] provided valuable insights on LC³ and its influence on hydration activities. Some recent studies of Reddy et al. [32] and Wang et al. [34], respectively, centred on stabilisation of zinc and radioactive borates contaminated soils with LC³ and demonstrated its capacity to alter the properties of treated soils through hydration reaction. Generally, the previous studies demonstrate the feasibility of LC³ as a great performance reliable cement. Just as Sheikh et al. [35], Ijaz et al. [2] showed that LC³ can be applied just as OPC in the construction industry and does not need a specialised training. Thus, BA can be incorporated with LC³ in the same manner the BA is incorporated with the OPC [37, 38]. Overall, a combined utilisation of BA and LC³ as cementitious material has a significant potential to meet the extensive

amounts of materials demanded by cement industry for BCS stabilisation practice in a green and cost-effective manner.

However, a study on bridging the behaviour of BA incorporating LC^3 system as a cementitious binder from BCS stabilisation perspective remains prominently absent. The fundamental stabilisation mechanism through which BA incorporating LC^3 system can interact with minerals present in BCS to enhance its properties needs to be investigated and determined. The suitability and effectiveness of BA incorporating LC^3 system in BCS stabilisation need to be explored and established. Hence, a relevant study with respect to the use of BA incorporating LC^3 system for BCS stabilisation is extensively required. Furthermore, a study on shearing and durability properties of treated BCS which is of great significance for geotechnical construction is limited. Moreover, Malawi experiences tropical climatic conditions in which shearing and durability performances become a key concern as wetting–drying cycle (WDC) leads to degradation of the properties of treated BCS mixture. Therefore, this study endeavours to bridge these critical knowledge gaps by carrying out an authoritative and extensive experimental investigation that delves into understanding of mechanisms of BA incorporating LC^3 system, considering its suitability and effectiveness in stabilisation of BCSs relevant to geotechnical construction in Shire Valley, Malawi, with respect to shearing and durability properties. This study promotes the high value use of BA and LC^3 materials for stabilisation of BCS in tropical climatic conditions. It also promotes the utilisation of BA incorporating LC^3 technique for mitigation of climate change environmental problems and reduction of high costs for BCS stabilisation science relevant to geotechnical construction.

2. Materials and Methods

BCS, BA and LC^3 are the prime materials used in this study and were all obtained from Shire Valley, Malawi. Figure 1 shows the location map of Shire Valley in Malawi. Its area is approximately 6696.54 km². Figure 2 presents the tropical climatic condition of Shire Valley.

The BCS was obtained from Marka, Mikalange and Kalambo areas (Figure 1) in Shire Valley at 1.5 m depth to avoid foreign and organic matters [3]. Initially, the collected BCS was dried in the sun, and later in an oven for 1 day at 110°C [7]. Thereafter, the oven-dried BCS was passed through 2.0 mm sieve to prepare homogenous specimen. Engineering characteristics of the BCS were depicted and are presented in Table 1. The determinations in Table 1 lie within the scope determined for BCS by other studies [6–9]. Based on Table 1, the BCS was classified as clayey silt, and as per AASHTO and USCS soil classification systems, the BCS was further classified as A-7-6 and CH, respectively. Thus, this BCS is very vulnerable to be utilised as a foundation material for geotechnical construction [4, 7, 9]. Table 2 presents the obtained elemental components of the BCS analysed using X-ray fluorescence (XRF).

The key material used in this study to stabilise the BCS was BA incorporating LC^3 . The BA was collected from

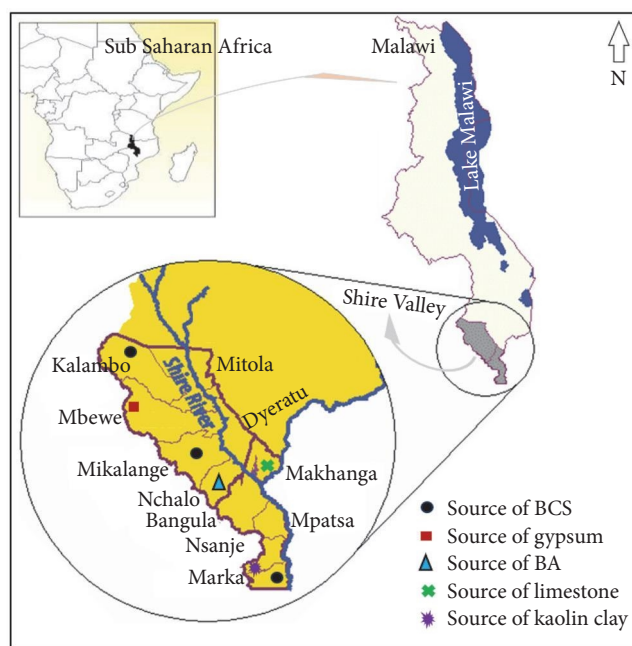


FIGURE 1: Map showing the geographical location of Shire Valley in Malawi.

ILLOVO Sugar Co., Ltd., in Nchalo (Figure 1). The LC^3 components such as limestone and kaolin clay were obtained from Makhanga and Marka, respectively (Figure 1). Currently, the OPC developed from clinker, is the mostly used cementitious binder in Malawi for geotechnical construction industry. Records display that the monthly OPC consumption exceeds approximately 30,000 tons in the whole Malawi, and approximately 1700 tons in Shire Valley alone [45]. The prevailing poor economic status of Malawi makes it hard for bulk utilisation of OPC for BCS stabilisation, resulting in geotechnical constructions that are vulnerable to failures initiated by BCS supporting those constructions (Figure 3). Besides, the ILLOVO Sugar Co., Ltd., alone produces at least 2000 tons of BA per month [5]. Thus, the monthly consumption of 1700 tons of cement makes the monthly 2000 tons of BA production in Shire Valley significant. Moreover, the BA is incorporated with the LC^3 , thus reducing its high consumption requirement, and rendering the proposed BA incorporating LC^3 technique for BCS stabilisation application in Shire Valley more sustainable.

For experimental tests, the obtained raw BA from ILLOVO Sugar Co., Ltd., was put for 24 h in an oven at 110°C to thoroughly dry it up prior to subsequent testing. The raw BA had fine and coarse fibres and 23.25% loss of ignition (LOI). It was then calcined at 600°C for 1 h in a muffle furnace to reduce its carbon content. The BA had 2.14% LOI after removing it from the furnace and cooling it in the air. Then, it was ball-milled for 20 min to obtain d_{50} equal to 12 μ m mean particle size. Table 2 presents the chemical composition of the BA obtained through XRF analysis. According to the properties of the BA depicted in Table 2, and with respect to specifications of ASTM C618 [46], a natural pozzolana with a total percentage of Fe_2O_3 , SiO_2 and Al_2O_3 above 70% is classified as Class F pozzolana. Hence, the BA in this study belongs to Class F pozzolana [46].

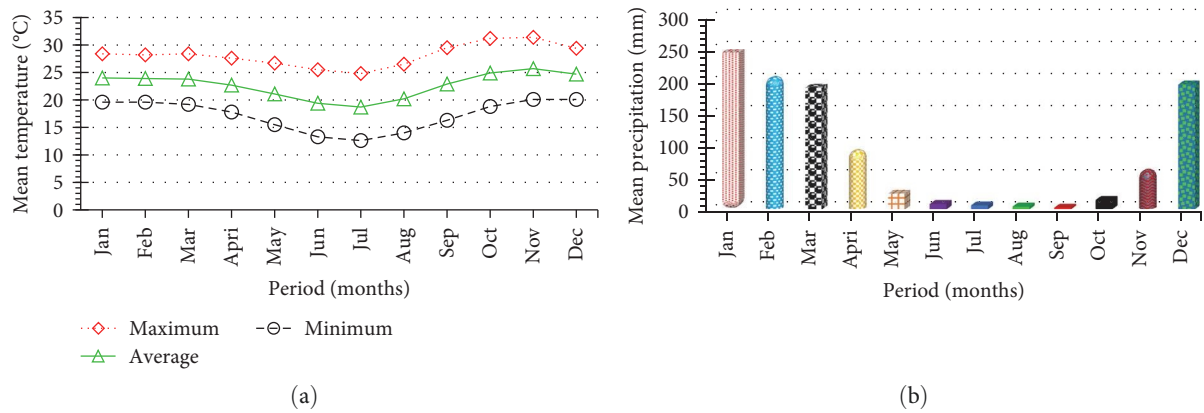


FIGURE 2: Tropical climatic condition of Shire Valley from 1991 to 2023 [39]: (a) temperature per month, and (b) precipitation per month.

TABLE 1: Properties of untreated black cotton soil (BCS).

Index properties	Test method	Mean value
Consistency	BS 1377 [40],	—
Liquid limit	—	67.2%
Plasticity	—	39.6%
Compaction (standard proctor test)	BS 1377 [40],	—
Optimum moisture content (OMC)	—	17.37%
Maximum dry density (MDD)	—	16.54%
Organic content	IS 1498 [41],	2.26%
Specific gravity	IS 2720 [42],	2.55
Free swell	IS 2720 [42],	126.8%
Unconfined compressive strength (UCS)	AS 1289 [43],	101.7 kPa
Particle size distribution	ASTM D6913 [44],	—
Clay	—	55.6%
Silt	—	34.9%
Sand	—	9.5%
Gravel	—	0.0%

TABLE 2: Chemical composition of BCS, BA, LC³, and reference OPC.

Properties	BCS	BA	LC ³ system	OPC (CEM I: 42.50 N)
Fe ₂ O ₃	8.65%	6.41%	3.36%	3.69%
SiO ₂	65.12%	61.62%	26.46%	20.51%
Al ₂ O ₃	12.03%	11.56%	5.01%	4.49%
K ₂ O	1.41%	3.51%	0.46%	0.51%
Na ₂ O	1.84%	1.07%	0.14%	0.33%
CaO	0.7%	6.51%	57.37%	61.92%
MgO	1.21%	3.17%	1.60%	1.22%
pH	7.96	10.71	11.33	12.54
LOI	5.67%	2.14%	1.57%	0.98%

Abbreviations: BA, bagasse ash; BCS, black cotton soil; LC³, limestone calcined clay cement; LOI, loss of ignition; OPC, ordinary Portland cement.

The main materials for LC³ development were calcined kaolin clay and limestone, which have valuable potential for wider acceptance because of their global availability [47]. It is estimated that in Shire Valley alone, the kaolin clay is over 4 million tonnes and limestone is over 10 million tonnes [36]. Several research works have shown that calcined clay in

combination with limestone filler can efficiently replace almost 50% of the clinker (the clinker in this study was obtained from Lafarge Cement Co. Ltd., present in Shire Valley) due to their better hydration properties, providing comparable strength to OPC at 5% gypsum [35]. The gypsum is estimated to be over 3000 tonnes in Shire Valley [36].



FIGURE 3: Typical representation of geotechnical constructions founded on black cotton soil (BCS) in Shire Valley.

It is believed that raw materials from Shire Valley can produce LC³ system with unique specific properties in regards to unique type of nature of geology of Malawi [36, 45]. This is because raw material is primarily country specific and whose property depends on geological formation [33, 36].

For experimental tests, the limestone, clinker and gypsum were grounded separately to produce fine powder. Kaolin clay was initially pulverised and passed through 75 μm sieve [32]. Only volumes of fine materials finer than 75 μm were used for preparation of LC³ system [34]. Kaolin clay was calcined at $800 \pm 10^\circ\text{C}$ for 30 min in muffle furnace [33]. LC³ system was prepared with 50% clinker, 30% calcined clay, 15% limestone filler, 5% gypsum and water ratio mix of 0.450 in order to make certain satisfactory development of mechanical strength as reported by previous studies [36, 47]. Besides, the OPC classified as CEM I: 42.50N which conforms to ASTM C150 [48], specifications, was used in this study as a control in order to compare its UCS performance with that of locally developed LC³ system. The OPC was purchased from Lafarge Cement Co. Ltd., Shire Valley, Malawi. To investigate the UCS development of LC³ system and that of reference OPC system, concrete cubes with sizes of 150.0 mm were prepared as per recommendation of BS EN 12390 [49]. Four test samples were kept for period of 7, 14, 28 and 90 days. The mean values of determined results are shown in Figure 4, and Table 2 presents the chemical composition obtained through XRF analysis of the LC³ and OPC systems. For UCS comparative purposes, Figure 4 denotes that LC³ system gained higher UCS values than OPC system from 28 days of curing period and afterward. Prior to 28 days of curing, OPC system possessed more UCS values than LC³ system. These determinations were attributed to calcium silicate different amounts containment in LC³ and OPC systems [35]. Calcium silicate proportions play a great role for enhanced early UCS of OPC system [35]. The gaining of higher UCS values of LC³

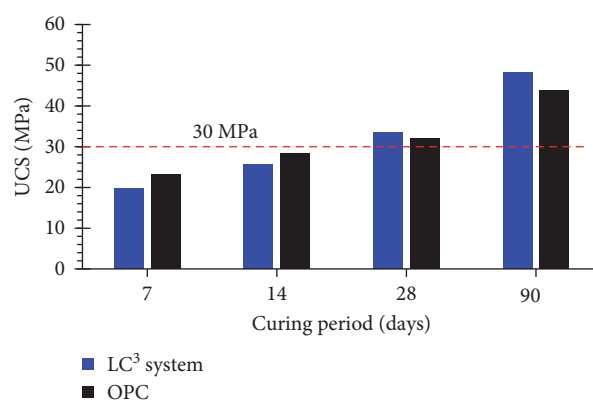


FIGURE 4: Unconfined compressive strength (UCS) of concrete cubes of limestone calcined clay cement (LC³) system and ordinary Portland cement (OPC) system for comparative purposes.

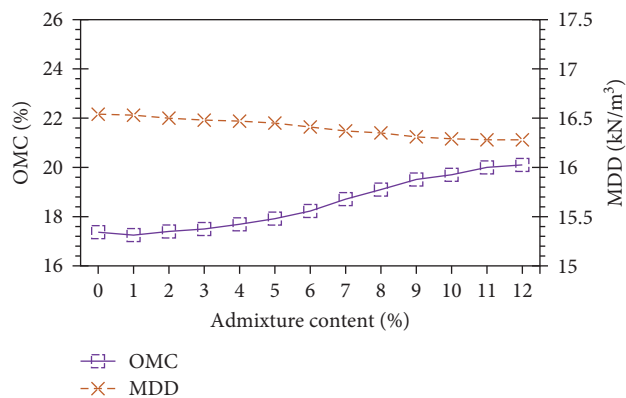
system than OPC system following 28 days of curing period and afterward was due to hydration reactivity of LC³ components [33, 47]. Besides, the obtained UCS results satisfy the stipulated target of 30 MPa minimum recommended allowable limit of compressive strength for concrete cubes at 28-day curing period [49]. Moreover, with respect to the specifications of ASTM C150 [48] and BS EN 197 [50], the properties of the LC³ in this study satisfied the standard strength requirement for ordinary Portland clinker cement.

Furthermore, the BA was incorporated with LC³ in the mix ratio of 2:1, respectively, and blended properly [37, 51]. The chemical components of the BA incorporating LC³ blend were characterised through XRF analysis and are presented in Table 3

To prepare the specimens for direct shear test and durability test, the 2:1 mix ratio of blended BA incorporating LC³ was mixed with the BCS in different percentage range of

TABLE 3: Chemical components of bagasse ash (BA) incorporating limestone calcined clay cement (LC³) system.

Properties (%)	Fe ₂ O ₃	SiO ₂	Al ₂ O ₃	K ₂ O	Na ₂ O	CaO	MgO	Loss of ignition (LOI)
BA incorporating LC ³	4.8	45.7	23.5	1.1	1.3	16.2	1.3	1.7

FIGURE 5: Variations in OMC and MDD of black cotton soil (BCS) at different bagasse ash (BA) incorporating limestone calcined clay cement (LC³) content.

0%–12%. The potable water similar to OMC quantity was supplemented to this mixture and mixed properly to get a solution. The standard compaction test was performed as per BS 1377 [40], specifications to get the compaction properties, and the findings are presented in Figure 5. With respect to Figure 5, the OMC and MDD vary with BA incorporating LC³ content increase. At smaller BA incorporating LC³ system percentages ($\leq 4\%$), variations of OMC and MDD are almost negligible. At larger BA incorporating LC³ system percentages ($>4\%$), there is a noticeable increase in OMC and slight reduction in MDD. These trends are consistent with previous studies [17, 32]. Variations in OMC and MDD values with BA incorporating LC³ system content increase were justified by agglomeration and flocculation between the BCS particles [6–9].

Moreover, Table 4 demonstrates the governing reinforcement mechanism of BA incorporating LC³ system—treated BCS mixture. The mixing of BA incorporating LC³, water, and BCS results in hydration and pozzolanic reactions and production of $\text{Ca}(\text{OH})_2$ and CSH as well as CAH compounds. The $\text{Ca}(\text{OH})_2$ reacts with chemical elements present in BCS. This generates ion products such as Ca^+ and OH^- , which wrap around BCS surface and create the network structure, thereby, optimising the pore structure [9, 34].

Furthermore, the 0%–12% of BA incorporating LC³ contents were investigated on the treated BCS mixtures in terms of shearing and durability properties.

For shearing properties, the direct shear test was employed and it was conducted in a controlled chamber in which the temperature ranged from $+10^\circ\text{C}$ to $+32^\circ\text{C}$ with an accuracy of $\pm 0.1^\circ\text{C}$ to simulate the temperature conditions of Shire Valley in Malawi. The simulated minimum temperature of 10°C and the maximum temperature of 32°C for direct shear test were selected based on the climatic mean

temperature conditions of Shire Valley as portrayed in Figure 2a. The specimens for direct shear test were cured for 3, 7, 15 and 30 days and subjected to three different confining pressures of 150, 300 and 450 kPa. The direct shear test was performed using GCTS STX-300 triaxial apparatus as per ASTM D3080 [52], specifications. Prior to the commencement of the triaxial tests, the lines of drainage were flushed with deaired water with the aim of avoiding any air inside the testing system. Samples were set on triaxial machine permeable base, then top cap was installed. Filter paper disc was employed to separate the specimen end and built-in porous stone. This helped prevent addition of the fines in the system [52].

The durability test was conducted through WDC in order to simulate the effect of climatic precipitation conditions experienced in Shire Valley (Figure 2b) on behaviour of treated BCS. The durability test through WDC was carried out for treated BCS mixtures in accordance with ASTM D559 [53]. After 7 curing days, samples with 104.5 mm and 115 mm diameter and height, respectively, were soaked for 6 h in water and dried-up at 72°C in oven for 41 h to represent the first wetting cycle [24, 54]. The 47-h WDC was repeated for 16 times. The UCS test was carried out on BCS specimens after 1, 4, 8, 12 and 16 cycles. It has to be said that UCS test is not a common procedure for durability assessment. Nevertheless, it gives a parameter to evaluate the degradation of the treated specimen [30, 54, 55].

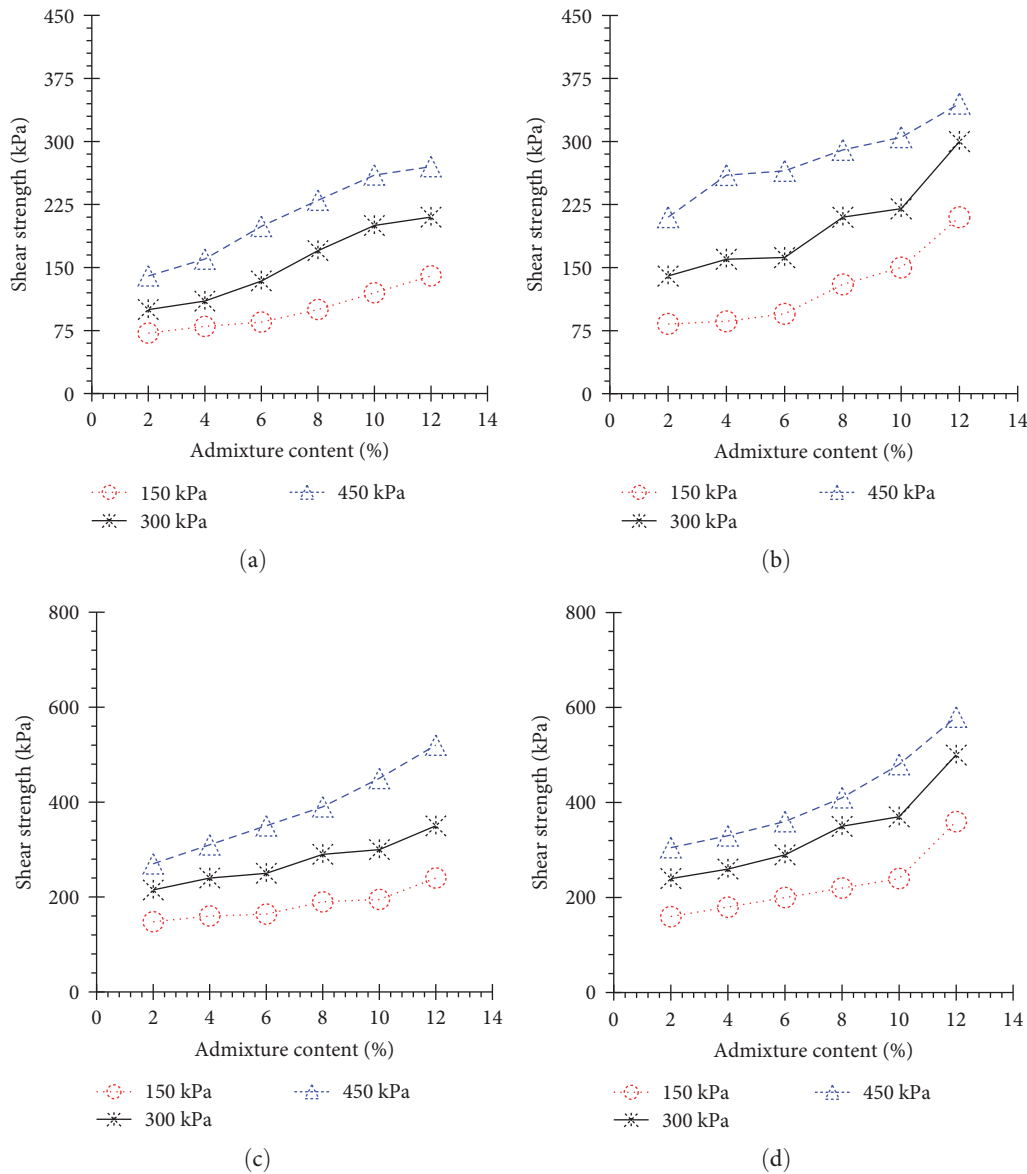
3. Results and Analysis

3.1. Shearing Properties. With respect to the climatic temperature conditions of Shire Valley in Malawi as shown in Figure 2a, the 10 and 32°C were selected as low and high curing temperatures respectively of BA incorporating LC³ system—treated BCS mixtures for direct shear test. Duration of 3, 7, 15 and 30 days was opted for curing the treated BCS mixtures. Figures 6 and 7 show the effect of BA incorporating LC³ system content on shear strength behaviour of treated BCS specimens.

In regards to Figures 6 and 7, the shear strength of treated BCS increases with BA incorporating LC³ system content increase. For example, for the BA incorporating LC³ system—treated BCS cured at 10°C for 30 days, the shear strength of the 12% treated BCS under 150, 300 and 450 kPa confining pressures were 360.32, 499.65 and 581.33 kPa, respectively, with an average shear strength of 480.43 kPa. The shear strength of 12% treated BCS increased by 71.58% on average and 105.31% on average higher than those of 6% and 2% treated BCS samples, respectively (Figure 6d). This was justified by the increase of BA incorporating LC³ content generating more hydration products, which resulted in formation of interface bonds on BCS pore surfaces [54]. This phenomenon resulted in the improvement of internal structural matrix and

TABLE 4: Reinforcement mechanism of bagasse ash (BA) incorporating limestone calcined clay cement (LC³) system—treated black cotton soil (BCS) mixture.

Reaction	Chemical process	Compound formation
Hydration	$\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$	Calcium hydrates (crystal-like structure)
Pozzolanic	$\text{Ca(OH)}_2 + \text{SiO}_2 \rightarrow \text{CSH}$	Calcium silica hydrates (gel-like structure)
Pozzolanic	$\text{Ca(OH)}_2 + \text{Al}_2\text{O}_3 \rightarrow \text{CAH}$	Calcium alumina hydrates (fibrous-like)
Dissociation	$\text{Ca(OH)}_2 \rightarrow \text{Ca}^{2+} + 2\text{OH}^-$	Calcium and hydroxide ions

FIGURE 6: Shear strength of bagasse ash (BA) incorporating limestone calcined clay cement (LC³) system—treated black cotton soil (BCS) mixtures at 10°C curing temperature. (a) Curing period of 3 days. (b) Curing period of 7 days. (c) Curing period of 15 days. (d) Curing period of 30 days.

subsequently the shear strength of BA incorporating LC³ system—treated BCS mixtures [56]. The improved effect was also justified by the variation in microstructure with regard to change of spacing of interparticles and reduction of pore sizes [57]. This significantly resulted in improving the compactness, and in return the shear strength of BA

incorporating LC³ system—treated BCS mixture. This discovery is consistent with previous research works [56–58].

Furthermore, it can be observed from Figures 6 and 7 that the shear strength of BA incorporating LC³ system—treated BCS increased with confining pressure, curing period and curing temperature. As confining pressure increased, the

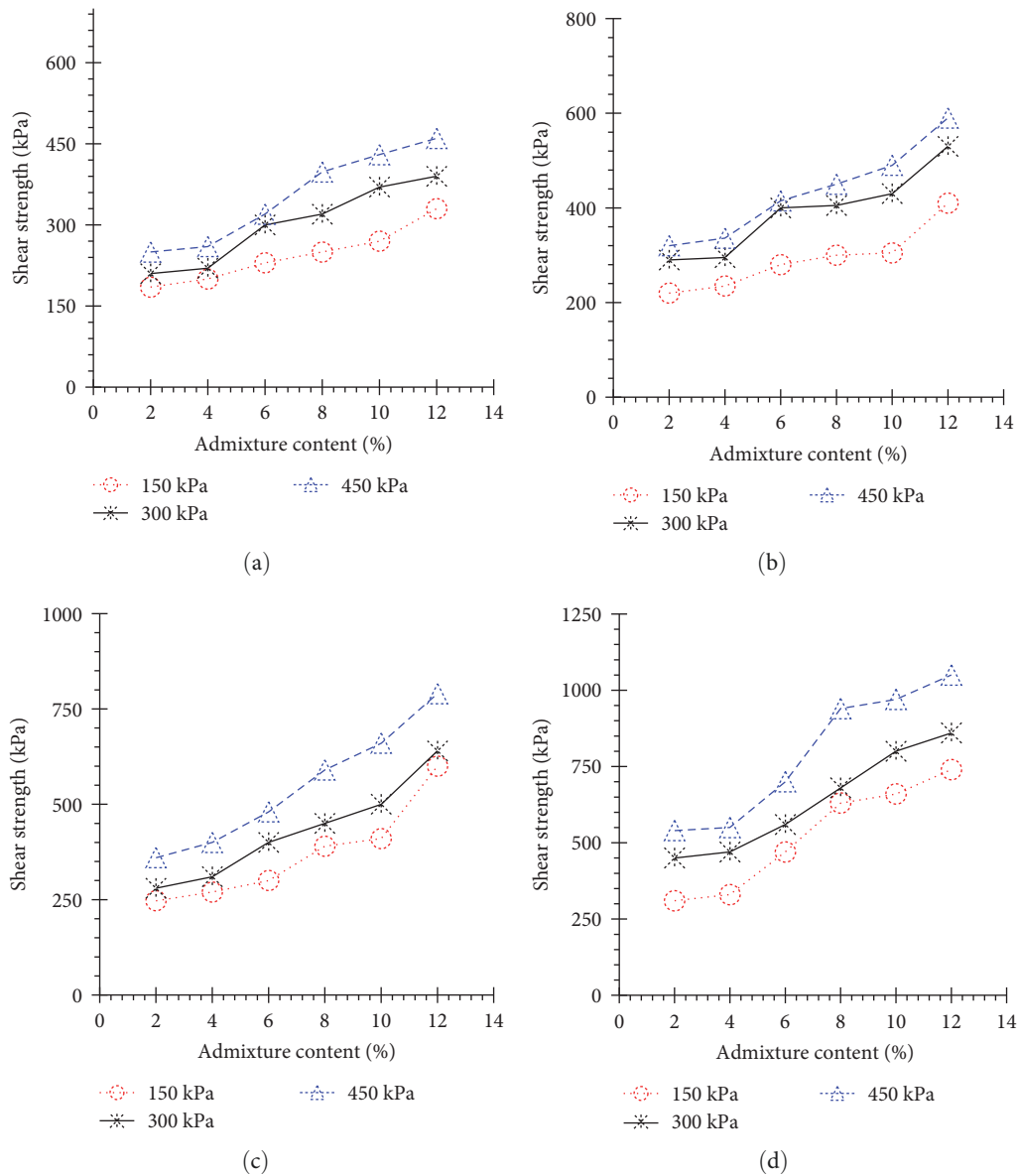


FIGURE 7: Shear strength of bagasse ash (BA) incorporating limestone calcined clay cement (LC^3) system—treated black cotton soil (BCS) mixtures at 32°C curing temperature. (a) Curing period of 3 days. (b) Curing period of 7 days. (c) Curing period of 15 days. (d) Curing period of 30 days.

shear strength demonstrated a significant increase. The 12% treated BCS exhibited a higher maximum shear strength at 450 kPa confining pressure in all testing cases (Figures 6 and 7). This led to a distinct mechanical behaviour associated with breakage of BCS particles and level of cementation [30, 58]. Thus, under low confining pressure, the treated BCS behaviour was more brittle and capable of resisting loads attributable to bonding strength and structural interlocking [58]. With high confining pressure, the treated BCS strength came from the strength of particles, arrangement and breakage [30]. Nagaraj and Miura [59] and Kasama, Zen and Iwataki [60] found that the increase in confining pressure results in the treated soil specimen to undergo a more significant fragmentation of particles, leading to a denser configuration and a spatial reorganisation. This phenomenon enables

the treated soils to withstand the increased confining pressures [59, 60].

In addition, the shear strength of BA incorporating LC^3 system—treated BCS cured at 10°C (Figure 6) was lower compared to that cured at 32°C (Figure 7). For example, at 32°C curing temperature (Figure 7), the maximum shear strength of treated BCS with BA incorporating LC^3 system content of 12% at 3, 7, 15 and 30 curing days was 459.53, 590.00, 789.85 and 1050.26 kPa, respectively. From which, the maximum shear strength at 32°C curing temperature increased by 66.67%, 70.44%, 72.65% and 80.75% at 3, 7, 15 and 30 curing days, respectively, than the maximum shear strength of treated BCS with BA incorporating LC^3 system content of 12% at curing temperature of 10°C (Figure 6). This phenomenon was attributed to different curing temperatures,

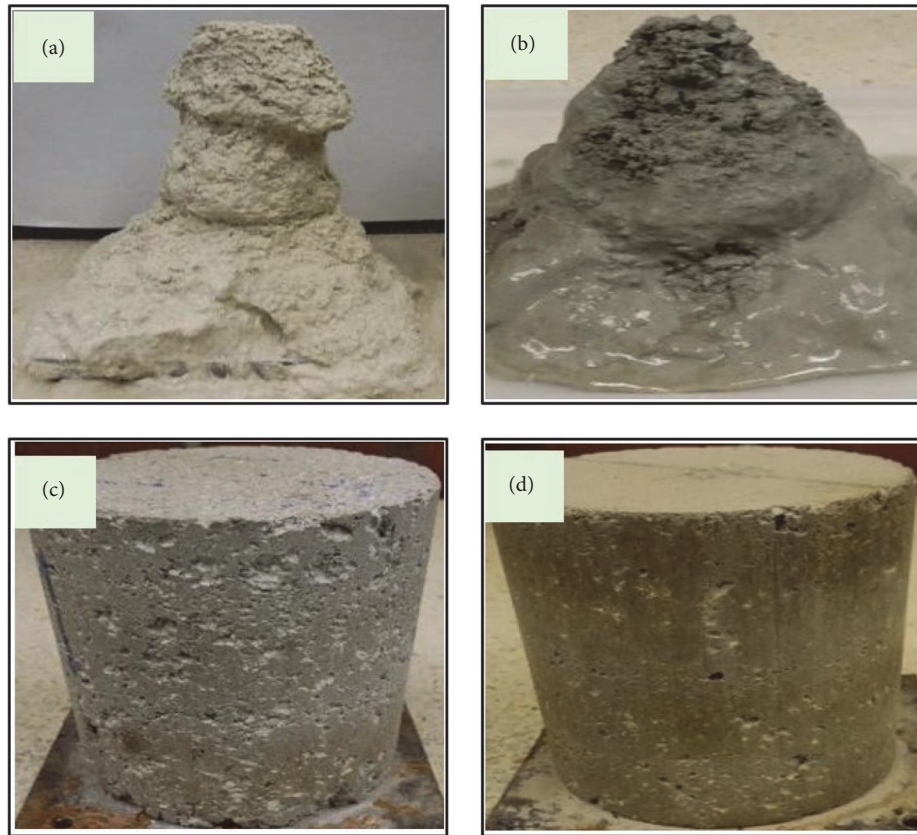


FIGURE 8: Changes of untreated and treated black cotton soil (BCS) samples under different wetting–drying cycle (WDC): (a) untreated – 1st WDC, (b) treated BCS with 4% bagasse ash (BA) incorporating limestone calcined clay cement (LC^3) system – 1st WDC, (c) treated BCS with 10% BA incorporating LC^3 system – 5th WDC, and (d) treated BCS with 12% BA incorporating LC^3 system – 16th WDC.

with the low temperature inhibiting the rate of hydration reaction, as also reported by Abdullah, Shahin and Walske [61], Calik and Sadoglu [56], and Kang, Gi and Liao [57].

3.2. Durability Properties. With respect to climatic precipitation conditions of Shire Valley as shown in Figure 2b, during the rainy period, the moisture content of BCS in Shire Valley increases and subsequently reduces during the dry period. BCS under such variation of season causes damage to geotechnical constructions founded on it [7, 9]. For sustainability assessment of BA incorporating LC^3 system—treated BCS under this long-term weather condition, WDC durability test was employed in this study. Figure 8 portrays the representation of durability behaviour for BA incorporating LC^3 system—treated BCS specimens, and Figure 9 shows the UCS durability test results of treated BCS specimens cured for 7 days.

In regards to Figures 8 and 9, the 4% BA incorporating LC^3 system—treated BCS specimens rapidly collapsed after immersing in water. This phenomenon indicated the insufficiency of BA incorporating LC^3 system at 4% content against the WDC. The disintegration noticeable at 4% BA incorporating LC^3 system content was due to the inadequate cementitious product formation and BCS clusters within the treated BCS mass. This finding agrees well with the conclusions made by Biswal, Sahoo and Dash [62]. The collapse phenomenon was justified by the presence of big pores within the

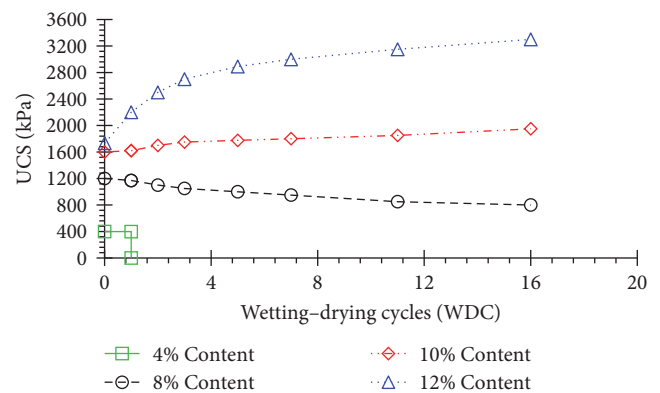


FIGURE 9: Unconfined compressive strength (UCS) durability through wetting–drying cycle (WDC) test results.

treated BCS specimen, resulting in more absorption of water, and thereby, loss of interparticle forces [26, 54]. Similarly, the 8% BA incorporating LC^3 system—treated BCS specimen portrayed a declining trend for UCS values against WDC (Figure 9). The UCS declining trend against WDC was due to bond degradation of treated BCS mixtures, a result which corresponds well with the findings of Chethan and Shankar [30] and Neramitkornburi et al. [55]. This aspect may have been initiated by the influence of pore-water absorption and

softening of treated BCS specimen due to the water immersion as also reported by Suddeepong et al. [54]. However, at the 16th WDC, the UCS value was above 800 kPa minimum recommended durability UCS value for geotechnical constructions [62, 63]. This indicated the long service life for the treated BCS mixtures as supported by previous studies [9, 30, 63].

Besides, the 10% and 12% BA incorporating LC³ system—treated BCS specimens manifested an increasing pattern, indicating BA incorporating LC³ system competent to react with BCS particles in the presence of water. This determination was justified by the pozzolanic and hydration chemical reactions, whereby more CAH and CSH were produced [58, 59]. Overall, the durability test results in this study denote that the treated BCSs with low BA incorporating LC³ system content result in short-term stabilisation of BCS, while the treated BCSs with more BA incorporating LC³ system content result in short- and long-term stabilisation of BCS.

4. Conclusion

The current study focused on investigating the effectiveness of BA incorporating LC³ system dosages on improvement of BCS relevant to geotechnical constructions in Shire Valley, Malawi, in terms of shearing and durability properties. Engineering properties of the untreated BCS were analysed. BCS was stabilised with 0%–12% of BA incorporating LC³ system content. Compaction properties of the treated BCS mixtures were evaluated. Shear strength laboratory tests were carried out on treated BCS considering different BA incorporating LC³ system additive content, curing period and curing temperature. Durability performance of the treated BCS mixtures was also investigated. Based on the study results, these conclusions were drawn.

1. BCS in this study was classified as clayey silt, and highly vulnerable to be employed as a foundation material for geotechnical constructions. Thus, a need to treat its properties. Different percentages of BA incorporating LC³ system in the range of 0%–12% were mixed with the BCS to improve its engineering properties.
2. BA incorporating LC³ system dosages enhanced the compaction properties of the BCS. Specifically, the OMC values minimally increased, and MDD values minimally decreased. The minimal increase and decrease variations in OMC and MDD values respectively with BA incorporating LC³ system dosage addition were justified by agglomeration and flocculation behaviour between the BCS particles.
3. The shear strength of treated BCS increased with BA incorporating LC³ system content, confining pressure, curing period and curing temperature. For the BA incorporating LC³ system—treated BCS cured at 10°C for 30 days, the shear strength of the 12% treated BCS under 150, 300 and 450 kPa confining pressures were 360.32, 499.65 and 581.33 kPa, respectively, with an average shear strength of 480.43 kPa. The shear

strength of 12% treated BCS increased by 71.58% on average and 105.31% on average higher than those of 6% and 2% treated BCS specimens. The 12% treated BCS exhibited a higher maximum shear strength at 450 kPa confining pressure in all testing cases.

4. The shear strength of BA incorporating LC³ system—treated BCS cured at 10°C temperature was lower compared to that cured at 32°C temperature. At 32°C curing temperature, the maximum shear strength of treated BCS with BA incorporating LC³ system content of 12% at 3, 7, 15 and 30 curing days was 459.53, 590.00, 789.85 and 1050.26 kPa, respectively. From which, the maximum shear strength at 32°C curing temperature increased by 66.67%, 70.44%, 72.65% and 80.75% for 3, 7, 15 and 30 curing days, respectively, than the obtained maximum shear strength of treated BCS with BA incorporating LC³ system content of 12% at curing temperature of 10°C.
5. The durability test results through WDC demonstrated that the BCS treated with 4% BA incorporating LC³ system content utterly collapsed after one WDC. In contrast, the BCS samples treated with 8% BA incorporating LC³ system content resisted against 16 WDC. The UCS of 8% BA incorporating LC³ system—treated BCS specimens reduced against WDC, but maintained the minimum 800 kPa UCS value under predetermined 16th WDC. Besides, the UCS durability test results displayed an increasing pattern against WDC for 10% and 12% BA incorporating LC³ system—treated BCS specimens, demonstrating the short- and long-term hydration and pozzolanic stabilisation reactions.
6. From the experimental results, it was found that the use of BA incorporating LC³ for BCS stabilisation significantly improved the shearing and durability properties of treated BCS. Thus, the use of BA incorporating LC³ for BCS stabilisation may improve the performance and lifespan of geotechnical constructions constructed on such treated BCS. This study demonstrated the technical feasibility of BA incorporating LC³ as a suitable cement replacement from BCS stabilisation perspective. It also verified the reuse of agricultural by-products and waste materials for application as cementitious materials. The study further promotes the use of BA incorporating LC³ technique for addressing climate change emergency and reducing high costs for routine BCS stabilisation practice.

This study has denoted that BA incorporating LC³ system—treated BCS exhibits excellent shear strength and WDC durability performance, which may help ensure the reliability and stability of geotechnical constructions in tropical climatic regions such as Shire Valley in Malawi. Nevertheless, only curing temperatures of 10°C minimum and 32°C maximum (considering the climatic conditions of Shire Valley), confining pressures of 150 to 450 kPa, and soil type of BCS were investigated. This may not comprehensively mirror the engineering properties of the treated BCS worldwide under other curing temperature conditions (i.e., lower

than 10°C and higher than 32°C), confining pressures (i.e., lower than 150 kPa and higher than 450 kPa), and different soil types (other than BCS). Hence, future research works should concentrate on other temperature conditions, a wider range of confining pressures and different soil types to fully evaluate the effectiveness of BA incorporating LC³ system in soil stabilisation science relevant to geotechnical construction projects.

Data Availability Statement

This article includes the data used to support the findings.

Conflicts of Interest

The authors declare no conflicts of interest.

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