Cleaner Waste Systems 10 (2025) 100226

Contents lists available at ScienceDirect

Cleaner Waste Systems

journal homepage: www.journals.elsevier.com/cleaner-waste-systems

Feasibility of using bagasse ash incorporating limestone calcined clay cement as ordinary Portland cement replacement for stabilisation of black cotton soils

Horris K. Nangulama [a,b,*,1], Siya P. Rimoy [a]

[a] Department of Transportation and Geotechnical Engineering, University of Dar Es Salaam, Dar Es Salaam, Tanzania
[b] Department of Mining Engineering, Malawi University of Business and Applied Sciences, Blantyre, Malawi

ARTICLE INFO

Keywords:
BA incorporating LC^3
Green and cost-effective cement system
OPC replacement
BCS stabilisation
BCS performance enhancement

ABSTRACT

In this study, a green and cost-effective cement system was developed with bagasse ash (BA incorporating limestone calcined clay cement (LC^3) as ordinary Portland cement (OPC) replacement from black cotton soil (BCS) stabilisation perspective. Effect of BA incorporating 20 % – 60 % range of LC^3 on standard consistency (SC), setting time (ST) and compressive strength properties was investigated and optimised through comparison studies with similar properties to BA incorporating 20 % – 60 % range of OPC. Optimum content of BA incorporating LC^3 was added to BCS in different mix proportion range of 0–18 %. Effect of addition of different content of BA incorporating LC^3 on performance of BCS specimens was examined in terms of compaction, free swell and durability properties. The results show that utilisation of BA incorporating LC^3 maintains compressive strength and improves SC as well as ST of BA incorporating LC^3 paste. Compared to BA incorporating OPC, BA incorporating 40 % of LC^3 content at 0.50 water-cement (w/c) ratio obtained a good comprehensive strength equivalent cement performance. From the experimental results, it was found that addition of BA incorporating LC^3 at optimal content significantly improved compaction, swell potential and durability properties of treated BCS. This study demonstrates technical feasibility of BA incorporating LC^3 as a cement replacement. It verifies the reuse of by-products from agriculture for application as cementitious materials. The study further promotes the utilisation of BA incorporating LC^3 for addressing climate change emergency and reducing high costs for routine BCS stabilisation practice.

1. Introduction

Black cotton soil (BCS) is naturally problematic soil and poses serious problems to the life-span of geotechnical constructions such as highways, railways and buildings because of its low strength and high compressibility properties (Aliyu et al., 2020; Amrutha et al., 2016; Himani et al., 2019; Mamatha and Dinesh, 2017). Treatment with ordinary Portland cement (OPC) has been broadly used as conventional chemical stabilisation method for BCS improvement to alter its properties through hydration reaction (Garcez et al., 2024; Lu et al., 2024). However, for decades, OPC production has been one of the major contributors to the global footprint of carbon, and actions have been proposed to minimise carbon emissions from OPC production in pursuit to battle the impacts of climate change (Izumi et al., 2021; Ghadira and Ranjbar, 2018; Shi et al., 2024; McLellan et al., 2011). This is so because OPC manufacturing of one tonne alone produces about one tonne of carbon dioxide anthropogenic emissions (Izumi et al., 2021). Additionally, OPC manufacture is energy intensive and expensive (McLellan et al., 2011). Several studies reveal significant environmental impacts of OPC production, accounting for 4.46 gigatons of carbon dioxide emissions from 2020 which grow by 4.6 % annually (Ijaz et al., 2024; Saingam et al., 2024; Sheikh et al., 2023; Makul et al., 2024; Abdalla et al., 2024). Moreover, where bulk BCS stabilisation is required, OPC consumption is quite high and expensive (Himani et al., 2019). Blended cements with higher strength performance than OPC have been produced through the use of supplementary cementitious materials (SCMs) as partial substitute for OPC in recent years (Saingam et al., 2024). Several studies have shown that approximately 25 % of SCMs such as fly

* Corresponding author at: Department of Transportation and Geotechnical Engineering, University of Dar Es Salaam, Dar Es Salaam, Tanzania.
E-mail addresses: hnangulama@mubas.ac.mw (H.K. Nangulama), rimoy@udsm.ac.tz (S.P. Rimoy).
[1] ORCID: 0000-0002-1984-2625

https://doi.org/10.1016/j.clwas.2025.100226
Received 17 September 2024; Received in revised form 31 January 2025; Accepted 3 February 2025
Available online 4 February 2025

ash, ground granulated blast-furnace slag (GGBS) and silica fume based geopolymers are incorporated as admixtures in cement (Longa et al., 2022; Yao et al., 2021; Gupta et al., 2024; Farhan et al., 2022). Geopolymer based materials have high potential for reduction of carbon emissions and consumption of resources (Yao et al., 2021; Gupta et al., 2024). Replacing OPC with geopolymer based materials has effectively improved properties of the treated BCS, and has minimised both environmental impacts and high BCS stabilisation costs (Ghadira and Ranjbar, 2018; Shi et al., 2024). However, in other countries such as Malawi, which does not depend on fossil fuel for power generation, the quality of fly ash and availability of GGBS are major setbacks in their utilisation for production of cement (Kafodya et al., 2023). Moreover, the practical use of geopolymer based materials is foreseen in medium to long term (Habert et al., 2011; Abdullah et al., 2019). Wider application of geopolymer based materials such as fly ash and GGBS in BCS stabilisation practice faces a number of restraints including limited accessibility, low reactivity and their different effect on the treated BCS performance (Maneli et al., 2016; Petersen et al., 2003; Chethan and Shankar, 2021). As geotechnical construction industry continues to expand rapidly, the use of new and locally available innovative techniques for BCS stabilisation is vitally important to address the carbon footprint and high BCS stabilisation cost requirement for a more sustainable future.

With regards to its high silica content and sustainability properties, bagasse ash (BA) produced through incineration of sugarcane bagasse agricultural wastes has attracted substantial interest in research paradigm (Wu et al., 2022; Jittin et al., 2020; Sudip et al., 2021; Serker et al., 2020; Chindaprasirt et al., 2019). Research works have shown that BA can be employed as cementitious material to replace OPC in BCS stabilisation (Himani et al., 2019; Bajaj and Vikash, April 2016). Similar to industrial by-products such as fly ash and GGBS based geopolymers, the BA maintains or improves the performance of treated BCS due to its pozzolanic reaction, and may yield benefits both environmentally and economically (Amrutha et al., 2016; Sudip et al., 2021). In addition, BA is produced continuously, making its application as a cementitious material in BCS stabilisation a promising research direction (Wu et al., 2022; Bajaj and Vikash, April 2016). A thousand kilogram (kg) of bagasse can yield approximately 30–40 kg of BA (Jittin et al., 2020). Several attempts have been made to use BA in many areas such as production of ceramic materials (Teixeira et al., 2008; Teixeira et al., 2014), sintered aggregates (light-weight) (Lyra et al., 2019), and silica aerogel (Nazriati et al., 2014). On contrary, these remarkable attempts do not represent the current direction of research of BA application. To date, most studies have used BA as a cementitious material such as in ordinary, self-compacting and pavement concretes (Chindaprasirt et al., 2019; Bahurudeen et al., 2015; Somna et al., 2012; Akram et al., 2009), and improved strength, durability and interface compactness properties have been reported. These studies justify the practicality of employment of BA as cementing material. In terms of BCS treatment, the adoption of BA as stabilising material has been broadly reported by several studies (Amrutha et al., 2016; Himani et al., 2019; Bajaj and Vikash, April 2016). However, the sole examination of BA to fulfill serviceability and strength criteria of treated BCS implies that BA alone is not suitable for stabilising BCS subgrades for geotechnical constructions (Bajaj and Vikash, April 2016). When BA was solely applied to stabilise BCS, vertical displacement increase was reported (Himani et al., 2019). Several studies assessed the incorporation of addition materials such as propylene fibre, lime, fly-ash and dolomite to BA for stabilisation of BCS (Akbar et al., 2021; Patel and Shahu, 2015; Chethan and Shankar, 2021). 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 (Sudip et al., 2021; Zareei et al., 2018). Application of BA incorporating OPC exhibited significant decline in PI, free swell index (FSI) potential, maximum dry density (MDD), and an increase of optimum moisture content (OMC) together with shear strength of treated BCS (Amrutha et al., 2016; Sudip et al., 2021; Bahurudeen et al., 2015). Himani et al., (Himani et al., 2019) assessed the reduction in heave and swell pressure 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 use 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 (Izumi et al., 2021; Ghadira and Ranjbar, 2018; Shi et al., 2024; McLellan et al., 2011; Ijaz et al., 2024).

Limestone calcined clay cement (LC^3) 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 (Díaz et al., 2016; Scrivener et al., 2018; Miller, 2018; Akindahunsi et al., 2020). With 0.3 calcined clay factor and 0.15 limestone factor, its performance is relative to or better than OPC at 0.5 and 0.05 clinker and gypsum factors respectively (Kafodya et al., 2023; Scrivener et al., 2018). Moreover, its manufacture does not require new technologies, making it inexpensive and easy to introduce to the geotechnical construction industry (Joseph et al., 2016). Compared to OPC, the LC^3 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 (Díaz et al., 2016; Akindahunsi et al., 2020). Thus, LC^3 can play a big part in combating the climate emergency and high costs associated with OPC industry in geotechnical construction sector (Akindahunsi et al., 2020; Joseph et al., 2016; Reddy et al., 2019; Wang et al., 2024). Several studies have been published so far with regard to the use of LC^3 as a substitute of OPC. For example, Kafodya et al., (Kafodya et al., 2023) analysed the impacts of calcined clay on performance of LC^3 concrete. Akindahunsi et al., (Akindahunsi et al., 2020) provided valuable insights into LC^3 and its influence on hydration activities. Some recent studies of Reddy et al., (Reddy et al., 2019) and Wang et al., (Wang et al., 2024) respectively centred on stabilisation of zinc and radio-active borates contaminated soils with LC^3, and demonstrated its capacity to alter the properties of treated soils through hydration reaction. Generally, the previous studies demonstrate the feasibility of LC^3 as a great performance reliable cement. Just as Sheikh et al., (Sheikh et al., 2023), Ijaz et al., (Ijaz et al., 2024) showed that LC^3 can be applied just as OPC in the construction industry, and does not need a specialised training. Thus, BA can be incorporated with LC^3 in the similar manner the BA is incorporated with the OPC (Wilińska et al., 2023; Eberemu and Adrian, 2013). Overall, a combined use of BA and LC^3 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 as cementitious binder from BCS stabilisation perspective remains prominently absent. The basic physicochemical properties and mechanical performance of BA incorporating LC^3 have not been explored. The fundamental stabilization mechanism through which BA incorporating LC^3 can interact with minerals present in BCS to enhance its properties has not been investigated. The suitability and effectiveness of BA incorporating LC^3 on BCS stabilisation have not been determined and established. Hence, a relevant study with respect to the use of BA incorporating LC^3 as cement replacement for BCS stabilisation is extensively required. 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 as OPC replacement, considering its suitability and effectiveness for stabilisation of black cotton soils. Through this study, the high value and safe use of BA as well as LC^3 materials are advanced. The use of BA incorporating LC^3 technique for mitigation of climate change environmental problems and reduction of high costs for BCS stabilisation practice in geotechnical construction industry is further promoted.

2. Materials and methods

The key material used in this study as OPC replacement and to stabilise the BCS was BA incorporating LC^3. All the constituent materials for the preparation of the BA incorporating LC^3 and the BCS for treatment were collected from Shire Valley in Malawi. Geographically, Shire Valley is located in southern part of Malawi between 15° 30' S - 16° 45' S latitude and between 34° 14' E – 35° 15' E longitude with elevation range of 35 – 105 m. There are significant amount of BA and natural raw materials such as kaolinite clays and limestone to produce green, cost-effective and sustainable BA incorporating LC^3 in Shire Valley, Malawi (TARA, 2016). The kaolinite clay is estimated to be over 2 million tons. Limestone resource is approximated to be over 40 million tons in the form of metamorphic marbles, and gypsum is estimated to be over 1000 tons. Despite of significant resources, the use of BA and LC^3 as cement replacement materials and for BCS stabilisation is not yet investigated. This can be due to limited availability of substantial data about the properties of BA and LC^3, and guidelines on BA incorporating LC^3 formulation. It is therefore important to explore the characteristics of BA incorporating LC^3 with materials sourced locally to establish a potential OPC replacement for BCS stabilisation to produce green, low-cost, durable, sustainable and resilient geotechnical constructions in the area.

BA was collected from ILLOVO Sugar Co., Ltd., in Shire Valley, Malawi. LC^3 components such as limestone and kaolinite clay were obtained from deposits in Shire Valley. Currently, the OPC developed from clinker, is the mostly used cementitious binder in Malawi for geotechnical construction industry. Records display that monthly OPC consumption exceeds approximately 35,000 tons the whole Malawi, and approximately 1700 tons in Shire Valley alone (Kafodya et al., 2023). Prevailing poor economic conditions 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. Besides, ILLOVO Sugar Co., Ltd., produces about 2000 tons of BA per month. 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 to be incorporated with the LC^3, thus reducing its high consumption requirement, and rendering the proposed BA incorporating LC^3 as OPC replacement for BCS stabilisation application more sustainable in Shire Valley, Malawi.

BA was obtained during boiler cleaning process at ILLOVO Sugar Co., Ltd. It was collected at 600 °C – 700 °C boiling temperature, and it was carefully sieved using 300μm sieve to get rid of undesirable materials (Himani et al., 2019; Wu et al., 2022). Then, it was ball-milled for 20 min to reduce its particle sizes (Eberemu and Adrian, 2013). Its physical properties were measured. To establish pozzolanic reaction of this BA, its chemical components also were measured using Panaco Axios Advanced: X-ray fluorescence (XRF) analyser. Results of the determined physical properties, including loss on ignition (LOI) index, and chemical properties of this BA are presented in Table 1. According to ASTM C618, (ASTM C618-08, 2008) specification, a pozzolana with above 70 % total percentage of Fe_2O_3, SiO_2 and Al_2O_3 is classified as F-class pozzolana. Therefore, this BA belongs to F-class pozzolana (ASTM C618-08, 2008). The grain size of this BA was obtained with Malvern Mastersizer 3000: Laser particle size (LPS) analyser. Fig. 1 shows the cumulative distribution of BA particle sizes. Specific surface area of this BA was determined using nitrogen absorption method (NAM) as 3.79 m^2/g.

Limestone, kaolinite clay and gypsum were collected from deposits in Shire Valley. Clinker was collected from local Lafarge Portland cement Co., Ltd. Limestone, clinker and gypsum were grounded separately to come up with fine powders. Kaolinite clays were initially pulverised and passed through 75 μm sieve (Akindahunsi et al., 2020). Only volumes of fine materials finer than 75 μm were used for preparation of LC^3 (Reddy et al., 2019). Kaolinite clay was calcined at 800 °C ± 10 °C for 30 min in muffle furnace in agreement with previous studies (Díaz et al., 2016; Wang et al., 2024). LC^3 was prepared with 5 % gypsum, 50 % clinker, 15 % limestone and 30 % calcined clay as pictured in Fig. 2 (Kafodya et al., 2023; Scrivener et al., 2018). Unlike OPC which is produced at temperature range of 1500 °C ± 100 °C (Lu et al., 2024; Chethan and Shankar, 2021), the temperature required to produce LC^3 was about 800 °C, thereby minimising carbon emissions by almost 40 % compared to OPC. In this study, the w/c ratio of 0.45 was used for preparation of LC^3 to make certain of satisfactory development of mechanical strength (Joseph et al., 2016; Reddy et al., 2019). The chemical components of the LC^3 were measured using XRF analysis and are presented in Table 2. Fig. 1 depicts the analysed cumulative distribution of LC^3 particle sizes. Specific surface area of LC^3 was measured using NAM as 1.03 m^2/g.

Table 1
Properties of bagasse ash (BA).

Properties			Values
Physical		Colour	Black
		Specific gravity	2.39
		Specific surface area	3.79 m^2/g
Chemical	F-Class Pozzolana (ASTM C618, (ASTM C618-08, 2008)) 70 % minimum	Fe_2O_3	6.41 %
		SiO_2	59.37 %
		Al_2O_3	6.65 %
			72.43 %
		K_2O	3.51 %
		Na_2O	1.07 %
		CaO	15.89 %
		MgO	3.14 %
		SO_3	1.89 %
		pH	10.71
		LOI	2.14 %

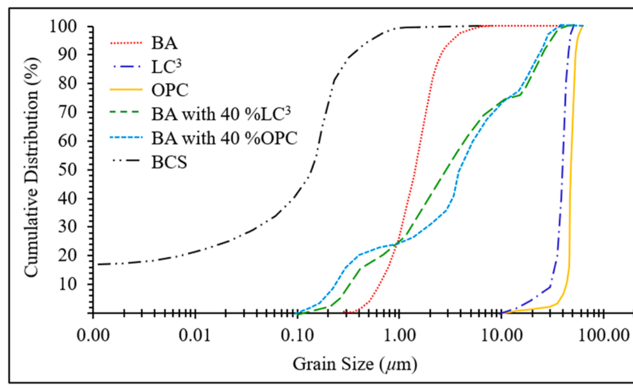

Fig. 1. Curve of grain size distribution of BA, LC^3, OPC, BA with 40 %LC^3, BA with 40 %OPC, and BCS.

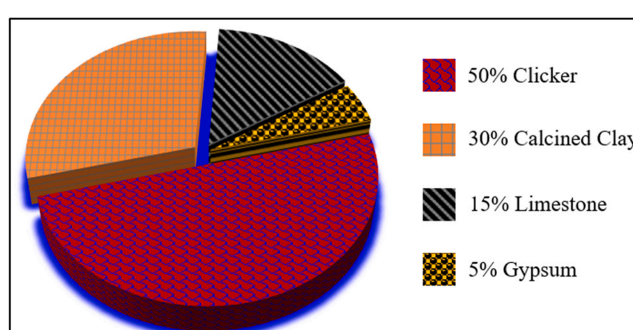

Fig. 2. Typical LC^3 recipe composition.

Table 2
Chemical properties of LC^3, OPC, BA with 40 %LC^3 and BA with 40 %OPC.

Properties	LC^3	OPC	BA with 40 %LC^3	BA with 40 %OPC
Fe_2O_3	3.36 %	3.69 %	4.10 %	3.21 %
SiO_2	26.46 %	20.51 %	29.32 %	23.86 %
AI_2O_3	5.01 %	4.49 %	9.12 %	8.98 %
K_2O	0.46 %	0.52 %	2.87 %	3.47 %
Na_2O	0.14 %	0.33 %	1.0 %	0.93 %
CaO	58.37 %	61.92 %	50.67 %	54.31 %
MgO	1.60 %	1.22 %	1.95 %	2.45 %
SO_3	3.54 %	2.93 %	2.60 %	2.38 %
pH	11.33	12.54	11.21	11.89
LOI	1.57 %	0.98 %	1.82 %	1.49 %

Besides, the OPC classified as CEM I: 42.50 N which conforms to ASTM C150, (ASTM C150-07, 2007) specification, was used in this study as a control. This was so because OPC (CEM I: 42.50 N) is considered to poses more strength (Sheikh et al., 2023). The OPC was purchased from local Lafarge Portland cement Co., Ltd. The chemical components of the OPC were determined using XRF analysis and are portrayed in Table 2. Fig. 1 portrays cumulative distribution of OPC particle sizes. Specific surface area of OPC was measured using NAM as 0.88 m^2/g.

To examine the UCS development trends of LC^3 and that of reference OPC, concrete tubes with sizes of 150.0 mm were prepared as per recommendation of BS EN 12390, (BS EN 12390, 2009). Four test samples were left for 7–90 days duration. Mean values of obtained results are given in Fig. 3. It is clear from Fig. 3 that LC^3 gained higher UCS values than OPC from 28 days of curing period and afterwards. Prior to 28 days of curing, OPC possessed more UCS values than LC^3. These determinations were attributed to calcium silicate different amounts containment in LC^3 and OPC (Sheikh et al., 2023). Calcium silicate proportions played a great role for enhanced early UCS of OPC (Sheikh et al., 2023). Gaining of higher UCS values of LC^3 than OPC following 28 days of curing period and afterwards was due to hydration and pozzolanic reactions of LC^3 components (Kafodya et al., 2023; Scrivener et al., 2018). Moreover, the obtained UCS results of both LC^3 and OPC in Fig. 3 satisfy the stipulated target of 30 MPa minimum recommended allowable limit of compressive strength for concrete cube at 28-day standard curing period (AS 1289, 2014).

BCS was obtained from Shire Valley, Malawi. It was taken at 1.50 m depth to avoid foreign and organic matters (Bajaj and Vikash, April 2016). Initially, the BCS was dried in sun, and then oven-dried for 24 h at 110 °C (Aliyu et al., 2020). Thereafter, the oven-dried BCS was passed through 2.0 mm sieves in order to prepare homogenous specimens (Aliyu et al., 2020; Mamatha and Dinesh, 2017). The BCS had whitish black colour indicating montmorillonite mineral presence (Amrutha et al., 2016; Himani et al., 2019). The engineering properties of this BCS were tested and the findings are outlined in Table 3. The findings in Table 3 lie within the range determined for BCS by other studies (Aliyu et al., 2020; Amrutha et al., 2016; Himani et al., 2019; Mamatha and Dinesh, 2017). This BCS was classified as clayey silt according to its

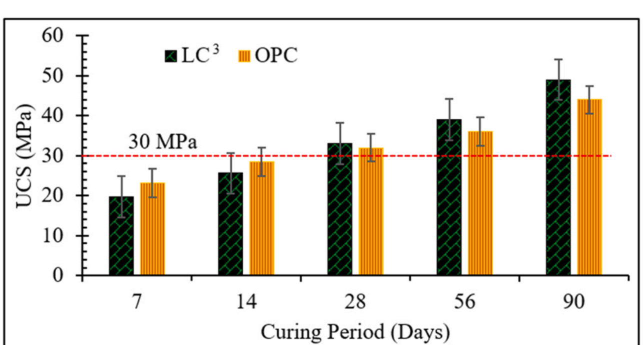

Fig. 3. Compressive strength comparative study between LC^3 and OPC.

Table 3
Properties of untreated BCS.

Properties	Testing Method	Mean Value
Consistency	BS 1377, (BS 1377, 1990)	-
Liquid limit	-	70.20 %
Plasticity index	-	39.25 %
Organic content	IS 1498, (IS 1498, 1970)	2.16 %
Specific gravity	IS 2720, (IS 2720, 2011)	2.55
Free swell	IS 2720, (IS 2720, 2011)	124.45 %
UCS	AS 1289, (AS 1289, 2014)	103.71 kPa
Compaction	BS 1377, (BS 1377, 1990)	-
OMC	-	17.37 %
MDD	-	16.54 kN/m^3
Specific surface area	NAM	3.00 m^2/g
Chemical composition	XRF analysis	-
Fe_2O_3	-	8.65 %
SiO_2	-	57.12 %
Al_2O_3	-	15.03 %
K_2O	-	1.41 %
Na_2O	-	1.84 %
CaO	-	0.70 %
MgO	-	1.21 %
SO_3	-	0.02 %
pH	BS ISO 10390, (BS ISO 10390, 2005)	7.56
LOI	BS 1377, (BS 1377, 1990)	5.67 %

distribution of grain sizes which was measured and is shown in Fig. 1. As per AASHTO and USCS soil classification systems, this 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 (Ackroyd and Husain, 1986; Hayder et al., 2016; Lucian et al., 2006).

To investigate the effect of BA incorporating LC^3 on standard consistency (SC), setting time (ST) and compressive strength, two cement systems of BA incorporating LC^3 and BA incorporating OPC were prepared. BA incorporating OPC was used for comparison purposes. For each system, three mix proportions of BA incorporating LC^3 and BA incorporating OPC were respectively designed as shown in Table 4. The cement systems were designed randomly with the mix proportions of 20 %, 40 % and 60 % (respectively abbreviated as BA with 20 %LC^3, BA with 40 %LC^3, and BA with 60 %LC^3) for investigation purposes. Similarly, for BA incorporating OPC, the cement systems were designed in the mix proportions of 20 %, 40 % and 60 % (respectively abbreviated as BA with 20 %OPC, BA with 40 %OPC, and BA with 60 %OPC) for reference and comparison purposes. For each mix percentage, w/c ratio was maintained at 0.45, 0.50 and 0.60, and properties of each cement system at each w/c ratio was distinctly examined. Cumulative grain size distribution curves of BA with 40 %LC^3 and BA with 40 %OPC (selected

Table 4
Mixture proportions of BA incorporating LC^3 and BA incorporating OPC specimens (kg/m^3).

Cement systems	Sample	BA	LC^3	w/c ratio		
BA incorporating LC^3				0.45	0.50	0.60
	Ref	1240.6	-	-	-	-
	BA with 20 %LC^3	992.48	248.12	558.27	620.30	744.36
	BA with 40 %LC^3	744.36	496.24	558.27	620.30	744.36
	BA with 60 %LC^3	496.24	744.36	558.27	620.30	744.36
BA incorporating OPC	**Sample**	**BA**	**OPC**	**w/c ratio**		
				0.45	0.50	0.60
	Ref	1240.6	-	-	-	-
	BA with 20 %OPC	992.48	248.12	558.27	620.30	744.36
	BA with 40 %OPC	744.36	496.24	558.27	620.30	744.36
	BA with 60 %OPC	496.24	744.36	558.27	620.30	744.36

as representative of mixtures) were measured and are given in Fig. 1. Moreover, Table 2 shows chemical compositions of representative BA with 40 %LC^3 and BA with 40 %OPC which were obtained using the XRF analysis.

The standard consistency (SC) and setting time (ST) laboratory tests were conducted to find workability of the two cement systems as per ASTM C187, (ASTM C187-16, 2016) and ASTM C191, (ASTM C191-21, 2021) guidelines, respectively. Three prismatic mortar specimens with dimensions of 40 × 40 × 160 mm^3 of BA incorporating LC^3 and BA incorporating OPC respectively, were prepared for compressive strength using standard sand (Abdullah et al., 2019; Serker et al., 2020). The specimens were mixed, casted and left for 24 h in controlled chamber at 20 °C and 95 % temperature and relative humidity respectively (Zareei et al., 2018). Thereafter, samples were demolded and exposed to 28 day - standard curing condition (Wu et al., 2022; Chethan and Shankar, 2021). The cured specimens were dried in air and tested for compressive strength as per BS EN 12390, (BS EN 12390, 2009) recommendation.

0 – 18 % of BA incorporating LC^3 contents at optimal cement system mix proportion were investigated on the treated BCS mixtures in terms of compaction, free swell index (FSI) and durability properties to assess the influence of BA incorporating LC^3 on the improvement of the BCS. Table 5 shows the adopted testing program for the BA incorporating LC^3 – treated BCS mixtures. Compaction properties of treated BCS were determined using a standard Proctor test as per BS 1377, (BS 1377, 1990) specification. The FSI of treated BCS were determined following procedure described in IS 2720, (IS 2720, 2011). Durability test through wetting – drying cycles (WDC) was conducted for the treated BCS in accordance with ASTM D559, (ASTM D559, 2003) procedure. To reduce experimental errors, three addition tests were performed separately, and the mean values of the findings were considered for interpretation.

3. Results and discussions

Fig. 4 shows effect of BA incorporating LC^3 on standard consistency (SC), and compares it with that of BA incorporating OPC. In regards to Fig. 4, the SC of both BA incorporating LC^3 and BA incorporating OPC respectively increased proportionally with LC^3 and OPC additive contents increase to the BA. The SC of BA incorporating LC^3 ranged from 36.5 % to 46.1 %. The SC of BA incorporating OPC varied from 34.5 % to 42.7 %. In comparison, the BA incorporating LC^3 exhibited SC of 1.4 % higher than that of BA incorporating OPC. This was justified by the nature of the LC^3, having amorphous calcined clay which provides large surface area for the absorption of water, hence, achieving higher cement paste consistency (Diadamony et al., 2018). This finding validated the previous studies performed by Kafodya et al., (Kafodya et al., 2023) and Sharma et al., (Sharma et al., 2021) which discovered that the amorphous phase has disordered molecule arrangement that allows water dissolution and penetration, and requires higher water quantity for cement consistency achievement. As confirmed by Anastasiou et al., (Anastasiou et al., 2017), water requirements of cementitious material increase with increasing the ratio of cement replacement. Similarly, other research works reported that when the ratio of cement

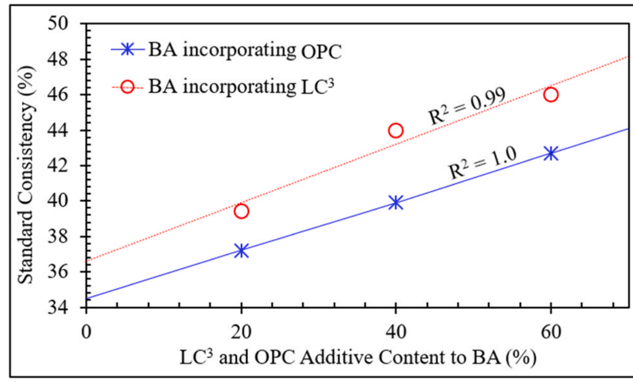

Fig. 4. Standard consistency (SC) variations of BA with LC^3 and BA with OPC additive content.

replacement is higher than 35 %, the workability of cementitious material containing BA linearly increases (Chindaprasirt et al., 2019; Bahurudeen et al., 2015). Overall, the workability of BA incorporating LC^3 and BA incorporating OPC mixtures in this study attained a similar linear relationship with the content of mixtures. This study depicted that replacing BA with LC^3 enhanced the tested mixture's workability. A 60 % BA replacement (BA with 60 %LC^3) achieved the best workability which was justified by the gel-like and compact structure of the LC^3 (Scrivener et al., 2018; Akindahunsi et al., 2020). Similar determinations were also depicted for BA with 60 %OPC.

Furthermore, Fig. 5 shows the effect of BA incorporating LC^3 content on setting time (ST), and compares it with that of BA incorporating OPC content. With respect to Fig. 5, the initial and final ST increased with both LC^3 and OPC additive content increase to the BA. The BA incorporating LC^3 depicted initial ST of 130 min for BA with 20 %LC^3

Table 5
Testing program for BA incorporating LC^3 cement system – treated BCS mixtures.

Samples	Testing category		Test sets
Treated BCS using BA incorporating LC^3 in mix proportions of 3, 6, 9, 12, 15 and 18 %	Compaction	Standard proctor	6
	Swell potential	Free swell index (FSI)	6
	Durability	Wetting – drying cycles (WDC)	6
Total test sets			18

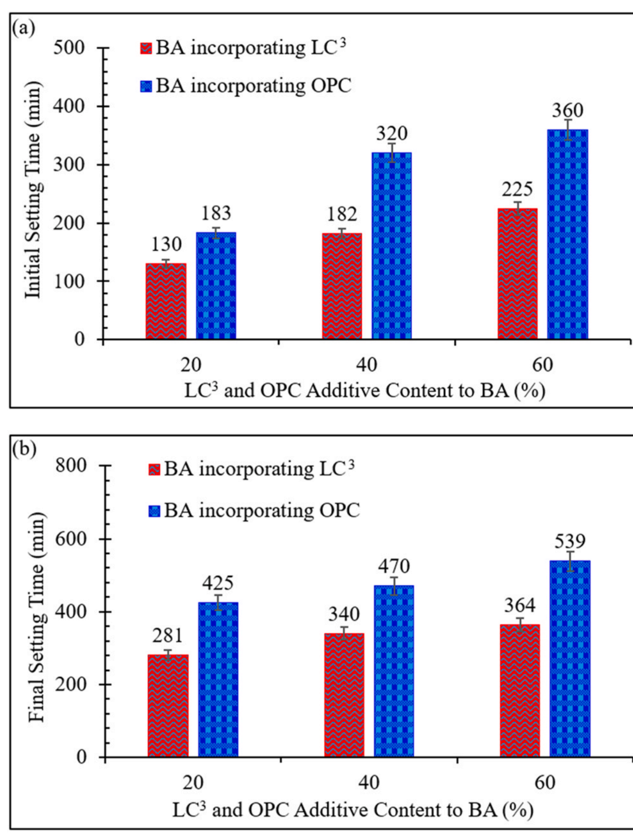

Fig. 5. Setting time (ST) variations with BA incorporating LC^3 and BA incorporating OPC additive contents: (a) Initial ST, and (b) Final ST.

content, 182 min for BA with 40 %LC^3 content and 225 min for BA with 60 %LC^3 content (Fig. 5a). On contrary, the initial ST for BA incorporating OPC was 183 min for BA with 20 %OPC content, 320 min for BA with 40 %OPC content and 360 min for BA with 60 %OPC content (Fig. 5a). An increase in addition of LC^3 and OPC content to the BA from 20 % to 60 % resulted in duplex increased initial ST (Fig. 5a). Similarly, the final ST demonstrated similar patterns with values of BA incorporating LC^3 varying between 281 min for BA with 20 %LC^3 content, 340 min for BA with 40 %LC^3 content and 364 min for BA with 60 %LC^3 content (Fig. 5b). For the BA incorporating OPC, the final ST was registered between 425 min for BA with 20 %OPC content, 470 min for BA with 40 %OPC content and 539 min for BA with 60 %OPC content (Fig. 5b). Overall, the final ST respectively increased by 83 min and 114 min for BA incorporating LC^3 and BA incorporating OPC cement systems (Fig. 5b). Addition content of both LC^3 to BA and OPC to BA resulted in an accelerated ST of around 100 min. Several previous research works have shown that cement with BA may prolong ST of ordinary concrete (Wu et al., 2022; Serker et al., 2020; Chindaprasirt et al., 2019). Due to low w/c ratio, the ST of cement concrete with BA is relatively long. By increasing BA substitution rate with LC^3 and OPC respectively, the initial ST changed minimally, but the final ST was pro-longed. This could be because of the reduction in BA content and the increase in LC^3 and OPC contents (Bahurudeen et al., 2015; Díaz et al., 2016). Nevertheless, the proportion of hydration of BA incorporating LC^3 and BA incorporating OPC cement systems was fairly minimal owing to low w/c ratio. Thus, the reduction in BA content and the increase in additive content of LC^3 and OPC respectively imposed no significant effect on the ST. The differences in ST between BA incorporating LC^3 and BA incorporating OPC cement systems were attributed to calcium silicate different amounts containment in LC^3 and OPC (Sheikh et al., 2023). Besides, the BS EN 197, (BS EN 197-1, 2011) advocates ST of more than 75 min for ordinary cements (class 32.50 MPa). Hence, both the BA incorporating LC^3 at all contents and BA incorporating OPC at all contents complied with the allowable ST (BS EN 197-1, 2011).

Besides, Fig. 6 shows standard 28-day compressive strength of BA incorporating LC^3 and BA incorporating OPC at varying additive contents of LC^3 and OPC to the BA. Compressive strength increased with increase in content of LC^3 and OPC for both BA incorporating LC^3 and BA incorporating OPC at different w/c ratios of 0.45, 0.50 and 0.60 (Fig. 6). Maximum compressive strength of BA incorporating LC^3 was 31.6 MPa, 38.7 MPa, and 28.5 MPa for respectively 0.45 (Fig. 6a), 0.50 (Fig. 6b) and 0.60 (Fig. 6c) w/c ratios. In case of BA incorporating OPC, maximum compressive strength was 25.1 MPa, 32.0 MPa and 29.0 MPa for 0.45 (Fig. 6a), 0.50 (Fig. 6b) and 0.60 (Fig. 6c) w/c ratios, respectively. It can be noticed from Fig. 6 that BA incorporating LC^3 showed a slight significant increase in compressive strength values than BA incorporating OPC. This was justified by calcium silicate different amounts containment in BA incorporating LC^3 and BA incorporating OPC (Sheikh et al., 2023; Srinivasan and Sathiya, 2010), with calcined clay and limestone proportions in BA incorporating LC^3 playing a great role for enhanced compressive strength values (Sheikh et al., 2023; Díaz et al., 2016). The highest strength (38.7 MPa at 0.50 w/c ratio of BA with 40 %LC^3 content) was justified by the high workability of the BA incorporating LC^3 cement system mixture (Zareei et al., 2018). High compaction of fresh BA incorporating LC^3 mortar led to a reduction in pore volume of the hardened BA incorporating LC^3 mortar and ultimately the high strength (Bahurudeen et al., 2015; Zareei et al., 2018). Furthermore, the availability of calcined clay in BA incorporating LC^3 resulted to an increase of dissolved $Ca(OH)_2$ level in liquid phase, allowing hydration of calcined clay, and in return facilitating final strength (Scrivener et al., 2018; Akindahunsi et al., 2020). With respect to the specifications of BS EN 197, (BS EN 197-1, 2011) and BS EN 413, (BS EN 413-1, 2011), the specimens for BA with 20 %LC^3 at 0.45 w/c ratio complied with ordinary Portland pozzolana cement strength requirement (Fig. 6a). The BA with 40 %LC^3 and BA with 60 %LC^3 satisfied the masonry cement strength requirement at 0.45 w/c ratio

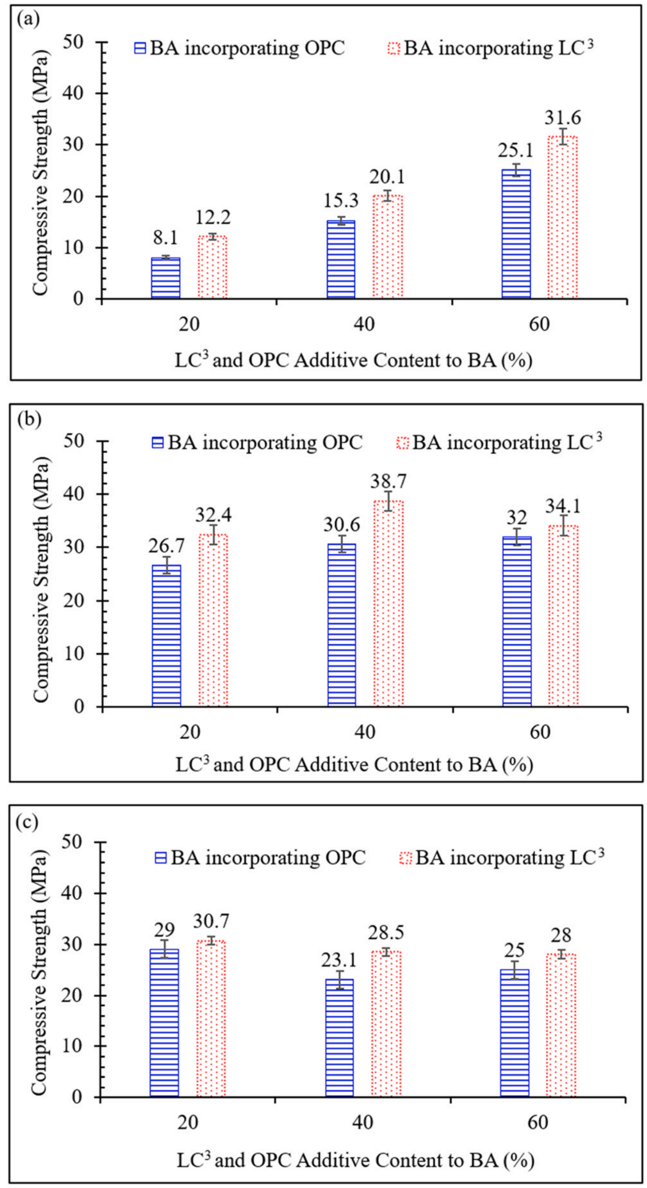

Fig. 6. Standard 28-day compressive strength with different additive content of LC^3 to the BA and OPC to the BA: (a) At 0.45 w/c ratio, (b) At 0.50 w/c ratio, and (c) At 0.60 w/c ratio.

(Fig. 6a). Further, the specimens for BA incorporating LC^3 at 0.50 w/c ratio showed the strength requirement for ordinary Portland clinker cement for the BA with 20 %LC^3, BA with 40 %LC^3 and BA with 60 % LC^3 contents (Fig. 6b). At 0.60 w/c ratio (Fig. 6c), the BA with 20 %LC^3, BA with 40 %LC^3 and BA with 60 %LC^3 contents satisfied the strength requirements for masonry cement. In accordance with the standard strength requirement for ordinary Portland clinker cement, BA incorporating 40 %LC^3 can potentially replace ordinary Portland cement at 0.50 w/c ratio (Sharma et al., 2021; Anastasiou et al., 2017; BS EN 197-1, 2011; Srinivasan and Sathiya, 2010; BS EN 413-1, 2011).

The effect of different percentage additives of BA incorporating 40 % LC^3 at 0.50 w/c ratio (from herein referred to as BA incorporating LC^3 cement system) on BCS improvement was investigated in terms of compaction, free swell index (FSI) and durability through wetting-drying cycle (WDC) properties.

Fig. 7 shows the determined compaction properties. It can be seen from Fig. 7 that OMC and MDD vary with the increase in BA incorporating LC^3 cement system content. Determinations in Fig. 7 show some

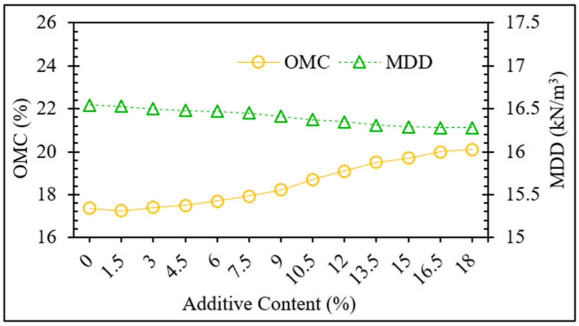

Fig. 7. Variations in OMC and MDD of treated BCS at different BA incorporating LC^3 cement system content.

OMC variation along with marginal effect variation on MDD when the content of BA incorporating LC^3 cement system increases from 0 % to 18 %. At low BA incorporating LC^3 cement system content ($\leq$ 6 %), variations in OMC and MDD are almost insignificant. At higher BA incorporating LC^3 system content (> 6 %), there is a minimal increase in OMC and minimal reduction in MDD values. Respective increasing and decreasing trends in OMC and MDD values with an increase of BA incorporating LC^3 cement system content in this study agree well with previous studies (Sudip et al., 2021; Reddy et al., 2019). Variations of OMC and MDD with addition of BA incorporating LC^3 cement system content can be justified by agglomeration and flocculation between the treated BCS particles (Aliyu et al., 2020; Amrutha et al., 2016; Himani et al., 2019; Mamatha and Dinesh, 2017). Also, Fig. 8 portrays the reinforcement mechanism representation of BA incorporating LC^3 cement system - treated BCS mixture. The mixing of BA incorporating LC^3 cement system, water, and BCS resulted in hydration and pozzolanic reactions and production of CSH-gel, CAH-fibre and $Ca(OH)_2$ compounds (Table 6). Reaction of $Ca(OH)_2$ and BCS particles generates more Ca^{2+} + $2OH^-$ products (Amrutha et al., 2016; Bajaj and Vikash, April 2016). The Ca^{2+} + $2OH^-$products wrap around BCS surface particles and create network structures (Fig. 8). The hydration and pozzolanic product bonding effects on particles of BCS significantly optimized pore structures, and the combined effect resulted in improvement of compactness and strength of BA incorporating LC^3 cement system – treated BCS.

To evaluate the influence of BA incorporating LC^3 cement system on swell behaviour of treated BCS, the FSI was investigated and the findings are portrayed in Fig. 9. This BCS was highly expansive considering the presence of montmorillonite mineral in it (Aliyu et al., 2020; Amrutha et al., 2016; Himani et al., 2019), and also by considering its measured FSI of about 124.45 % (Himani et al., 2019). Such high expansive degree is catastrophic and may result in disastrous failures of geotechnical constructions founded on this BCS (Amrutha et al., 2016; Lucian et al.,

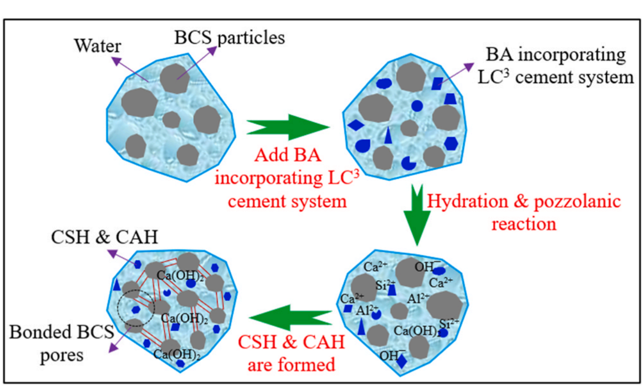

Fig. 8. Schematic diagram about stabilization mechanism of BA incorporating LC^3 cement system – treated BCS mixture.

Table 6
Governing chemical reaction processes.

Process	Chemical reaction	Compound
Hydration	$CaO + H_2O \rightarrow Ca(OH)_2$	Calcium hydrates (crystal-like structure)
Pozzolanic	$Ca(OH)_2 + SiO_2 \rightarrow CSH$	Calcium silica hydrates (gel-like structure)
Pozzolanic	$Ca(OH)_2 + Al_2O_3 \rightarrow CAH$	Calcium alumina hydrates (fibrous-like)
Dissociation	$Ca(OH)_2 \rightarrow Ca^{2+} + 2OH^-$	Calcium and hydroxide ions

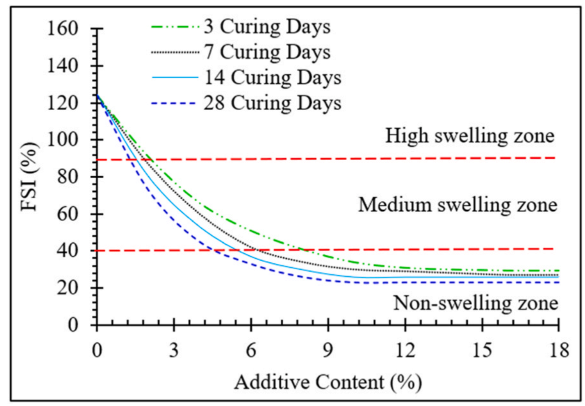

Fig. 9. Free swell index (FSI) of treated BCS with BA incorporating LC^3 cement system at different additive content and curing period.

2006). However, with BA incorporating LC^3 cement system content addition, FSI decreased significantly. It can be observed from Fig. 9 that just above 6 % of BA incorporating LC^3 cement system content, the FSI declined from 124.45 % to 25.03 % at 28 days of curing. Subsequently, transforming the BCS to non swelling zone from the high swelling zone, with a decline of more than 80 %. This remarkable improvement in FSI was justified by possible ionization within BCS particles and BA incorporating LC^3 cement system matrix, resulting in cementation properties, as previously argued (Bajaj and Vikash, April 2016; Wang et al., 2024).

In addition, during the rainy period, the moisture content of BCS increases and subsequently reduces during the dry period (Aliyu et al., 2020). BCS under such variation of season causes damage to geotechnical constructions founded on it (Patel and Shahu, 2015; Chethan and Shankar, 2021). For sustainability assessment of BA incorporating LC^3 cement system – treated BCS mixture under this long-term weather condition, WDC durability test was employed in this study. After curing period of 7 days, specimens with 104.5 mm and 115.0 mm of diameter and height respectively were immersed for 6 h in water and dried at 72 °C for 41 h in the oven for durability test to represent the first wetting cycle (Biswal et al., 2018). The 47-hour WDC was repeated for 16 times. Unconfined compressive strength (UCS) test was performed on BCS specimens after 1, 4, 8, 12 and 16 cycles. It has to be acknowledged that the UCS is not a common test for durability assessment. Nevertheless, it gives parameters to evaluate degradation of treated soil (Suddeepong et al., 2018; Biswal et al., 2018).

Fig. 10 shows the UCS durability test results of treated BCS specimens. In regards to Fig. 10, the 3 % BA incorporating LC^3 cement system - treated BCS specimens rapidly collapsed after immersing in water. The 6 % BA incorporating LC^3 cement system - treated BCS specimens almost collapsed at 16th WDC. These phenomena indicated the insufficiency of BA incorporating LC^3 cement system at less than 6 % content against the WDC. The collapse phenomenon at 3 % content was justified by the presence of big pores within the treated BCS specimen, resulting in more absorption of water, and thereby loss of inter-particle forces (Suddeepong et al., 2018; Chittoori et al., 2018). Similarly, the 9 % BA incorporating LC^3 cement system - treated BCS specimen portrayed a

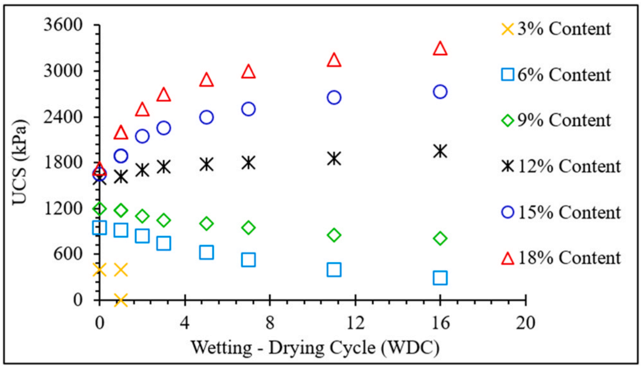

Fig. 10. Unconfined compressive strength (UCS) durability through wetting-drying cycles (WDC) for treated BCS at different BA incorporating LC^3 cement system content.

declining trend for UCS values against WDC (Fig. 10). The UCS declining trend against WDC was due to bond degradation of treated BCS mixtures (Amrutha et al., 2016; Nangulama and Rimoy, 2024). This aspect may have been initiated by the influence of pore water absorption and softening of treated BCS specimen due to the water immersion (Chittoori et al., 2018; Nangulama and Rimoy, 2024). However, at the 16th WDC, the UCS value was above 800.0 kPa minimum recommended durability UCS value for geotechnical construction subgrades (Neramitkornburi et al., 2015). This indicated the long service life for the treated BCS mixtures (Mamatha and Dinesh, 2017; Maneli et al., 2016). Besides, the 12 %, 15 % and 18 % BA incorporating LC^3 cement system - treated BCS specimens manifested an increasing pattern, indicating BA incorporating LC^3 cement system competent to react with BCS particles in the presence of water (Chittoori et al., 2018). This determination was justified by the pozzolanic and hydration chemical reactions, whereby more CAH and CSH were produced (Himani et al., 2019; Bajaj and Vikash, April 2016). Overall, the determined durability through WDC determinations suggest that the treated BCS with low BA incorporating LC^3 cement system content results in short-term stabilisation of BCS, while treated BCS with more BA incorporating LC^3 cement system content results in short-and long-term stabilisation of BCS.

4. Conclusion

In this study, bagasse ash (BA) incorporating limestone calcined clay cement (LC^3) was adopted as replacement of ordinary Portland cement (OPC) to prepare eco-friendly stabilising binder for black cotton soil (BCS). With respect to the test results, these conclusions can be made:

(1) Addition of LC^3 content to the BA resulted in the increased standard consistency (SC) of BA incorporating LC^3 samples. BA incorporating LC^3 exhibited SC of 1.4 % higher than that of BA incorporating OPC which was used as a reference for comparison purposes. Initial setting time (ST) of BA incorporating LC^3 was slightly pro-longed, however the final ST was highly prolonged. LC^3 additive content to the BA exerted a remarkable contributing effect on compressive strength development of BA incorporating LC^3 mixture. Comparably, BA incorporating 40 %LC^3 at 0.50 w/c ratio significantly portrayed the best compressive strength effect.
(2) Test results on the use of BA incorporating LC^3 as a cement mortar verified the technical feasibility of the utilization of BA incorporating LC^3 as OPC replacement.
(3) BA incorporating 40 %LC^3 at 0.50 w/c ratio was adopted in mix proportions of 0 – 18 % to investigate its influence on engineering properties of treated BCS, in terms of compaction, free swell potential and durability properties. The OMC and MDD compaction parameters of treated BCS significantly improved. BCS transformed from high swelling to non-swelling zone. UCS durability test results displayed an increasing trend against WDC for treated BCS, indicating short and long-term hydration stabilisation reaction.
(4) Test results on the use of BA incorporating LC^3 as BCS stabilising binder validated the practicality of the reuse of agricultural by-products and waste materials as cementitious materials in a quest to address the climate change emergency and reduce high costs from BCS stabilisation perspective.
(5) This study has shown that BA incorporating LC^3 can be used as OPC replacement for stabilisation of BCS. The BA incorporating LC^3 cement paste portrays excellent SC, ST and compressive strength. BA incorporating LC^3 - treated BCS significantly exhibits good compaction, FSI and WDC durability performance, which may help to ensure the reliability and stability of geotechnical constructions founded on BCS. However, only SC, ST and compressive strength of prepared BA incorporating LC^3 cement paste, and the compaction, FSI and WDC durability properties of treated BCS were investigated. Besides, this study mainly compared the combination of BA with LC^3 and the combination of BA with OPC. These may not comprehensively mirror other engineering properties of BA incorporating LC^3 cement paste, BA incorporated with other cementitious materials, or fully reflect the performance of treated BCS under other engineering conditions. Hence, future research works should concentrate on other engineering characterisation properties of BA incorporating LC^3 cement paste, BA incorporated with other cementitious materials, and other engineering properties of treated BCS with BA incorporating LC^3 cement system. Further studies should also consider carrying out a comprehensive comparative analysis of BA incorporating LC^3 with other common stabilization techniques, including its field application during actual construction, to fully evaluate the feasibility of BA incorporating LC^3 as OPC replacement for stabilisation of black cotton soils.

CRediT authorship contribution statement

NANGULAMA Horris K.: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Siya P. Rimoy:** Writing – review & editing, Visualization, Validation, Supervision, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by Malawi University of Business and Applied Sciences (MUBAS), School of Engineering and Department of Mining Engineering under MUBAS. Their support is greatly acknowledged.

Data availability

Data will be made available on request.

References

Abdalla, T.A., Hussein, A.E., Ahmed, Y.H., Semmana, Q., 2024. Strength, durability, and microstructure properties of concrete containing bagasse ash – a review of 15 years of perspectives, progress and future insights. Results Eng. 21.
Abdullah, H., Shahin, M.A., Sarker, P., 2019. Use of fly-ash geopolymer incorporating ground granulated slag for stabilisation of kaolin clay cured at ambient temperature. Geotech. Geol. Eng. 37 (2), 721–740.

Ackroyd, L.W., Husain, R., 1986. Residual and lacustrine black cotton soils of north-east Nigeria. Geotechnique 36, 113–118.

Akbar, A., Farooq, F., Shafique, M., Aslam, F., Alyousef, R., Alabduljabbar, H., 2021. Sugarcane bagasse ash-based engineered geopolymer mortar incorporating propylene fibers. J. Build. Eng. 33.

Akindahunsi, A., Avet, F., Scrivener, K., 2020. The influence of some calcined clays from Nigeria as clinker substitute in cementitious systems. Case Stud. Constr. Mater. 13.

Akram, T., Memon, S.A., Obaid, H., 2009. Production of low-cost self compacting concrete using bagasse ash. Constr. Build. Mater. 23 (2), 703–712.

Aliyu, M.J., Adam, L.Z., Kunya, S.U., 2020. Investigating the engineering properties of black cotton soil treated with rice husk ash. Afr. Sch. J. Environ. Des. Constr. Manag. 18 (4).

Amrutha, P.K., Muthu, K.S., Vaishnavi, V.B., Mahesh, S.S., Aavani, P., 2016. Black cotton soil stabilization using bagasse ash and lime. IJCIET 67 (6), 460–471.

Anastasiou, E.K., Liapis, A., Papachristoforou, M., 2017. Life cycle assessment of concrete products for special applications containing EAF slag. Procedia Environ. Sci. 38, 469–476.

AS 1289, Method of testing soils for engineering purposes, Standards Australia, 2014.

ASTM C150-07, Standard specification for Portland cement, ASTM: West Conshohocken, PA, USA, 2007.

ASTM C187-16, Standard test method for amount of water required for normal consistency of hydraulic cement paste, ASTM: West Conshohocken, PA, USA, 2016.

ASTM C191-21, "Standard test methods for time of setting of hydraulic cement by vicat Needle," ASTM: West Conshohocken, PA, USA, 2021.

ASTM C618-08, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, Annual Book of ASTM Standards, West Conshohocken, PA, USA, 2008.

ASTM D559, Standard test methods for wetting and drying compacted soil-cement mixtures, 2003.

Bahurudeen, A., Kanraj, D., Gokul, V., Santhanam, M., 2015. Performance evaluation of sugarcane bagasse ash blended cement in concrete. Cem. Concr. Compos. 59, 77–88.

Bajaj, Jheelu, Vikash, Kumar Singh, April 2016. Performance evaluation of black cotton soil stabilized with sugarcane bagasse ash and randomly distributed coir fibres. IJIRST 02 (– 11).

Biswal, D.R., Sahoo, U.C., Dash, S.R., 2018. Durability and shrinkage studies of cement stabilised granular lateritic soils. Int. J. Pavement Eng.

BS 1377, Methods for test of soils for civil engineering works, British Standards Institution, U.K, 1990.

BS EN 12390, Testing hardened concrete: Compressive strength of test specimens, British Standards, England, UK, 2009.

BS EN 197-1, Composition, specifications and conformity criteria for common cements, BSI., London, UK, 2011.

BS EN 413-1, Masonry cement composition, specification and conformity criteria. BSI., London, UK, 2011.

BS ISO 10390, Soil quality - determination of pH, British Standards Institution, U.K, 2005.

Chethan, B.A., Shankar, A.U., 2021. Strength and durability characteristics of cement and class F fly ash-treated black cotton soil. Indian Geotech. J. 51 (5), 1121–1133.

Chethan, B.A., Shankar, A.U., 2021. Strength and durability characteristics of cement and class F fly ash-treated black cotton soil. Indian Geotech. J. 51 (5), 1121–1133.

Chindaprasirt, P., Sujumnongtokul, P., Posi, P., 2019. Durability and mechanical properties of pavement concrete containing bagasse ash materials. Today Proc. 17, 1612–1626.

Chittoori, B.C.S., Puppala, A.J., Pedarla, A., 2018. Addressing clay mineralogy effects on performance of chemically stabilized expansive soils subjected to seasonal wetting and drying. J. Geotech. Geoenviron. Eng. 144 (1).

Diadamony, H., Amer, A.A., Sokkary, T.M., Hoseny, S., 2018. Hydration and characteristics of metakaolin pozzolanic cement pastes. HBRC J. 14, 150–158.

Díaz, Y.C., Berriel, S.S., Heierli, U., Favier, A.R., Machado, I.R., Scrivener, K.L., Hernández, J.F.M., Habert, G., 2016. Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies. Dev. Eng. 2, 82–91.

Eberemu, A.O., Adrian, O., 2013. Evaluation of bagasse ash treated lateritic soil as a potential barrier material in waste containment application. Acta Geotech. 8 (4), 407–421.

Farhan, S.M., Ali, A., Khushnood, R.A., Tufail, R.F., Majdi, A., Nawaz, A., Durdyev, S., Burduhos, D.D.N., Ahmad, J., 2022. Effect of bentonite as partial replacement of cement on residual properties of concrete exposed to elevated temperatures. Sustainability 14.

Garcez, L.R., Balestra, C.E.T., Monteiro, N.B.R., Filho, J.A.M., Gil, M.A.R., 2024. Mechanical strength and Life cycle assessment (LCA) of soil-cement: comparison between mixtures of soil with ASTM type III cement, LC3, and the incorporation of by products and agro-industrial residues. Constr. Build. Mater. 411.

Ghadira, P., Ranjbar, N., 2018. Clayey soil stabilization using geopolymer and Portland cement. Constr. Build. Mater. 188, 361–371.

Gupta, S., Kumar, S., Pradeep, N.M., Nishant, M., 2024. Behavior of an embankment on soft ground improved with soil–geopolymer deep mix columns under static and cyclic loadings. Int. J. Geo Mech. 25 (2).

Habert, G., Lacaillerie, E., Roussel, N., 2011. An environmental evaluation of geopolymer based concrete production: reviewing current research trends. J. Clean. Prod. 19, 1229–1239.

Hayder, H., Dang, L., Khabbaz, H., Fatahi, B., Terzaghi, S., 2016. Remediation of expansive soils using agricultural waste bagasse ash. Adv. Transp. Geotech. 3. 3rd Int. Conf. Transp. Geotech. 143, 1368–1375.

Himani, S., Kitendra, J., Biswajit, A., 2019. Stabilization of black cotton soil by using sugarcane bagasse ash. Int. J. Sci. Res. Rev. 7 (1).

Ijaz, N., Ye, W., Rehman, Z., Ijaz, Z., Junaid, M.F., 2024. Global insights into micro-macro mechanisms and environmental implications of limestone calcined clay cement (LC3) for sustainable construction applications. Sci. Total Environ. 907.

IS 1498 (1970), Classification and identification of soils for general engineering purposes. Bureau of Indian Standards, India.

IS 2720, Determination of water content dry density relation using light compaction, Bureau of Indian Standards, India, 2011.

Izumi, Y., Iizuka, A., Ho, H.J., 2021. "Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry. J. Clean. Prod. 312.

Jittin, V., Minnu, S.N., Bahurudeen, A., 2020. Potential of sugarcane bagasse ash as supplementary cementitious material and comparison with currently used rice husk ash. Constr. Build. Mater. 273.

Joseph, S., Bishnoi, S., Maity, S., 2016. An economic analysis of the production of limestone calcined clay cement in India. Indian Concr. J. 90, 22–27.

Kafodya, I., Basuroy, D., Marangu, J.M., Kululanga, G., Maddalena, R., Novelli, V.I., 2023. Mechanical performance and physico-chemical properties of limestone calcined clay cement (LC3) in Malawi. Buildings.

Longa, W.J., Wu, Z., Khayat, K.H., Wei, J., Donga, B., Xinga, F., Zhang, J., 2022. Design, dynamic performance and ecological efficiency of fiber-reinforced mortars with different binder systems: ordinary Portland cement, limestone calcined clay cement and alkali-activated slag. J. Clean. Prod. 337.

Lu, J., Tan, L., Pei, W., Gao, J., Deng, F., Zhou, X., Zhang, Z., 2024. Shear behaviour of cement-stabilized silty clay exposed to low-temperature curing. Cold Reg. Sci. Technol. 223.

Lucian, C., Hintze, S., Stille, H., 2006. Damage to buildings on expansive soils in Kibaha, Tanzania. J. Build. Land Manag. 13, 39–47.

Lyra, G.P., Santos, V., Santis, B.C., Rivaben, R.R., Fischer, C., Pallone, E.A., Rossignolo, J. A., 2019. Reuse of sugarcane bagasse ash to produce a lightweight aggregate using microwave oven sintering. Constr. Build. Mater. 222, 222–228.

Makul, N., Hussain, Q., Nawaz, A., Saingam, P., Gritsada, S., 2024. Effect of para-wood ash and calcium carbonate on the properties of eco-friendly self-compacting mortar reinforced with electronic waste fibers. J. Build. Eng. 95.

Mamatha, K.H., Dinesh, S.V., 2017. Resilient modulus of black cotton soil. Int. J. Pavement Res. Technol. 10, 171–184.

Maneli, A., Kupolati, W.K., Abiola, O.S., Ndambuki, J.M., 2016. Influence of fly ash, ground-granulated blast furnace slag and lime on unconfined compressive strength of black cotton soil. Road. Mater. Pavement Des. 17, 252–260.

McLellan, B.C., Williams, R.P., Lay, J., Riessen, A.V., Corder, G.D., 2011. Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement. J. Clean. Prod. 19, 1080–1090.

Miller, S.A., 2018. Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: Can there be too much of a good thing? J. Clean. Prod. 178, 587–598.

Nangulama, H.K., Rimoy, S., 2024. Effectiveness of bagasse ash incorporating limestone calcined clay cement (LC3) in improving shear strength and durability properties of black cotton soils. Adv. Civ. Eng. 2024, 1–12.

Nazriati, N., Setyawan, H., Affandi, S., Yuwana, M., Winardi, S., 2014. Using bagasse ash as a silica source when preparing silica aerogels via ambient pressure drying. J. Non-Cryst. Solids 400, 6–11.

Neramitkornburi, A., Horpibulsuk, S., Shen, S.L., Chinkulkijniwat, A., Arulrajah, A., Disfani, M.M., 2015. Durability against wetting— drying cycles of sustainable lightweight cellular cemented construction material comprising clay and fly ash wastes. Constr. Build. Mater. 77 (1), 41–49.

Patel, S., Shahu, J.T., 2015. Engineering properties of black cotton soil–dolime mix for its use as subbase material in pavements. Int. J. Geomate 8, 159–1166.

Petersen, D., Link, R., Pandian, N., Krishna, K., 2003. The pozzolanic effect of fly ash on the California bearing ratio behavior of black cotton soil. J. Test. Eval. 31.

Reddy, V.A., Solanki, C.H., Kumar, S., Reddy, K.R., Du, Y.J., 2019. New ternary blend limestone calcined clay cement for solidification/stabilization of zinc contaminated soil. Chemosphere 235, 308–315.

Saingam, P., Chatveera, B., Promsawat, P., Hussain, Q., Nawaz, A., Makul, N., Gritsada, S., 2024. Synergizing Portland cement, high-volume fly ash and calcined calcium carbonate in producing self-compacting concrete: a comprehensive investigation of rheological, mechanical, and microstructural properties. Case Stud. Constr. Mater. 21.

Scrivener, K., Martirena, F., Bishnoi, S., Maity, S., 2018. Calcined clay limestone cements (LC3). Cem. Concr. Res. 114, 49–56.

Serker, N.H., Hafiz, R.U., Rahman, A.H., Ashikuzzaman, M., 2020. Suitability of using sugarcane bagasse ash as partial replacement of cement in concrete, 5th International Conference on Advances in Civil Engineering, CUET.

Sharma, M., Bishnoi, S., Martirena, F., Scrivener, K., 2021. Limestone calcined clay cement and concrete: a state-of-the-art review. Cem. Concr. Res. 149.

Sheikh, M.D., Khan, A., Jamil, T., Ayub, T., Bilal, S.M., Hu, C., 2023. Comparative study on LC3-50 with OPC concrete using raw materials from Pakistan. Adv. Mater. Sci. Eng.

Shi, D., Xia, Y., Wang, J., Chen, F., Ma, X., Zhao, Y., Liu, M., Yu, K., 2024. Recycling E-waste CRT glass in sustainable geopolymer concrete for radiation shielding applications. J. Environ. Chem. Eng. 12.

Somna, R., Jaturapitakkul, C., Rattanachu, P., Chalee, W., 2012. Effect of ground bagasse ash on mechanical and durability properties of recycled aggregate concrete. Mater. Des. 36, 597–603.

Srinivasan, R., Sathiya, K., 2010. Experimental study on bagasse ash in concrete. Int. J. Serv. Learn. Eng. 5 (2), 60–66.

Suddeepong, A., Intra, A., Horpibulsuk, S., Suksiripattanapong, C., 2018. Durability against wetting-drying cycles for cement-stabilized reclaimed asphalt pavement blended with crushed rock. Soils Found. 58, 333–343.
Sudip, B., Goswami, G., Hadi, K., Moses, K., Parinita, B., Kalita, N., 2021. Comparative study on soil stabilization relevant to transport infrastructure using bagasse ash and stone dust and cost effectiveness. Civ. Eng. J. 7 (11).
TARA, Analysis of raw materials and assessment of the reactivity of china clay from Malawi for LC3 application: Technology and Action for Rural Advancement (TARA), New Delhi, India, 2016.
Teixeira, S.R., Magalhaes, R.S., Arenales, A., Souza, A.E., Romero, M., Rincon, J.M., 2014. Valorization of sugarcane bagasse ash: producing glass-ceramic materials. J. Environ. Manag. 134, 15–19.
Teixeira, S.R., Souza, A.E., Santos, G.T., Vilche, A.F., Miguel, A.G., 2008. Sugarcane bagasse ash as a potential quartz replacement in red ceramic. J. Am. Ceram. Soc. 91 (6), 1883–1887.
Wang, J., Shi, D., Xia, Y., Liu, M., Ma, X., Yu, K., Zhao, Y., Zhang, J., 2024. Stabilization/solidification of radioactive borate waste via low-carbon limestone calcined clay cement (LC3). J. Environ. Chem. Eng.
Wilińska, I., Barbara, P., Ostrowski, A., 2023. Investigation of different ways of activation of fly ash–cement mixtures: Part 2 - mechanical activation. J. Therm. Anal. Calorim.
Wu, N., Ji, T., Huang, P., Fu, T., Zheng, X., Xu, Q., 2022. Use of sugar cane bagasse ash in ultra-high-performance concrete (UHPC) as cement replacement. Constr. Build. Mater. 317.
Yao, J., Qiu, H., He, H., Chen, X., Hao, G., 2021. Application of a soft soil stabilized by composite geopolymer. J. Perform. Constr. Facil. 35 (4).
Zareei, S.A., Ameri, F., Bahrami, N., 2018. Microstructure, strength, and durability of eco- friendly concretes containing sugarcane bagasse ash. Constr. Build. Mater. 184, 258–268.