Research Article

Bagasse Ash as an Auxiliary Additive to Lime Stabilization of an Expansive Soil: Strength and Microstructural Investigation

Jijo James (ID)[1] **and P. Kasinatha Pandian**[2]

[1]*SSN College of Engineering, Rajiv Gandhi Salai, Kalavakkam, Tamil Nadu 603110, India*
[2]*Karpaga Vinayaga College of Engineering and Technology, Chinnakolambakkam, Padalam, Kanchipuram 603308, India*

Correspondence should be addressed to Jijo James; jijothegreat@gmail.com

The study dealt with the effect of addition of sugarcane bagasse ash (BA) on the strength development of a lime stabilized expansive soil. Unlike previous investigations with combinations of lime and BA, this study compares the effect of lime contents determined by scientifically established procedures and the effect of BA on the stabilization of lime at different proportions with additional microstructural investigations. The minimum lime content required for stabilization known as initial consumption of lime (ICL) was determined using the Eades and Grim pH test as 5.5%. The optimum lime content (OLC) was determined using unconfined compression strength (UCS) tests as 7%. Another lime content less than ICL was randomly adopted as 3%. The three lime contents were mixed with 0.25%, 0.5%, 1%, and 2% BA. UCS samples of dimension 38 mm × 76 mm were prepared at a fixed dry density and moisture content and cured for periods of 2 hours (0 days), 3, 7, 14, and 28 days to study the development of strength and effect of BA. Mineralogical and microstructural analyses were performed on the pulverized UCS samples after failure. The results revealed that the addition of BA increased the immediate, early, and delayed strength of lime stabilized soil further, even when the lime content was lower than ICL. Addition of BA produced maximum immediate, early, and delayed strength gains of 58.3%, 20.7%, and 32.7%, respectively. Higher proportion of BA was required when lime content was above ICL, for maximum strength. Addition of BA resulted in better utilization of quartz in lime-soil reactions leading to formation of CSH and CAH minerals. A dense compact matrix was seen on analyzing the microstructure of the stabilized soil composite.

1. Introduction

Lime stabilization is one of the most commonly adopted techniques for stabilization of expansive soils that have always posed problems to civil and geotechnical engineers all over the world. However, in recent times, the focus is on the utilization of industrial waste materials along with lime in order to achieve improved performance and waste management. There is extensive literature in utilization of industrial wastes in combination with lime for beneficial effects in lime stabilization [1–8]. Similarly, this study envisages to investigate the effect of sugarcane bagasse ash (BA), one of the many industrial wastes produced in India, on the strength of a lime stabilized expansive soil. Bagasse is the fibrous residue remaining after the extraction of the cane juice from sugarcane. In sugarcane industries, bagasse is used as fuel

resulting in its combustion and production of ash as the end product. This waste is typically disposed into pits and also used as soil amendment in some areas [9]. Earlier work on BA involves its utilization as replacement in concrete [10, 11], compressed stabilized earth blocks [6, 12–14], and sintered blocks/tiles [15–17] apart from soil stabilization. The utilization of BA in soil stabilization has been increasing in recent years. Muazu studied the plasticity and particle size distribution [18] and effect of compaction [19] on BA amended cement-treated lateritic soil. Chittaranjan et al. [20] explored the effect of BA on the CBR value of stabilized soil. Onyelowe [21] investigated the effect of BA as an admixture to cement stabilization of lateritic soil. Sabat [22] evaluated the performance of expansive soil stabilized using combinations of lime sludge and BA. Osinubi et al. [23] looked into the compatibility of stabilization of lateritic soil with BA and
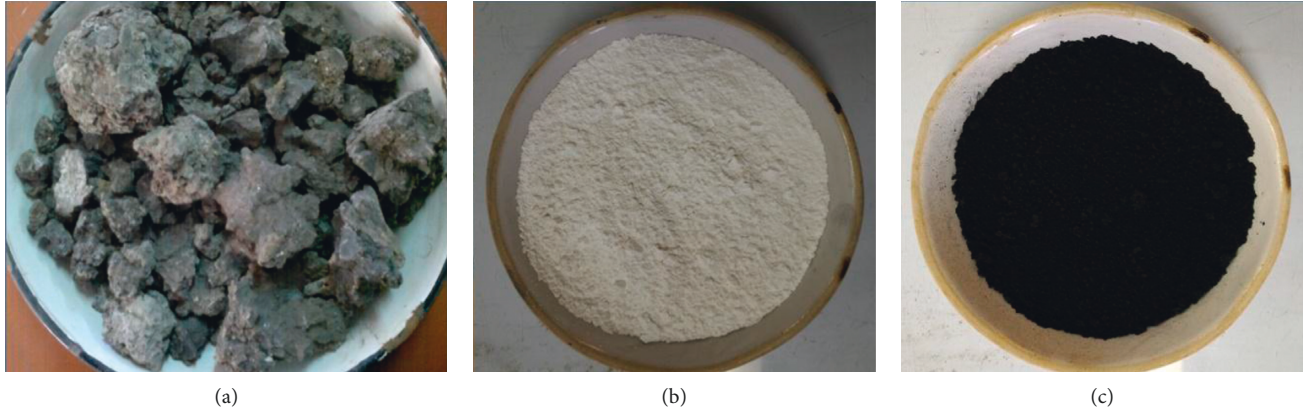
(a)   (b)   (c)

FIGURE 1: Materials adopted in the study: (a) soil, (b) lime, and (c) BA.

TABLE 1: Properties of soil.

w_L (%)	w_P (%)	I_P (%)	w_S (%)	G_s	γ_{dmax} (kN/m^3)	w_{opt} (%)	UCS (kPa)	pH	FSI (%)
68	27	41	10	2.76	15.3	25	115.8	6.53	98%
% gravel		% sand			% silt		% clay		Classification
0		2.5			60.5		37		CH

municipal solid waste leachate. Osinube and Thomas [24] studied influence of compaction on BA-treated black cotton soil. Ali et al. [25] investigated the effects of combination of marble dust and BA in stabilization of an expansive soil. Osinubi et al. [26] examined the strength and CBR of lime stabilized soil with BA. Manigandan and Moganraj [8] evaluated the consolidation characteristics of lime stabilized soil with BA. Sadeeq et al. [27] explored the effect of BA on lime stabilized lateritic soil. Dang et al. [28, 29] studied the strength and mechanical behaviour of lime and BA treated expansive soil. Hasan et al. [30] investigated the strength property of expansive soils treated with lime and BA and the effect of wetting and drying cycles on the durability of the stabilized soil. Jamsawang et al. [31] looked into the potential of BA waste as a replacement for cement in stabilization of soft clay. Lime stabilization has been and still is one of the preferred methods of soil stabilization for expansive soils. The concepts of Initial Consumption of Lime (ICL) and Optimum Lime Content (OLC) have been well established through several literature works. However, in studies on combinations of lime with pozzolans, very few researchers have adopted the scientifically established concepts of ICL and OLC for stabilization. It is also observed that researchers still adopt trial and error method for identifying lime contents for use in soil stabilization with pozzolans. It was also noticed that investigators adopted either ICL or OLC while working on lime stabilization of soils with pozzolans. Very few investigations have been carried out on the comparison of the effects of these two scientifically established lime contents. Considering the case of stabilization with lime-pozzolan (like BA), work details are further limited. In fact, the majority of such lime-pozzolan-based studies adopted combinations on a trial and error basis [32]. Hence, a detailed investigation on the performance of lime stabilized soil amended with BA was necessitated. Thus, an experimental study was devised to study the strength and index properties of an expansive soil treated with lime and BA with mineralogical and microstructural studies. This study, however, deals only with the strength characteristics of lime treated expansive soil amended with BA along with mineralogical and microstructural studies.
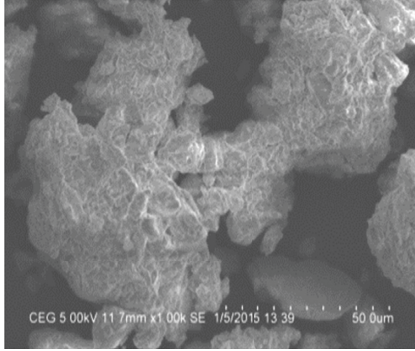
2. Materials

The materials adopted in this study are the natural soil, lime used for stabilization, and BA used as admixture and are shown in Figure 1. The natural soil was obtained from Thatthamanji village located in Thiruvallur district, Tamil Nadu, India. Its geotechnical properties are tabulated in Table 1. The lime used for the investigation was laboratory-grade hydrated lime [Ca(OH)$_2$] manufactured by Nice Chemicals India Pvt. Ltd. Laboratory-grade lime was used as available out of the bottle without any preparation. BA used in this study was sourced from Thirutthani Sugar Mills Pvt. Ltd. in Arakkonam district of Tamil Nadu, India. The chemical composition of materials used in the study is tabulated in Table 2.

Scanning electron microscopy (SEM) images were used to study the morphology of the materials. Figure 2 shows the structure of the materials adopted in the study from SEM. The micrograph reveals that soil particles are aggregated into lumps due to cohesive nature of the clayey soil. However, it also shows the platy clay particles that make up the soil aggregates. Lime possesses very fine-grained particles when compared to the other waste materials. It can also be seen that the lime particles are also aggregated into larger lumps. The microstructure of BA showed well-defined burnt flakes of bagasse. The field of view shows the charred cellular
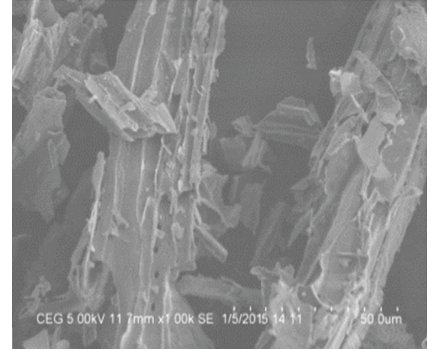
TABLE 2: Chemical composition of materials.

	SiO$_2$ (%)	Al$_2$O$_3$ (%)	CaO (%)	Fe$_2$O$_3$ (%)	K$_2$O (%)	MgO (%)	MnO (%)	Na$_2$O (%)	P$_2$O$_5$ (%)	TiO$_2$ (%)	SO$_3$ (%)
Soil	63.62	18.82	2.30	7.48	2.29	1.74	0.04	1.42	0.04	0.88	0.20
Lime	0.25	0.05	72.77	0.04	0.003	14.60	0.004	0.05	0.005	0.003	0.05
BA	35.17	0.281	2.07	5.22	3.75	0.91	0.04	0.01	1.03	0.02	0.03
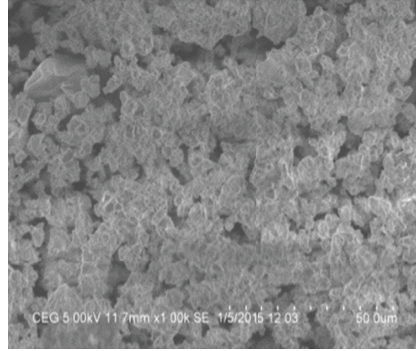
(a)   (b)   (c)

FIGURE 2: SEM micrograph of the materials adopted in the study: (a) soil, (b) lime, and (c) BA.

structure of bagasse preserved due to the high temperature of burning; however, there is a slight collapse of structure due to the fragile nature of the burnt flakes. However, BA consists of both crystalline bulky grains and pyrolyzed organic fractions [17]. Figure 3 shows the XRD patterns of the material used. A basic analysis of the XRD patterns was performed with Crystal Impact Match! Software Version 3.0.3 and Crystallography Open Database for reference patterns. Mineralogical analysis of soil from Figure 3 indicates the presence of montmorillonite and quartz. The identification of montmorillonite can be done by the presence of a peak at location of 14 Å [33]. Other peak location indicators of the mineral include 4.49 Å, 9.0 Å, and 18.0 Å [34]. The d-spacing of 4.49 Å corresponds to a 2-theta value of 19.78°. On close observation of the scatter pattern of the soil sample, a peak corresponding to this location was noticed. This was also reported by Kalkan [35]. The 2-theta values corresponding to the other d-spacings do not fall within the available range of the test performed. A peak at 2-theta value of 28° [35] and 36° [36] also indicates the presence of montmorillonite mineral. Similar peaks were also found in the scatter pattern of the soil under study confirming the presence of the mineral. Quartz can be identified at d-spacings of 1.15 Å, 1.18 Å, 1.37 Å, 1.82 Å, and 3.34 Å [37]. Similarly, peaks corresponding to the above locations were also found in the present soil. The diffractogram of lime revealed the presence of calcium hydroxide. A minor peak of calcite was also noticed. Similar peaks were also reported by Kampala and Horpibulsuk [38] and Solanki and Zaman [39]. The mineralogical characterization of BA shed light on the presence of cristobalite (low), quartz, and calcium carbonate/calcite. Cristobalite (low) is meta-stable, whereas cristobalite (high) is unstable at low temperatures. Others have reported the presence of quartz, cristobalite, calcite, calcium phosphate, mullite, iron oxide, and microcline among others [31, 40–44].

3. Methods

The geotechnical properties of the soil were determined in the laboratory in accordance with BIS specifications which included liquid and plastic limit [45], shrinkage limit [46], specific gravity [47], grain size distribution [48], compaction characteristics [49], unconfined compressive strength (UCS) [50], and pH [51], followed by classification [52] of the soil. Following the characterization of various materials used in the investigation, the quantity of lime required for improving the soil properties was determined. Nasrizar et al. [53] state that there are three phases in the relationship between strength and lime content in lime stabilization of soils, namely, below ICL, between ICL and OLC, and above OLC. Based on this, three different lime contents were adopted for soil modification in this investigation, namely, ICL, OLC, and one value less than ICL (LICL). The ICL value was determined from the Eades and Grim pH test in accordance with ASTM code [54] while OLC was determined based on procedure described by Thompson [55]. The same procedure was also adopted by others in their investigations [56–58]. A random value of lime content below ICL was selected for the investigation.

Following the determination of the lime contents, four additive dosages were selected at random, namely, 0.25%, 0.5%, 1%, and 2%. The experimental investigation began with determination of the altered compaction characteristics of lime stabilized soil. Compaction tests were performed on soil stabilized with different lime contents in a Jodhpur mini compactor apparatus based on the procedure laid down by Singh and Punmia [59]. Each trial in the Jodhpur Compaction test was done with a fresh batch of soil mixed with the required quantity of lime by weight with the quantity of water alone increasing with each subsequent trial in accordance with BIS [60]. The optimum moisture content and
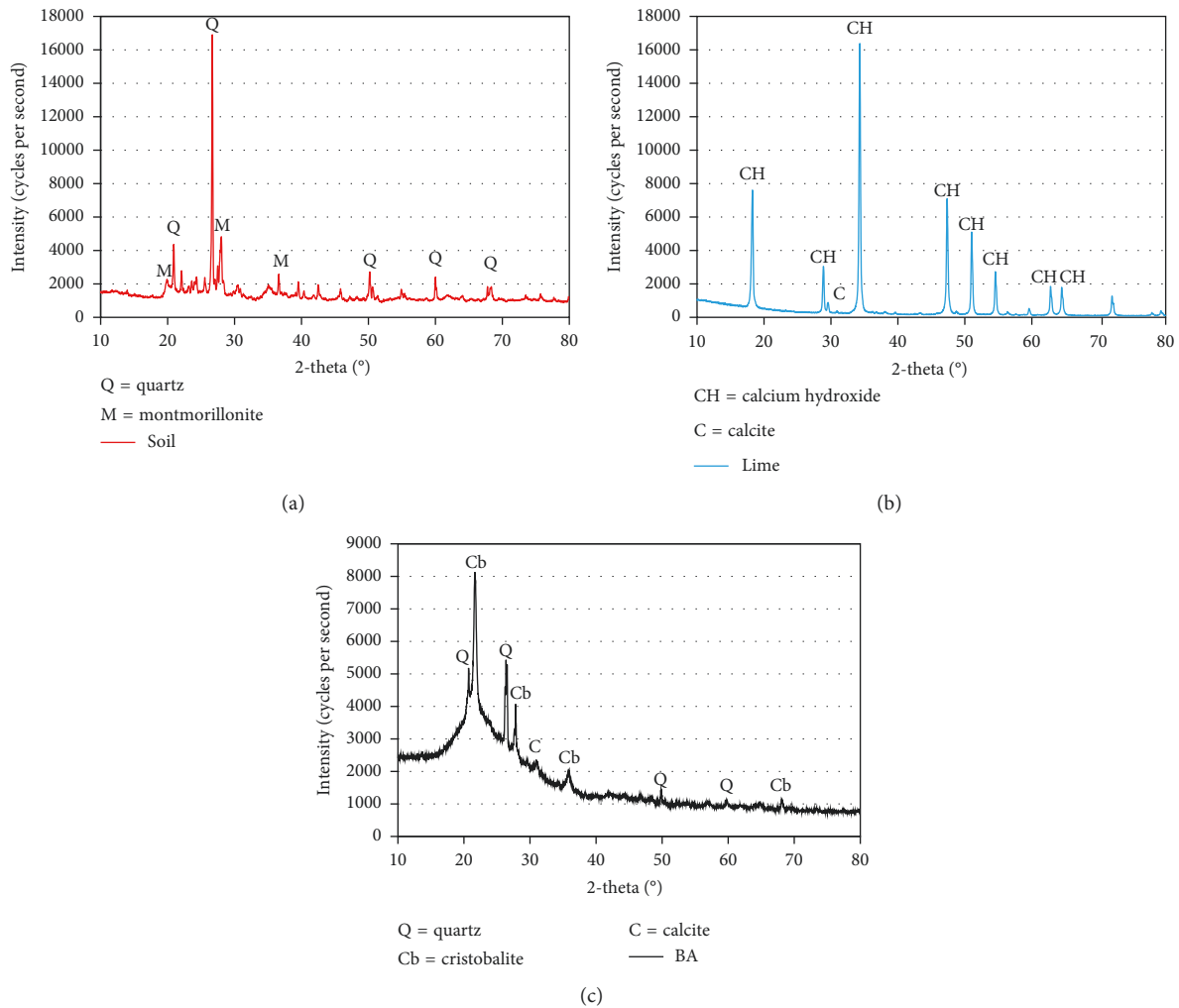
(a)

(b)

(c)

Figure 3: X-ray diffractograms of (a) soil, (b) lime, and (c) BA.

maximum dry density determined from the Jodhpur mini compaction test are close to the values obtained by the Standard Proctor compaction test within the close limits of experimental error [59]. The Jodhpur compaction tests were performed only for the three lime contents adopted for stabilization. One value of moisture content and dry density was selected out of the three sets of values obtained and set as the dry density and moisture content for preparation of all UCS test samples. A similar procedure was also adopted by Wild et al. [1] and Bagheri et al. [61]. Basically, all samples had the same density and moisture content within the limits of experimental error. In the present investigation, all samples were prepared to a target dry density of $14.72 \, kN/m^3$, at 25% water content. The UCS samples were prepared in a constant volume split mould of dimensions $38 \, mm \times 76 \, mm$. Measured quantities of soil, lime, and BA, calculated to achieve the target dry density, were taken in a pan and was mixed by hand in dry conditions. The required quantity of water based on the specified water content was sprinkled over the mix and was thoroughly and uniformly mixed to achieve a wet mix. The UCS mould was prepared by lubricating its interior surface

with oil, and one end was plugged using an end plug. The wet mix was then packed in the UCS mould in layers with gentle pressure provided using the compaction plug to ensure a good packing of the mix. This was repeated until the entire measured mix was packed into the mould. Another end plug was used to plug the top, and it was statically compacted using a universal sample compactor cum extruder. It was ensured that while packing the mould, the mix was alternatively introduced from either end and compacted statically from the corresponding end [62]. This enabled a uniformly compacted UCS specimen and reduced the possibilities of loose pockets in the specimen. The sample was then demoulded by splitting open the mould and providing a gentle push using the compaction plug from one end of the specimen. The samples were immediately placed inside a sealable polythene cover for curing. Three samples were prepared for testing each of the combinations. The samples were cured at a room temperature of $30 \pm 2°C$, for periods of 2 hours, 3, 7, 14, and 28 days for determination of strength of the stabilized soil. At the end of the set periods of curing, the samples were removed from their sealed polythene covers and loaded axially until failure at

FIGURE 4: Preparation of UCS sample.

a strain rate of 0.625 mm/min. The tested samples were then crushed, pulverized, dried, and sieved for mineralogical analysis. Fractured pieces of the test specimen were also sent for microstructural analysis. XRD was performed in a benchtop diffractometer model Rigaku Miniflex 2C. X-rays of wavelength of 1.54 Å was adopted with continuous mode Gonio scan between 2-theta positions of 10° and 90° with a scan step of 0.02° and a scan speed of 25°/minute. A current of 10 mA and a voltage of 30 kV were set in the generator. Figure 4 shows the preparation of test specimens for strength tests.

4. Results and Discussion

The ICL indicates the minimum amount of lime needed to achieve a pH of 12.4 and bring about prominent changes to soil properties, plasticity, and compaction in particular, along with activation of pozzolanic reactions [63]. Based on the experimental investigation, ICL was fixed as 5.5% and OLC as 7%, and LICL was randomly taken as 3%.

4.1. Effect of BA Quantum on the Uniaxial Strength. The influence of BA on the UCS of lime stabilized expansive soil at various curing periods is displayed in Figure 5. It is evident that addition of BA increases the strength of lime stabilized soil irrespective of lime content adopted for stabilization. When 3% lime content was amended with 0.25% BA, the strength of the soil increased by 23.7% to 677.25 kPa. Similarly, for 5.5% lime stabilization, the strength increased even further by 32.7% to 1856.39 kPa. When 7% lime content was amended with 0.5% BA, a strength gain of 17.5% was

(a)   (b)

(c)   (d)
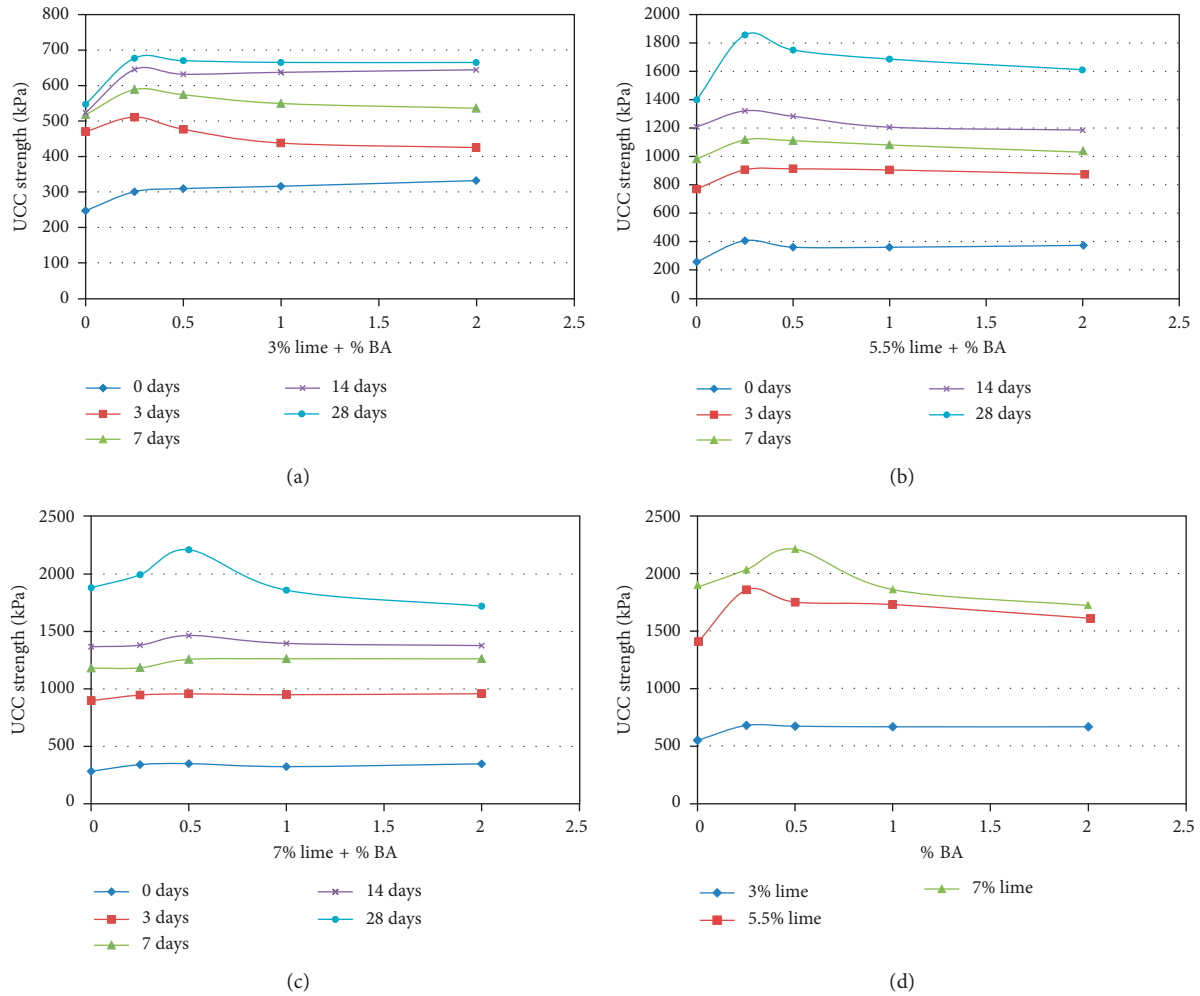
FIGURE 5: Variation of UCS with % BA for lime stabilized soil: (a) 3%, (b) 5.5%, (c) 7%, and (d) 28-day UCS comparison.

obtained, raising the strength to 2211.11 kPa. All three lime contents when amended with BA have produced gain in strength after 28 days of curing with at least two combinations of BA. A similar result has been reported in the investigations of earlier researchers with an increase in strength when combinations of lime and BA were used [27–30]. The increase in strength of the stabilized soil due to addition of BA can be attributed to chemical reactions taking place in the form of cation exchange, pozzolanic reaction, and cementation. Dang et al. [29] stated that the flocculation and agglomeration of soil due to stabilization results in the soil resisting compressive stress effectively than virgin expansive soil. The pozzolanic reactions take place between calcium from lime and silica and alumina from soil and BA in the presence of water to form cementitious compounds CSH and CAH which result in enhanced strength of the stabilized composite [6, 27, 64, 65].

Another major inference is that when the lime content is higher than ICL, there is an increase in BA content that produces maximum strength of the stabilized soil. This, however, cannot be seen below ICL wherein the optimal dose of BA remains the same. James and Pandian [58] found a similar trend wherein more PG was required to achieve

high strength with high lime content in soil stabilization. In similar terms, it can be stated that more BA gets involved in the pozzolanic reactions when more lime is available for stabilization. A similar trend was also noticed in the work done by Hasan et al. [30] with combinations of lime and BA. However, for lime content at and below ICL, similar optimal BA content may be due to the limitation of the test programme of not having any trial BA content below 0.25%.

It may be noticed that for LICL and ICL stabilized soil, all combinations of BA produced positive strength addition. But at higher OLC stabilization, only two out of the four BA contents resulted in strength improvement. In terms of utilization, BA seems to be more effective in bringing about positive strength benefits at lower doses of lime content when compared to higher lime content. The absolute increase in strength may be higher at higher lime content; however, the quantum of gain is better at lower lime contents of ICL and LICL when compared to OLC. It can be postulated that BA amendment of lime stabilization is effective at lower lime contents, particularly close to ICL rather than OLC. James et al. [13] reported that BA was more effective in enhancing the strength of cement stabilized soil blocks at lower cement content when compared to higher

cement content. Similar effects were also found in the other works analyzed [12, 66] as a part of the work done by James et al. [13].

Looking at earlier work done, Sadeeq et al. [27] adopted combinations of lime and BA for stabilization of lateritic soil but the UCS of the optimal combination of lime (8%) and BA (6%) was below 1000 kPa, whereas in the present study, the addition of BA to lime stabilization of an expansive soil resulted in strength in excess of 2000 kPa. Sabat [22] adopted a combination of lime sludge and BA to increase the strength of an expansive soil. The optimal combination of 16% lime sludge and 8% BA almost doubled the UCS of the soil; however, a strength of 120 kPa of the stabilized soil was very low in comparison with the present study which may be due to the use of lime sludge instead of lime whose calcium content is lesser than lab grade lime. Osinube and Thomas [24] found that combinations of 8% cement and 4% BA produced significant improvement in soil strength but still did not meet the criteria of 1710 kPa strength for use as base materials suggested by TRRL. Earlier work cited adopted trial and error combinations of lime and BA, and the strengths reported were low. In the present work, the approach for determining ICL and OLC for stabilization in combination with BA resulted in significant strength of the expansive soil.

4.2. Effect of Curing on Strength of Lime-BA Stabilized Soil.

Figure 6 shows the effect of curing on the development of strength of BA admixed lime stabilized soil. The graph reveals the development of strength of optimal BA content admixed lime stabilized soil. It can be clearly seen that provision of curing significantly influences the strength development of BA amended lime stabilized soil. In fact, BA amended lime stabilized soil develops strength more rapidly in comparison to pure lime stabilized soil. Similar results were reported by Hasan et al. [30] as well as Dang et al. [29]. It can be inferred that the most significant gain in strength of stabilized soil takes place when ICL content is admixed with 0.25% BA. However, BA is capable of raising the strength of the lime stabilized soil at all three contents. At LICL content, it can be seen that the gain in strength is below par at early curing of 3 days; however, beyond seven days of curing, the strength gain is more or less stable. At 7 days of curing, the strength gain is 13% whilst it is 23.7% at 28 days of curing which is almost a one-fourth gain in strength. Although BA addition increases the strength of the soil stabilized at LICL content, the strength curve becomes asymptotic before 28 days of curing, indicating that the lime is used up for short-term reactions rather than pozzolanic reactions [67] and, hence, BA complements the short-term reactions of lime resulting in the strength gain seen at this stage of lime stabilization. At ICL content, the strength gain is 21% at 3 days and 13% at 7 days. However, the greatest gain is achieved at 28 days of curing at 32.7%. This is almost a one-third gain in strength. At OLC content, the addition of BA results in a comparatively lesser gain in strength though the absolute strength values are higher. The strength gain hovers around 7% till 14 days of curing and then jumps to gain
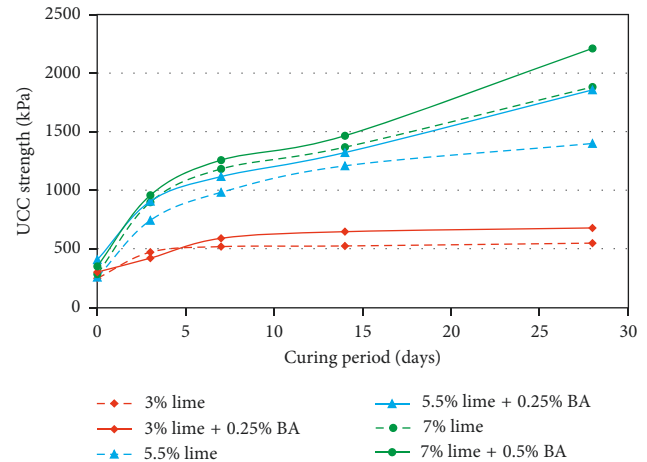

FIGURE 6: Comparison of UCS with curing period of lime stabilized soil with and without BA.

17.5% at 28 days of curing. It is clear that lime content below ICL does not have a significant impact on the strength gain despite BA addition augmenting it slightly. A similar result was also reported by Dang et al. [29] wherein they state a low threshold of lime has little impact on the strength gain of expansive soil. This may be due to insufficient lime available to supply calcium ions for pozzolanic reactions to continue over a longer period of time. It can also be noticed that the strength development of 5.5% lime stabilized soil admixed with 0.25% BA almost touches the strength developed by 7% lime stabilized soil at 28 days of curing. Thus, BA addition can result in similar strength at lower lime content. Hasan et al. [30] stated that the presence of BA accelerates the cementitious reactions between lime and soil. In an earlier work done by James and Pandian [58], PG could not achieve such a similar effect of producing similar strength at low lime content. There was a noticeable difference between the strength of 5.5% lime stabilized soil with PG and 7% lime stabilized soil. Osinubi et al. [26] had reported that combinations of 8% lime with 4% BA did not achieve a 7-day evaluative strength criteria of 1034.25 kPa, whereas in the present study, ICL with 0.25% BA and OLC with 0.5% BA developed higher strengths of 1115.88 kPa and 1256.76 kPa, respectively.

4.3. Percentage Strength Gain.

A percentage strength gain analysis was performed from the point of view of additive proportions and curing period. The percentage strength gain analysis was done by comparing the strength of pure lime stabilized soil with that of additive dosed lime stabilized soil at corresponding curing periods. This enables to understand the development of strength in percentage for different additive dosages. Three curing periods were specifically chosen for the analysis, namely, 0 days, 7 days, and 28 days. The strength developed corresponding to these three curing periods were designated "Immediate Strength," "Early Strength," and "Delayed Strength," respectively. The term "Late Strength" was not adopted for 28 days of curing because the development of strength continues for weeks or

(a)   (b)
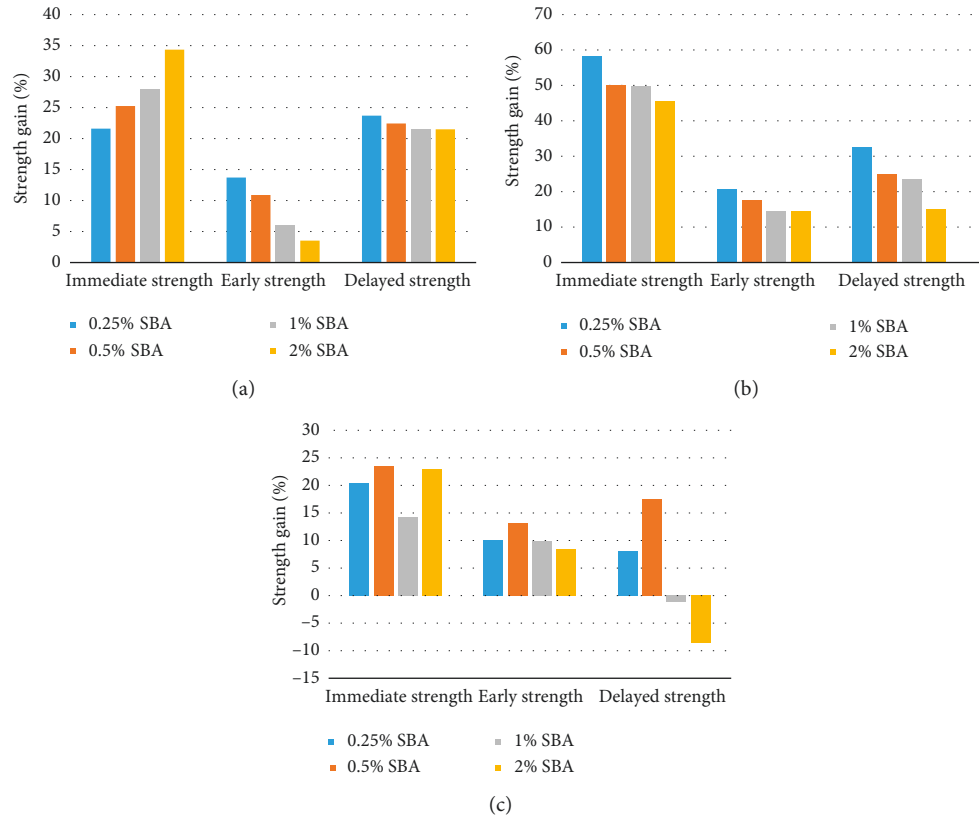

(c)

FIGURE 7: Percentage strength gain of (a) 3%, (b) 5.5%, and (c) 7% lime stabilized soil with BA.

even months beyond 28 days of curing [36]. Hence, there are periods later than 28 days that contribute to strength development. Three-day strength was not considered as early strength in this study because there was better demarcation in trends at 7 days of curing which was better from the point of view of analysis.

4.3.1. Percentage Strength Gain with Additive Quanta. The effect of BA on the development of strength of lime stabilized soil is presented in Figure 7. A brief glance easily reveals that the addition of BA results in a significant improvement in the immediate, early, and delayed strength of lime stabilized soil at all three lime contents. For 3% lime stabilized soil, 0.25% BA was found to be optimal dosage despite the fact that all BA additions produced positive strength gain. It produced a gain of 21.6% in immediate strength, 13.71% gain in early strength, and 23.7% gain in delayed strength. When 0.25% BA was added to 5.5% lime stabilized soil, it resulted in a 58.27% gain in immediate strength, 20.72% gain in early strength, and 32.72% gain in delayed strength. At 7% lime content for soil stabilization, 0.5% BA gave the maximum percentage gain in strength. At this dosage, the immediate, early, and delayed strength gains were 23.53%, 13.21% and 17.52%, respectively. It should be noted that, at lower lime contents of 3% and 5.5%, all BA contents gave positive strength gain, whereas at higher lime content of 7%, higher BA contents of 1% and 2% resulted in a loss in strength. One obvious inference that can be seen when comparing the

three different strengths, namely, immediate, early, and delayed strength of a particular lime dosage, the maximum effect is observed on immediate strength followed by delayed strength due to BA amendment. The least effect can be seen on the early strength. This is true, irrespective of lime content as the trends are similar across lime contents for all BA contents tested. Comparing the corresponding strength, not only delayed strength, in the cases of early as well as immediate strengths, BA seems to be effective at lower lime contents of LICL and ICL when compared to OLC. The maximum percentage gains are at ICL; however, the percentage gains of LICL are higher than OLC. When analyzing the work done by Hasan et al. [30], a similar trend was seen in which strength gain due to BA amendments of 4.5% lime was better than 6.5% lime stabilization. The strength increased from 750 kPa to around 1000 kPa when 4.5% lime was amended with BA, while when 6.5% lime was amended with BA, the strength increased from close to 950 kPa to just above 1000 kPa. It is clear that BA amendment of lower lime content performed better when compared to higher lime content.

4.3.2. Percentage Strength Gain with Curing Period. The percentage strength improvement of BA admixed lime stabilized soil with curing period is presented in Figure 8. Percentage strength gain for subsequent curing periods involved the calculation of percentage difference in peak strengths for subsequent curing periods to understand the
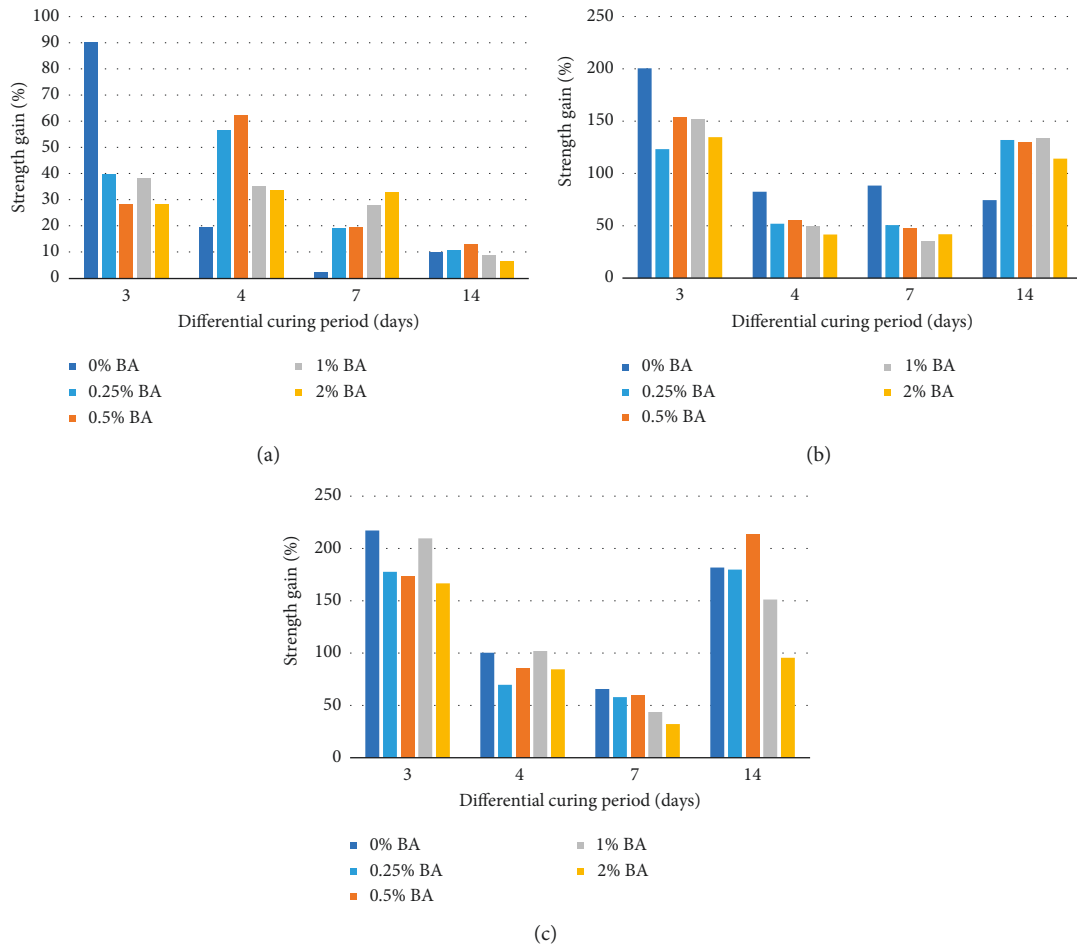
(a)

(b)

(c)

FIGURE 8: Percentage strength gain of (a) 3%, (b) 5.5%, and (c) 7% lime stabilized soil with curing period.

stages of strength gain for different combinations. For this analysis, all curing periods adopted in the study were considered for the calculation of strength gain to understand strength development. A similar percentage strength gain analysis was earlier done for subsequent curing periods by Bhuvaneshwari et al. [36]. However, they had performed the analysis for only lime stabilized soil composites. But the trends exhibited by lime stabilized soil with a very high strength gain at 3 days, followed by strength gain reducing till 21 days of curing and again increasing at 28 days, were also similar to the ones exhibited in the present study. It is revealed that, with the exception of 3% lime stabilized soil admixed with BA, the percentage gain in strength is similar as in lime stabilization, that is, maximum gain within first three days. In the case of 3% lime stabilization, there was better percentage strength gain in the second stage of curing which may be due to the delayed onset of pozzolanic reactions between lime and BA at lower lime content as indicated. At higher lime content of 5.5% and 7%, it can be seen that availability of lime for pozzolanic reactions at stage four of curing results in a significant percentage of the strength gained after 14 days of curing. Early strength has been an important part of studies carried out by several researchers [68–75] with a few studying it exclusively [68, 73–75].

Early strength development gains prominence in highway works where the need for quick opening of the road for traffic is of paramount importance. Several industrial wastes provide a good solution for enhancing the early strength of the stabilized soil due to the early formation of reaction products resulting in quick strength. In some cases, addition of industrial wastes to lime results in positive early strength development but also results in poor late strength performance [76]. Even chemical additives have been attempted for accelerating pozzolanic reactions for early strength gain [77]. Hence, the need to analyze not only early strength but late strength as well arises for adoption of industrial wastes as additives in soil stabilization. This study confines itself to the utilization of an industrial waste, BA, for improving the early as well as delayed strength of stabilized soil and has tried to analyze the positive effects on the same due to addition of BA.

4.4. Mineralogy of BA Amended Lime Stabilized Soil. The XRD scatter pattern can give a clear indication of the presence of crystalline and amorphous phases. Crystalline phases induce sharper peaks, whereas amorphous phases result in the formation of a broad hump. Figure 9 reveals the mineralogy of 7% lime stabilized soil amended with 0.5%

minerals [79]. Tricalcium dialuminium hydroxide and tetracalcium dialuminium pentahydrate are hydrates of calcium and alumina or CAH minerals. The formation and deposition of CSH and CAH minerals result in the cementation of the stabilized soil composite resulting in strength gain. A small proportion of portlandite was also detected. Portlandite contributes slightly to the strength as it reduces pore volume by converting some of the liquid water into solid form [80]. Calcite formation, however, was not detected which indicates that carbonation of lime has not taken place [36].

4.5. Microstructural Study. A microstructural study was performed to understand the changes taking place in the microstructure of stabilized soil due to the stabilization products. Figure 10 reveals the comparison of the microstructure of lime stabilized soil admixed with optimal dosage of BA. The micrographs reveal the changes in the microstructure of the soil due to addition of lime and BA to the soil. The platy structures are no longer clearly visible in the stabilized soil sample. This is due to the destruction of their structure due to dissolution and recombination during pozzolanic reactions. Wang et al. [81] revealed through SEM micrographs the destruction of flyash structure during stabilization of soil with lime and flyash. It can be seen that when 3% lime is added to the soil, there are portions of unreacted soil as 3% lime is not enough for modification of the soil properties. When 0.25% BA is added to the stabilized soil, the microstructure looks different due to enhanced pozzolanic reactions in the presence of BA. There appears to be more foil like leafy formations indicating a better progress in pozzolanic reactions and cementitious connectors that result in better aggregation of soil particles. Bhuvaneshwari et al. [36] also reported similar formations in the microstructure of lime stabilized soil. The zones of unreacted soil have also reduced and are barely noticeable.

In the case of 5.5% and 7% lime stabilized soil, there is a more even matrix of the stabilized soil with a denser microstructure in comparison with 3%. Presence of unreacted soil zones is not seen, indicating a better reaction between soil and lime. The microstructure reveals a more even cementation rather than cementitious connectors, indicating a further progress in pozzolanic reaction and deposition of reaction products. BA amended 5.5% and 7% lime stabilized soil specimens show a more even, compact, and denser matrix when compared to pure lime stabilized soil. They show well-developed floccules due to the cementations. Sante et al. [82] and Bhuvaneshwari et al. [83] also reported development of such floccules in the case of lime treated clayey soil and lime-flyash treated dispersive clay, respectively. The voids in the BA amended soil matrix are also less distinct when compared to pure lime stabilization, indicating a better aggregation of the soil during stabilization reaction resulting in higher strength. Muhmed and Wanatowski [84] attributed the presence of such voids devoid of cementing products in the microstructure for a reduced UCS of lime stabilized kaolinite. Jamsawang et al. [31] attributed the filling of pore spaces due to cementitious compounds which enhance the intercluster bonding resulting in strength gain.

5. Conclusion

The study involved the investigation of the effect of addition of BA to lime stabilization of an expansive soil. Three different lime contents were selected by determining lime contents scientifically required for modifying and stabilizing soil based on established procedures. These lime contents were amended with four different BA contents to study the effect of amendment on lime stabilization. The results of the study shed light on the following important revelations:

(i) For the soil under investigation, the minimum lime content required for modifying soil properties was found to be 5.5% and optimum lime content for stabilizing the soil was found to be 7%. These two lime contents divide the relationship between lime content and strength development into three stages. Based on this, 3%, 5.5%, and 7% lime contents were selected for investigation to understand BA amendment in different stages of lime stabilization. BA amendment of the three lime contents revealed that it was capable of further enhancing the strength of lime stabilized soil irrespective of lime content adopted for stabilization. Thus, BA amendment of lime stabilization works for any stage of lime stabilization.

(ii) Curing plays an important role in development of strength of BA amended lime stabilized soil. Curing influences strength development irrespective of lime content adopted for stabilization. Provision of curing results in a significant gain in strength of the stabilized soil. Addition of BA resulted in significant increase in immediate strength for all three lime contents in the range of 24% to 58%. The amendment also resulted in a 13% to 21% increase in the early strength and a 18% to 33% increase in the delayed strength. Thus, BA amendment results in immediate initiation of pozzolanic reactions, resulting in strength gain at 2 hours of curing. BA amendment of lime stabilization is also capable of sustaining enhanced rate of pozzolanic reactions over extended curing periods, resulting in strength enhancement across different curing periods investigated. ICL content with optimal BA can produce almost the same strength as OLC without BA. Hence, addition of BA to lime stabilized soil is capable of developing similar strength at lower lime content than without BA at higher lime content when sufficient curing is provided. It can be stated that BA amended lime stabilized soil develops strength quicker when compared to pure lime stabilization, resulting in higher strength at similar curing periods.

(iii) The optimal dosage of BA for developing maximum strength of lime stabilized soil was between 0.25% and 0.5% for the soil under investigation for all three lime contents. The BA required for higher strength development remained static below ICL but increased when lime content went above ICL. This indicated that when sufficient lime was available

(a)

(b)

(c)

(d)

(e)

(f)
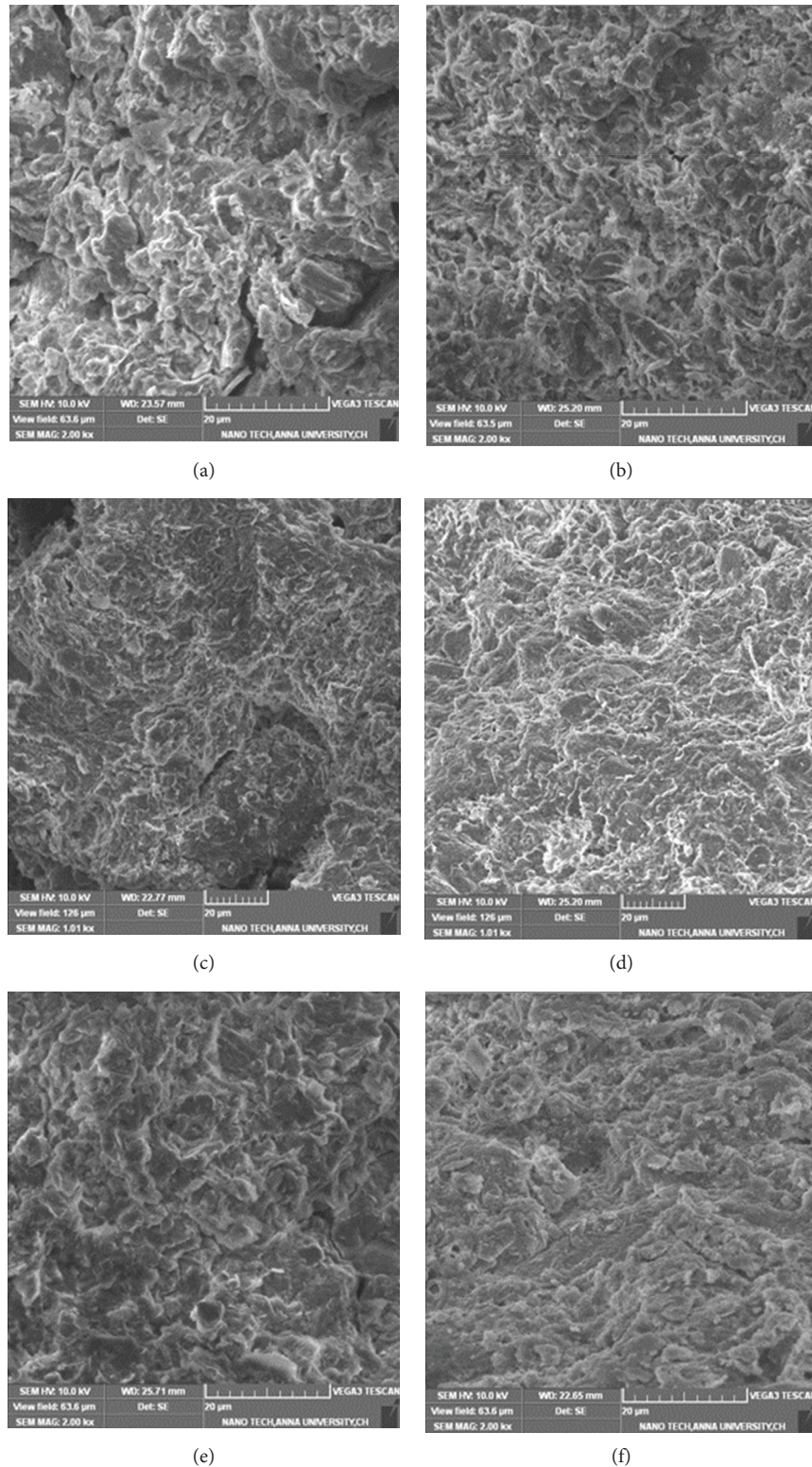
FIGURE 10: SEM micrographs of lime stabilized soil: (a) soil + 3% lime; (b) soil + 3% lime + 0.25% BA; (c) soil + 5.5% lime; (d) soil + 5.5% lime + 0.25% BA; (e) soil + 7% lime; (f) soil + 7% lime + 0.5% BA.

for stabilization, more BA got involved in the sta- bilization reaction resulting in higher BA requirement for developing maximum strength. However, the

effectiveness of BA in enhancing the strength of lime stabilized soil is better when lime content is up to ICL as indicated by the percentage strength gains. The

maximum strength gain on addition of BA was achieved not at OLC but at ICL.

(iv) The percentage strength gains of all three lime contents admixed with BA showed a similar pattern with relatively higher immediate strength gain, lower early strength gain, and moderate delayed strength gain. This may be indicative of a relative slowdown in the pozzolanic activity of the combination during the early stages of curing which slowly increases with prolonged curing. Percentage strength gain with curing indicated that the maximum strength gain was achieved within the first three days of curing. However, at higher lime content, the percentage strength gain at later stages of curing was comparable to that of early strength gain due to the availability of sufficient lime for pozzolanic reactions to proceed. The patterns of percentage strength gain were similar for pure lime stabilization as well as BA amended lime stabilization of expansive soil.

(v) Mineralogical investigation on OLC stabilized soil amended with 0.5% BA indicated reduction in peaks of quartz and montmorillonite and development of new peaks corresponding to reaction products of pozzolanic reactions. The reduction in peaks is a clear indication of destruction of the crystal structure and its use in pozzolanic reactions resulting in the formation of CSH and CAH minerals responsible for increase in strength. Addition of BA resulted in much better utilization of quartz present in the soil in the lime-soil reactions, leading to a reduced quartz proportion and increased strength. Addition of BA to lime produces an even and dense matrix of stabilized soil similar to that of pure lime stabilized soil.

Thus, BA can be used as an effective additive for augmenting the immediate, early, and delayed strength of lime stabilized soil. The overall picture indicates that 0.5% BA or lesser is enough to produce optimal improvements to the strength of the stabilized soil.

Abbreviations

ASTM: American Society for Testing and Materials
BA: Bagasse ash
BIS: Bureau of Indian standards
CAH: Calcium aluminate hydrate
CH: High plastic clay
CSH: Calcium silicate hydrate
FSI: Free swell index
G_s: Specific gravity of solids
ICL: Initial consumption of lime
I_P: Plasticity index
LICL: Less than ICL
OLC: Optimum lime content
PG: Phosphogypsum
SEM: Scanning electron microscopy
TRRL: Transport and Road Research Laboratory
UCS: Unconfined compression strength
w_L: Liquid limit
w_{opt}: Optimum moisture content
w_P: Plastic limit
w_S: Shrinkage limit
XRD: X-ray diffraction
XRF: X-ray fluorescence
γ_{dmax}: Maximum dry density.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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