Microstructural Characterization of Lime Modified Bagasse Ash Blended Expansive Clays using Digital Image Analysis

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Article

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Abstract

In the field practice, industrial wastes are recommended for use in construction to achieve both environmental and economic benefits. A novel technique of supplementing lime to the black cotton soil stabilized with bagasse ash is adopted to overcome the shortcomings of the black cotton soil stabilized with bagasse ash alone. The experiments have been conducted by adding lime to the black cotton soil mixed with varied percentages i.e., 0%, 5%, 10%, 15% and 20% of bagasse ash to ameliorate the properties of black cotton soil stabilized along with bagasse ash. Microstructural characterisation is done by X-ray Diffraction, Energy Dispersive X-Ray Spectroscopy coupled Field emission the scanning electron microscopy (FE-SEM) and Fourier Transform Infrared (FTIR) analyses were done to examine the changes caused by the additives. This phenomenon is keenly examined with FE-SEM images by analysing them using digital imaging technique. The imaging technique carried out using Image J, depicts the reduction in void spaces and identified that lime has a perceptible influence in the formation of stable and dense structure of black cotton soil stabilized with bagasse ash rather than stabilizing the black cotton soil with bagasse ash alone. In extension to these studies new technique in analysing the shrinkage properties using Python was proposed and the results have been upheld with Image J measurements. Based on the analysis of experimental results, it was found that with inculcation of portlandite rich hydrated lime, better reactivity is resulted in enhancing the engineering characteristics of the black cotton soil rather than utilization of bagasse ash alone in the stabilization of black cotton soil

Introduction

Generally Black cotton soils are classified under expansive soils, have propensity to change volume when they imbibe moisture and shrink when moisture ceases from them (Chen, 1988). This swell-shrink behaviour under transforming moisture content owes to the existence of expandable clay mineral namely montmorillonite. Therefore the black cotton soil causes severe damage to the structures founded on them. The damage engendered due to expansive soils is far more than the damages due to natural disasters like earthquakes, deluges, etc. and the annual financial loss caused by the expansive soils is estimated to be nearly 1000 million dollars in the United States alone (Qi and Vanapalli, 2015). Numerous techniques are practiced for mitigating the problems posed by the black cotton soil. These techniques include physical stabilization such as mixing of coarser fractions, soil replacement etc. and chemical stabilization using various admixtures like lime, cement, calcium chloride, lignosulfonate etc. (Eujine et al., 2017; Muthukumar and Shukla, 2018; Chijioke and Donald, 2019). Nowadays, the industrial wastes and by-products are used in order to valorize the engineering behaviour of black cotton soils, as they have a good pozzolanic activity with the soil. They not only alleviate the disposal problems, but they also bring the cost benefits (Ikeagwuani & Nwonu, 2019).

Bagasse ash is a multi-processed by-product produced from sugarcane industries. Sugarcane stands to be the widely cultivated crop worldwide and it is found that 1500 million tonnes of sugarcane is produced annually. India alone produces more than 300 million tonnes annually leading to the generation of about 10 million tonnes of bagasse ash left unutilized (Prashant and Vyawahare, 2013; Yadav et al, 2020). This material is fibrous by nature, and poses serious problems in disposal (Yadav et al., 2020). Bagasse ash is also identified as a good adsorbent and pozzolanic material, but there is limited study on its use for stabilization of black cotton soil (Bahadori et al. 2019; jijo James, 2020). However, the studies reveal that the volume change attributes are not completely ceased for any percentage of addition of bagasse ash. Moreover the internal mechanism with micro-structural analysis in the utilization of bagasse ash was not revealed. Hence there is a need to explore the possibility of sustainable solution in utilization of bagasse ash to completely cease or minimize the idiosyncrasy of an expansive soils. Hence to attain a sustainable solution, bagasse ash in conjunction with lime was explored in the present study, as the lime could trigger the pozzolanic activity and control the volume change attributes of the black cotton soil to an acceptable level. The pozzolanic activity and the changes in the microstructural levels are examined using digital imaging technique.

Moreover, expansive soils are prone to volumetric changes due to seasonal fluctuations and the shrinkage is accompanied by desiccation cracks during drying and presence of such cracks hinders the accuracy of volume measurements. Vernier calliper measurement do not capture volume of cracks and inaccuracy in volume measurements by mercury displacement method due to entrapped mercury in cracked specimens (Juliana and Tyagaraj, 2019). A new break through is achieved in current study in adopting a programming language for shrinkage crack measurements. Digital image processing is done with Python and Image J software for precise assessment of volumetric reductions due to shrinkage. Thus, this paper aims to provide a better understanding of micro structural changes that take place upon addition of lime to the expansive soil blended with bagasse ash in combating the volume change attributes of the black cotton soil in combination with Image processing and programming language tools.

Materials

2.1 *Black cotton soil*

The black cotton (BC) soil was procured from Mummidivaram village of Amalapuram mandal of East Godavari district, Andra Pradesh, India. The village is located in the deltaic region of the Godavari River. The index and engineering properties tests were assessed and the results have been given in Table 1. From the results of the tests, the soil has been identified to be the clay with high plasticity (CH). The free swell index (FSI) for the black cotton soil was tested to be 130%. According to Chen (1998), based on the value of FSI, the degree of expansiveness of the soil is classified as very high.

2.2 *Additives*

Hydrated lime and bagasse ash have been used in the present study. Bagasse ash (BA) was collected from Vellore Co-operative Mill and Sugar Research Institute, Vellore, Tamil Nadu, India. The ash contained some extra waste and 95% of the sample was passed through 425-micron sieve. Pozzolanic properties were identified in bagasse ash due to the presence of substantial amounts of aluminum, amorphous silica, calcium and iron oxides. Hydrated lime was used in the present work and its chemical composition is presented in Table 2.

The previous studies revealed that the quantity of lime required for stabilization depended on several factors. The pH experiment is used for finding the minimum quantity of lime needed for stabilization. According to this procedure, the percentage of lime is found to be 3%. This was ensured in the index properties test on BC soil. Hence to enhance the stabilization of BC soil and BA blends, 5% of lime content was used for different proportions of BA blended with BC soil. The chemical constitution of BC soil and bagasse ash is revealed by Energy Dispersive Spectroscopy (EDS) is presented in Table 3 and their respective morphology is depicted in Figure1.

Methods

3.1 Preparation of Samples

The sample was oven dried for duration of 24 hours at a standard temperature of 105°C. After drying in the oven, the sample was sieved according to the requirement of the test standards. Bagasse ash collected as waste material from power plant is heated at temperature of 650^0C termed as calcinations process to impart changes to the microstructure of soil upon amendment. The lime content and bagasse ash were adopted based on the prior studies by various researchers (Dash and Hussian, 2012; Ejune et al., 2017; Bahadori et al. 2019). To study the influence of lime on the BC soil blended with BA content, different amounts of BA by dry weight of the soil (5%, 10%, 15% and 20%) and 5% of lime were blended with the prepared dry BC soil.

3.2 Shrinkage characteristics of expansive soils

Accuracy of digital measurements is high when compared to manual measurements as the chance of crack initiation and minor cracks can be easily identified and measured which is successful in realistic shrinkage measurements even on repeatability. Advantage of considering minor irregular cracks is to provide accuracy and thus helps in best characterization of expansive soils (Puppala et al, 2004)

3.2.1 Manual measurements*:* All the manual measurements are made on Mitutoyo digital Vernier calipers with 0.01mm accuracy to compare the results obtained from the digital measurements. Measuring of average diameter and average height for each specimen after desiccation for 24 hours is done with the help of Vernier callipers with sharp edges to compare the linear shrinkage attained on image processing tools (Image J) and programming language (Phython).

3.2.2 Crack and volume measurements using programming language Python:

3.2.2.1. Data Acquisition: All the data obtained for the image study are obtained by photographs of specimens which are taken at a constant distance to the image at same focal lengths and the same images are used for image processing by Image J to avoid dissimilarity in measurements. Experimental platform and analysis includes the hardware that includes Laptop with Intel(R) Core(TM) i5-8250U CPU @ 1.60GHz, 64-bit processor with 8GB RAM. The software environments are python 3.9.7, VGG tool, and Open Computer Vision running on Windows 10 OS 21H1. The experiments are performed on data set of 8 images which were photographed at same focal lengths.

3.2.2.2. *Pre-processing*: Essential part of working in Python involves in importing libraries of numerical python, cv2 and matplot for displaying and processing images for computations. Pre-processing step in our method involves in removal of black background from the raw images. The raw images are read using Open CV python library. It includes reading image, creation of white background, binarize masks, blur alpha mask and alpha-blending to merge the foreground and background images. Reading image involves in adjusting the image size so that it matches the r channel of RGB image which is done by DeepLab V3 and by calling decode_map function. This operation is followed by creating a NumPy array of ones with the same shape as the RGB output map obtained from DeepLab V3 to create a white background and scaled to pixel intensity of 255 which is white background.

Binarized mask is generated by converting both the foreground and background of image to float type from uint8 and cv2.threshold function used to compare the pixels against the threshold value. Binary thresholding is the simplest form of global thresholding where each pixel location (x, y), the pixel intensity at that location is compared to a threshold value. The input code applies an adaptive threshold to an array. This is the function that transforms a gray scale image to a binary image according to the formulae:

$$f(x,y)= \begin{cases} \text{Max value if } g(x,y) > \text{threshold} \\ \text{Else } 0 \end{cases}$$

Post threshold, background pixels have a value of 0 and a foreground pixels with value 1 which is essentially cracked part in the input image. The output of the threshold function is stored in the alpha. In order to take care of the quality of picture at edges a Gaussian blur filter is applied before using the masks to avoid undulating edges. Alpha mask is normalized to have an intensity between 0 and 1 by alpha blending foreground and background for this multiply foreground with alpha and background with the 1 – alpha respectively and the actual merging happens between masked foreground and background before displaying normalized output .

segment(dlab, './images/bgremoval/5BA.png', show_orig=False)

3.2.2.3. Segmentation with VGG tool: VGG Image Annotator (VIA) tool is used to define regions of interest in an image which supports different region shapes such as Circle, ellipse and polygon to select the boundary of soil pat and shrinkage dish, whereas polyline to select the cracked part of the image as represented in Figure 2. The annotated image is then exported in JavaScript object notation syntax (json file format) which is further read through sublime editor for the area co-ordinates. The co-ordinates upon selection for typical specimen 5BA are presented below.

3.2.2.3.1. Coordinates generated through sublime editor:

{"5BA.png3030174":{"filename":"5BA.png","size":3030174,"regions":[{"shape_attributes":{"name":"polyline","all_points_x":
[364,456,493,558,619,783,946,1062,1201,1330,1416,1487,1531,1569,1501,1429,1300,1205,1048,973,871,759,674,630,575,565,606,592,565,524,500,374],"all_p
[1317,1330,1327,1456,1541,1664,1749,1773,1756,1756,1725,1739,1797,1807,1712,1695,1708,1708,1725,1708,1657,1599,1531,1497,1429,1402,1399,1368,13
{}},{"shape_attributes":{"name":"circle","cx":1059,"cy":1289,"r":772.421},"region_attributes":{}},{"shape_attributes":
{"name":"circle","cx":1085,"cy":1101,"r":1029.253},"region_attributes":{}}],"file_attributes":{}}}

3.2.2.4. Area computations using NumPy

Numerical python is used in area determinable functions from python library. As the images are represented in form of pixel elements with intensities in matrix form, NumPy library is used as it supports adding multi-dimensional arrays and matrices and high-level mathematical functions to operate on these arrays. Area coordinates fetched from the above process are used for the generation of crack area. The area of shrinkage dish and the pat are determined for volumetric analysis of the soil.

3.3. Digital measurements using Image J:

Novelty of this method lies in applying the study to the samples of shrinkage limit where the time can be saved and the same sample can be analysed for the volumetric shrinkage parameters without need to cast analyse and study specimens at larger scale (Manuel et al., 2021). Moreover the study is compared with the imaging software python for analysing shrinkage parameters and the impact of bagasse ash in volumetric shrinkage strains is evaluated. Lime content is varied in the preliminary image analysis of the specimens, where parameters like volumetric shrinkage strains (VSS), change in volume and linear shrinkages are determined. Dosages of lime content are tested for 0%, 1%, 3% and 5% in weight percentage for volumetric study. Raw images as input images after pre-processing to remove noise are thresholded to find the required volume as listed in Table 6 with corresponding VSS in Table 7. Based on the preliminary studies, conclusions are drawn for the major study in fixing the dosage of lime to 5% in order to study the reactivity among clay-bagasse ash blended mixes.

Image processing technique is performed by tool named Image J from NIH to study the volumetric and fractographic images of soil specimens adjusted to suitable scale. This suggests a novel approach in determination of shrinkage parameters occurred in expansive clays due to desiccation. The initial proportions which decide volumetric shrinkage strains such as Surface Area Ratio (SAR), Perimeter Ratio (PR) and Circular Area Ratio (CAR) images which are determined from image processing technique. Accurate crack width measurements that even measure minor shrinkage cracks helped in exact evaluation of shrinkage strains thus adopting digital image processing helps in choosing best stabilisation strategies for characterisation of expansive soils (Puppala et al., 2004).

Images are pre-processed so that for analysing them for the assessment of required parameters becomes easy (Patrick and Chakravarthy, 2020). Functions like binary threshold are utilised for the enhancement of image clarity in identifying the crack width. Threshold function helps in highlighting the region of interest making the background dark by setting a threshold value to measure crack area. Region selection tools are used to find the geometrical parameters such as area, perimeter, volume and diameter which are essential in determination of Volumetric Shrinkage Strains (VSS). Comparable chart of operations on raw images for computing volumetric shrinkage entities are listed in Figure 3.

3.4 Morphological and micro-structural characterizations

3.4.1 Field Emission Scanning Electron Microscopy (FE-SEM)

Influence of the waste material in imparting changes to mechanical and physical properties of soil is difficult to explain without keen observation of microstructural changes that occur within the soil matrix. Field Emission Scanning electron microscopy (FE-SEM) characterization is used to evaluate pre-treated and post treated soil samples by lime and bagasse ash for comparative analytical studies of soil samples. Hence SEM analysis of high resolution are required to keenly observe the changes that takes place.

To understand the microstructure and nano-particle structural distribution of soil, FE-SEM analysis is performed in thermo Fisher FEI QUANTA 250FEG for morphological understanding of different mixes adopted. The instrument is equipped with Schottky field emission electron gun as source of electrons with operating range 5kV-30kV offering high resolution of 1.2 nm at 30kV at high vacuum conditions adjoined with Everhart thornley detector for secondary electrons at high vacuum for coated samples. The sample preparation is done by placing 10 milligram of dried sample on stubs. Oven dried soil is selected to eliminate the charging effect on the microstructure and to obtain better illuminated image with high resolution. To avoid this, all the samples are sputter coated in Quantum Q150T S plus either with chromium or gold as the soil is non-conductive. Surface morphology and fractographic information helped in assessing the microstructural modification with the addition of stabilizer and which discusses change in shape and size of the particle.

3.4.2 crystal structure and mineralogical modifications of clay with proportional lime and bagasse ash by X-ray Diffractionn (XRD) analysis

Peak alterations in intensities with respect to the diffraction angle are keenly observed through illustrations of X-ray powder diffraction (XRD) of all the 8 mixes along with bagasse ash and expansive clay. Black cotton soil is primarily analysed to match with the other mixes to assess the rate of pozzolanic reaction happened. The prominence of the angle between incident ray and diffracted ray diffraction between 15°to 35° is reported by researchers for bagasse ash in deciding the mineralogy and crystal structure.

3.4.3 Fourier Transform- Infrared Radiation (FT-IR)

The amount of light that is transmitted through the elemental matrix of soil sample is plotted against Wave numbers. Expansive soil elements are analysed to check the variation in structure through amendment which is sensed through bond formation and distinct elemental vibrational behaviour to infrared radiation pertaining range 400–4000 cm^{-1}.

The tetrahedral and octahedral sheets in clays are bonded by weak inter layer bonds and the presence of water molecule is the main reason for the expansiveness of soil minerals. Clays can only form bonds at the edges due to large surface area of clay exchange of cations adhesion to the clay particle due to difference in ion concentration. Soil Samples with addition of industrial waste such as bagasse ash and lime as stabilising agent are subjected to infrared radiations to inspect the chemical bond formation and reactivity between them along with soil mineralogy. Curing time is fixed as 7 days for the physiochemical changes to happen between the admixtures.

Results And Discussion

4.1 Influence of lime on the shrinkage properties of black cotton soil

Shrinkage limit test is conducted on specimens with the varied percentages of bagasse ash with and without addition of 5% lime to observe the shrinkage characteristics. Reduction in shrinkage upon addition of lime is evident from the final volume of soil pat attained on drying. The intricacy in manual measurement of cracked specimens upon desiccation is solved by adopting image processing tools. Complexity in the measurements made by Vernier callipers is the possible breaking of specimens into fractions while handling fractured portion of pat when measured on bevelled edges and inclusion of crack volume may lead to erroneous measurements misleading the assessment of volume parameters.

Reduction in linear measurements with bagasse ash indicates the included bottom measurements reduced the accuracy. Linear Shrinkage faulty assessment is notified in accounting crack width in manual and image J measurements, whereas python programming and tools could effectively eliminate the cracked width by averaging the crack width with coordinates to find the crack width. This crack width is excluded from linear measurements and hence surge in peak at 10% BA. Figure 4(a) show the correct assessment of cracked specimens. Minor crack accountability lead to the perfectness in assessment through both image tools and lacked behind in vernier calliper measurements at 15% BA mix and with mild variations in 20% BA mix caused by mask generation overlap in python on to the real image.

Figure 4 (b) depicts the comparison charts of lime blended bagasse ash specimens, where the linear shrinkage of the specimens measured by Vernier callipers and image processing tools such as python and image J shows the reliability of the study. Slight increment in linear shrinkage values of specimens with 20% bagasse ash with and without lime resulted in increased overlap of the binary filter over the edges of shrinkage dish in the images. This possible minute errors can be rectified by adopting best suited preprocessing techniques. Deviation in the radial shrinkage of specimens measured with vernier callipers resulted in measurements on pat at different heights. Further the usage of image J in measuring volumetric shrinkage strains are in correlation with the VSS measured from python and deviation at mercury displacement method for cracked specimen is witnessed at 5 BA. The other mixes show a similar trend with possible minute errors which is evident in Figure 4(c) and Figure 4(d). As per the expansive soil characterisation studies cited by Puppala et al., (2004) severity of shrinkage for VSS and Linear shrinkage which is very high without lime admixture drifted nearer to medium and low with the reactivity of portlandite (lime) with clay and agricultural waste.

Usage of wax method by researchers instead of mercury displacement method gave possible scope in experimentation of measuring shrinkage parameters with Digital Image processing. Alternative methods are employed as the disposal and handling of mercury is environmental concern. Fractographic images of specimens with bagasse ash shows the precision of python in measuring the cracked portions where deviated manual measurements shows the accounted crack width that led to faulty measurements. On the other hand these python based measurements fall in line for uncracked specimens at CAR measured with image J. The feasibility of selection of crack width in the form of coordinates (x, y) aided in precision of measurements with python. This has edge over the measurements done on image J, where there is possibility of unwanted crack width creeps in the form of background separation. All together image studies showed the employability and adaptability in measurement of shrinkage parameters of expansive clays. Usage of bagasse ash in the presence of 5% lime helped in the reduction of crack initiation and propagation due to the binding pozzoloans forming C-S-H, C-A-S-H and M-S-H bonding in the clay matrix.

4.2 Morphological and Micro-structural studies on clay amended with bagasse ash and lime

Changes in the XRD elemental structure is proven to be true with the morphological changes analysed through high resolution Field Emission Scanning Electron Microscopy. Major composition of Bagasse ash being Quartz and Cristobalite basically in forms of silica, the later mineral is attained by polymorphism of silica at high temperature resulted due to calcification. Optimum duration for the calcinations is supposed to be 3 hrs in order to enhance formation of cementitious pozzolans. Pozzolanic activity is directly related to the portion of amorphous silica which is relied on the temperature of calcination so the temperature is set to 700°C which is fixed from the experimental studies done by Yadav A.L. et al., (2020). Change in the 2θ values of cubic cristoballite in the lime modified mixes suggests the change in mineralogical composition of soil through amendment. Ekrem & Kalkan (2011) justifies the peak value formed near 28°as montmorillonite which is found to be true in this case. In lime blended 15BA and 20BA mixes a new peak emerged indicating the C-A-S-H agglomeration recognised in formation of Margarite. Little deviation in silica peaks is observed in L+15BA and L+20BA due to formation of CSH and CAH bond with –OH from FTIR results is main reason for invigoration of UCC values. Major observed peaks related to Hexagonal Quartz (Q), Cristobalite (C), Hydrated Halloysite (H), Illite-Montmorillonite (I-M) and attapulgite (A) with minor peaks of oxides of elements like iron, titanium, aluminates and silicates is seen in Figure 7 (a) and 7 (b). BA and expansive soil mixes show no major modification except presence of Goethite (F), Kaolinite (K), Titanium(T) with the lime amendment formation of alumino silicates bond with hydrogen, potassium and calcium which indicates bonding between bagasse ash, lime and soil.

4.3 Infrared absorption spectroscopy of clay blends

Minute variation of FT-IR peaks of clay with BA can be seen in Figure 8 (a) where formation of inner -OH stretching bond vibration peak is most predominant within clay at 3616 cm-1 and intermolecular –OH bond at 3371. Unique IR spectral peak for all mixes is observed at 1633 cm-1, is due to OH vibration and stretching mode of water at which H-O-H bending mode of less strongly bonded water indicates inter layer liquid water in montmorillonite. The absorption bands at 912 cm−1 were attributed to AlAlOH and presence of quartz at appreciable level by is at 777 wavelength. Researchers suggest that possible -OH bending at 912 resulted in partially submission of Fe and Mg in place of Al octahedral units. Octahedral Al cation bonds to form Si-O-Al, or the occurrence of Al-OH groups can be sensed with 501 cm− 1. Si-O-Si bending vibrations at wave lengths confining 418 to 457 range.

Variation of FT-IR peaks of clay with BA and lime is witnessed with Variation of -OH bond and for the rest of its composites it ranged between 3614 cm-1 and 3616 cm-1, for mixes with L+15BA and L+20BA, the bond formation disappeared due to the reaction between the –OH and lead to formation of CAH CSH bond that imparted strength properties to the soil and hence UCC samples tested for such mixes outnumbered. Intermolecular bond –OH stretching of hydroxyl groups in smectite for unaltered clay is at 3371 and it shifted towards 3394 with increase in wave number suggesting more absorbance in BA treated samples and for lime treated samples it reached 3375 which suggests the modification in crystal size of particle and hence the swelling property of clay is witnessed in Figure 8 (b).

AlAlOH is obtained at same wavelength in all the blends with BA and BC soil except for 20BA it shifted to 916.916 continued in L+5BA mix whereas 10 and 20 BA the peak diminished as the prominence of AlFeOH is witnessed in all the lime blended mixes at 875 cm-1 at constant rate. The absorption band at 916 cm−1 and 885 cm−1 were attributed to AlAlOH and AlFeOH with Fe. Minimal shifting 2theta value at XRD in lime blended BA mixed clay resulted in the slight modifications of how the IR wavelengths are in synchronisation with the variation in 2 theta values of quartz at 775-796 or 777-796 is the region where quartz is predominant and slight changes with peak values in XRD resembles the same.

4.4 Scanning electron microscopy (SEM) analysis

Transformations of clay morphology on stabilization with FE-SEM

Clay fabric is basically a series of honey combed structures with clay minerals formed by slight variations in pore spaces, Congregation and positioning of particles. Flocculation is a function of the size, shape, a high amount of surface area and a negative surface charge of clay particles orientation range between flocculation and dispersion based on association or dissociation of two clay minerals which is resulted from net push–pull force between them. Reduction in volume of voids is dependent on orientation of particles. The clay fabric of soil is structural arrangement of clusters formed by attractive and repulsive forces forming honey combs and leaving voids in Figure 9(a). The Figure 9 (b) represents the void spaces in the clay fabric resulted in such formation of clay structure. This can be visualized through high resolution FE-SEM image at Figure 9(c).

As the size of clay particle is less than 2 micron it can range from micro size to nano-size sometimes can be visible only under microscope, hence the particle to particle bonding and strength decides the property of the clay employed for the study. Stabilization of the macro structure is interrelated to the bonding between the clay particles and the behaviour of admixtures in the pore spaces and the intra particle structural arrangements. The tendency of the clay particle due to its large surface area and negative charge in the same plane leads to repulsion and dipolar effect of water increases the clay affinity to water molecules can form bond with adjoining particle.

Essentiality of structural examination in understanding the mechanism of stabilization/modification at microstructural level is addressed. This factor governs the alteration in physical and mechanical properties of clay. The level of improvement at micro level is assessed by observation of improvement in microstructure with the action of additives which reflects increase in strength, decrease in volume differences, swelling and compressibility. The presence of clay mineral, its type, size and percentage of clay mineral are the key factors on which the soil plasticity properties relies on as it decides the affinity of clay particle to water. Water molecule adsorption to negatively charged surface of clay particle initiates chemical change between adsorbed water, dissolved ions, and clay minerals. This decides microstructure of clays. In contrast to the gravel and sand, the clayey soils are identified by their cohesion and plasticity properties instead of size

For the identification of the micro-structural changes, scanning electron microscopy (SEM) analyses were conducted. Soil with 5% lime, 5% lime +10% BA, 5% lime + 15% BA and 5% lime + 20% BA.X- Ray diffraction (XRD) analysis was held upon on the soil specimens. Figure 1(a) and 1(b) show the SEM image and EDX analysis of the black cotton soil and bagasse ash respectively. The elements identified in the EDX analyses matches with the chemical composition of the materials (Table 5). Figure 1 (a) ensures the black cotton soil having lamellar texture which indicates the presence of smectites, resembles the layered structure of monmorillonite [20]. Figure 1 (b) reveals the fibrous nature of the bagasse ash. From the XRD analysis also, the presence of montmorillonite is assured in the soil specimen. The high volume change attribute of this black cotton soil is because of the presence of mineral, called the montmorillonite. Hence, addition of pozzolanic material (BA) engenders physiochemical reactions with the black cotton soil. The physiochemical reaction is ineffectual due to the presence of limited amounts of calcium and magnesium ions (Table 4).

This incomplete physiochemical reaction is observed in SEM analysis (Figure 5 (a)). Figure 5 (a) and Figure 5 (b) represents the BC soil stabilized with 10% of BA and 20% of BA respectively. However the adhesion of BA to the clay particle is due to the net negative charge of clay and anions present in bagasse ash helped in reduction of pore volume from 69% to 29% depicted through image analysis done on FE-SEM images at magnification of 500nm between clay and 15BA in Figure 10.

Where the black coloured particles indicates the dispersed clay particles and the bonding between the clay particles with Bagasse ash to form strong honey combed structure with minimum void spaces due to the attraction of cations in bagasse ash to net negative charged unstable clay particle. The instability of clay particle is assessed from the zeta potential analysis in Horiba analyser which is found to be -23.1 mV when plotted with intensity on ordinate in Figure 11 measured at Dispersion Medium Viscosity of 0.891 mPa·s and Conductivity rate is 0.444mS/cm.

The observation of SEM analyses showed the partially reacted soil particles. The unreacted BA particles lead to the poor microstructure and increased porosity leading to the poor volume reduction of the BC soil. This infers that the additional quantity of lime is required for complete physiochemical reactions to occur. Figure 5 (c) shows the image of the clay specimen blended with 5% of lime and 5% of BA. From Figure 5 (c) it is noticed that blending of 5% lime to BC soil, helped in the formation of aggregated structure. Addition of 5% lime+10% BA content leads to the rearrangement of particles and increases the structural integrity (Figure 5(d)). The interaction between the clay surface and water reduces due to the agglomeration of the particles, leading to the change in the behaviour of the BC soil. Further incorporation of BA leads to the development of more cementing compounds like magnesium silicate hydrates (MSH), calcium aluminate hydrates (CAH) and calcium silicate hydrates (CSH), such compounds proved to be helpful in binding the soil particles together and also reduce the voids prevailing in the soil. These cementitious materials are clearly visible in the Figure 5(e). Due to the formation of cementitious matters on addition of 5% lime + 15% BA, the UCS of the soil was found to have increased (Figure 6). Further addition of BA ends in increasing in the void space among fine grained soil and also reduces the bonding between the cementing compounds. This phenomenon is ensured in Figure 5 (f). Hence, the strength of the BC soil decreased when BA content is increased beyond 15%.

Conclusions

The conclusions arrived have been stated below on the basis of studies done and results obtained:

1. Due to the physiochemical reactions between the ions present in the black cotton soil, lime and bagasse ash cause significant reduction in shrinkage potential and volumetric shrinkage strains of the BC soil. The components of silica and alumina ions of soil interact with the magnesium and calcium ions in bagasse ash and lime help in the formation of calcium aluminate hydrates, calcium silicate hydrates and magnesium aluminium silicates. These compounds act as cementing agents and reduce the shrinkage characteristics of BC soil. The fibrous nature of bagasse ash also form a better interphase at micro level in bond formation with clay compounds which is evident on image analysis on FE-SEM images at 500nm scale.
2. With inculcation of portlandite rich hydrated lime better reactivity is resulted from FT-IR studies, a new peak formation in range of 1427–1444 cm − 1 suggests the occurance of calcite which is in inverse relation with the amount of carbon detected in EDS studies suggests the possible consumption lime and reactivity with clay compounds that helped in strengthening of microstructure of expansive clays.
3. Geoenvironmental concern of disposing bagasse ash is solved through proportionate addition to expansive clays with lime to minimise shrinkage is examined through agglomerated particles at SEM images and change in quartz peak with each mix through XRD studies.
4. Ease of measuring cracked patterns of fractographic soil pat through imaging techniques using tools such as python and image J implied accuracy and adoptability over error prone manual and mercury displacement methods. Annotating the coordinates of minute cracks through the tool and assimilation of volumetric shrinkage characteristics through numPy has considerate applications in shrinkage studies.
5. The threshold values of lime and bagasse ash were found to be 5% and 15% respectively. This proposed combination of optimum percentage of lime to the black cotton soil is proved to be beneficial in enhancing the engineering characteristics of the black cotton soil rather than utilization of bagasse ash alone in the stabilization of black cotton soil. Furthermore, this study also reduces the burden on sugarcane industries in disposal of bagasse ash and so it provides a sustainable and cost-effective solution for stabilization of black cotton soils.

Declarations

Data Availability Statement

All data, models, and code generated or used during the study appear in the submitted article.

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Tables

Table 1. Properties of black cotton soil

Properties	Value
Specific gravity	2.6
Liquid limit (%)	77
Plastic limit (%)	33
Plasticity index (%)	44
Shrinkage limit (%)	13
OMC (%)	24
Maximum Dry Unit Weight (kN/m^3)	18.02
Unconfined Compressive Strength (kN/m^2)	85.38
Free Swell Index (%)	130

Table 2. Chemical composition of lime

Chemical composition	(%)
Silica (SiO_2)	1.6
Calcium hydroxide (CaOH)	91.8
Calcium carbonate ($CaCO_3$)	1.7
Magnesium oxide (MgO)	0.4
Aluminium oxide (Al_20_3)	0.3
Ferric oxide (Fe_20_3)	0.3
Sulphur trioxide (SO_3)	0.4

Table 3. Elemental composition of expansive soil and bagasse ash test results

Minerals	Black cotton soil (%)	Bagasse ash (%)
SiO_2	56.00	50.69
Al_2O_3	19.00	13.56
Fe_2O_3	7.8	11.78
TiO_2	0.21	-
K_2O_3	1.48	0.49
Na_2O	5.2	3.06
MgO	2.63	4.24
CaO	3.28	10.57
SO_3	-	0.04
Cl^-	-	0.18
LOI	10.4	4.41

Table 4.Elemental composition of black cotton soil & bagasse ash blends without addition of lime

Mix	C	O	Mg	Al	Si	Fe	k	Ca
5BA	52.36	33.74	0.45	2.00	5.99	5.46	-	-
10BA	58.15	34.42	0.40	1.62	5.41	-	-	-
15BA	20.18	43.25	1.36	4.74	18.01	10.16	1.30	1.00
20BA	48.55	34.88	0.60	2.31	8.95	4.13	0.57	-

Table 5. Elemental composition of black cotton soil & bagasse ash blends with addition of lime

Mix	C	O	Mg	Al	Si	Fe	k	Ca	Na/Zn
L+5BA	19.22	43.90	1.05	4.71	14.62	10.85	0.95	4.16	0.55 Na
L+10BA	41.61	35.74	0.78	3.00	8.83	5.67	0.82	2.91	0.63 Zn
L+15BA	38.64	36.76	0.93	3.21	9.51	7.34	1.14	2.49	-
L+20BA	25.01	43.14	0.98	3.86	14.23	6.89	1.19	4.71	-

Table 6. Study on Lime and clay mixtures for volume reductions

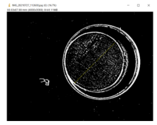
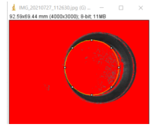
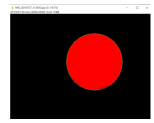
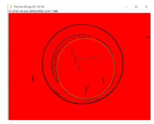
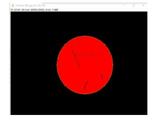
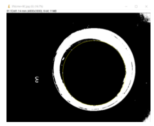
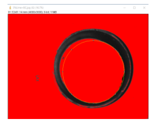
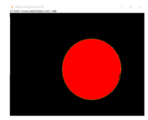
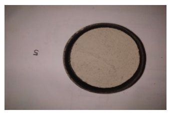
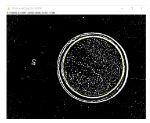
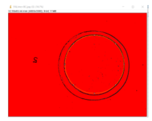
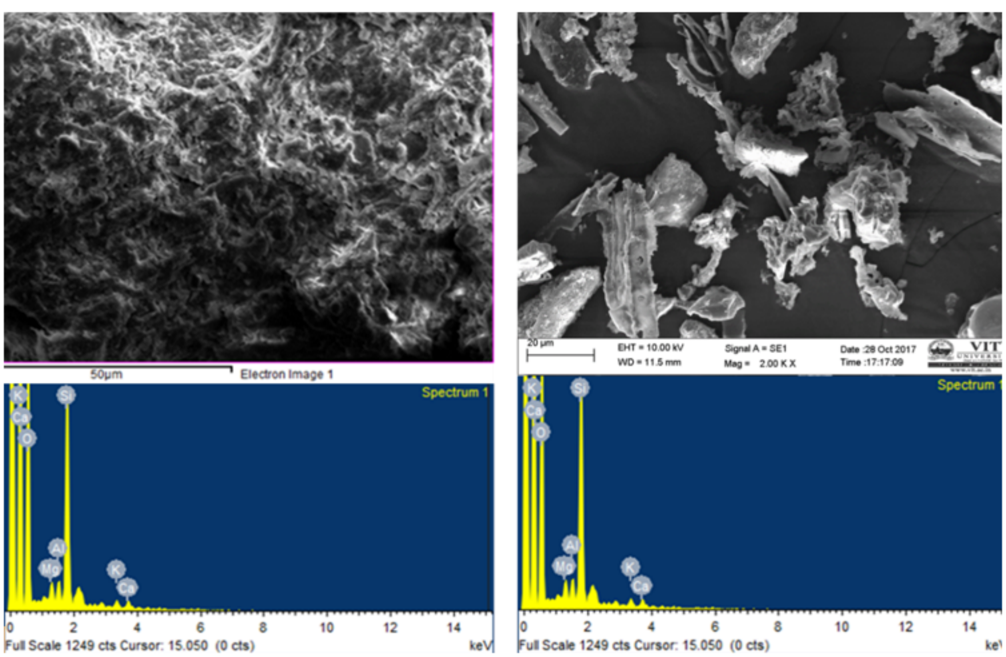
Mix	Raw Image	Binary Image	Thresholded Image	Extrusion of soil pat from Image
BC Soil				
1%Lime+ Clay				
3%Lime+ Clay				
5%Lime+ Clay				

Table 7. Comparison of volumetric shrinkage strains

Proportion of lime	Sample	Manual Measurements	Digital Measurements	Variation
0	clay	55.19	50.09	5.1
1	1%Lime +BC	58.61	53.26	5.35
3	3%Lime+BC	51.41	37.99	13.42
5	5%Lime+BC	43.6	26.59	17.01

Figures



(a) (b)

Figure 1

SEM images of (a) Raw Black Cotton soil and (b) Bagasse Ash

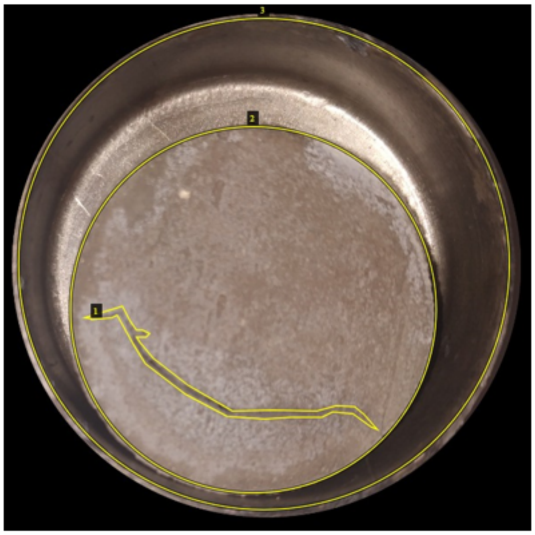


Figure 2

Segmentation of areas of shrinkage dish, crack and soil pat by VGG tool

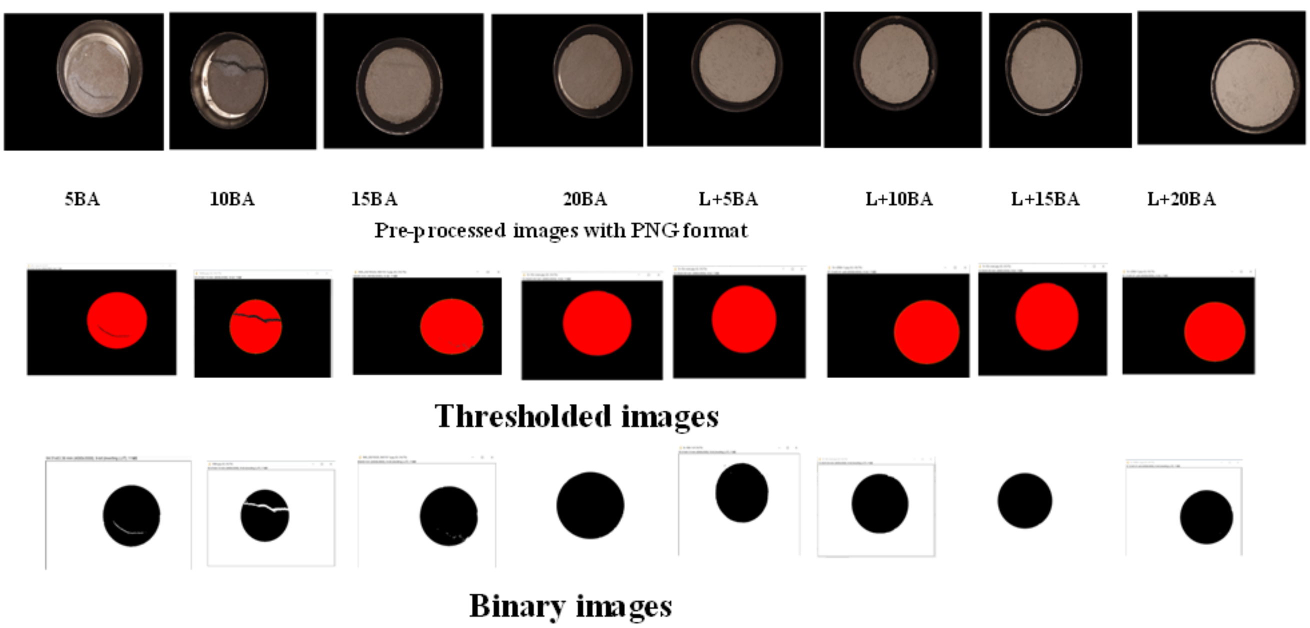


Figure 3

Image processing of specimens with different blends for shrinkage parameters

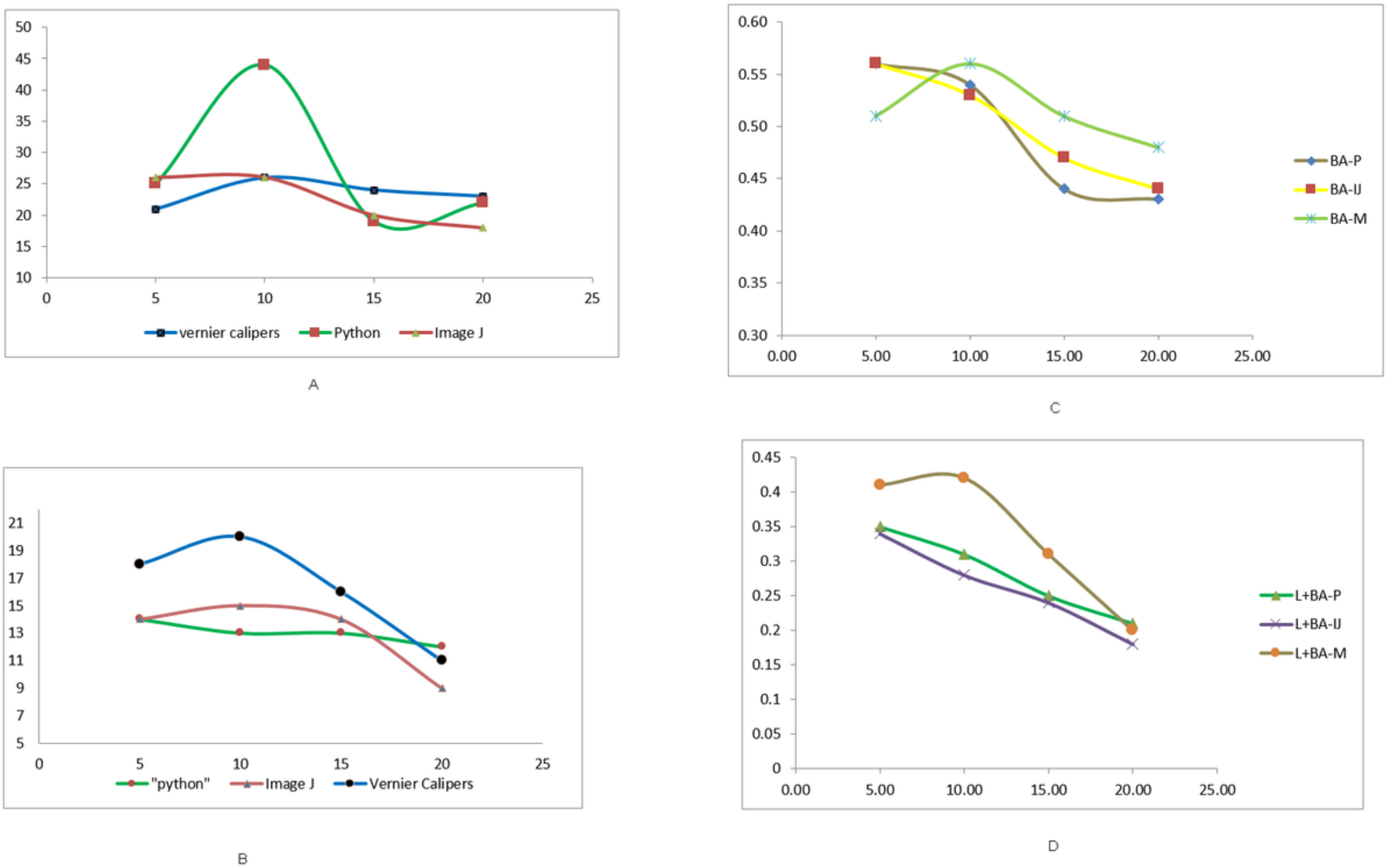


Figure 4

(a). Variation in linear shrinkage of BA mixes with different measuring techniques (b). Variation in linear shrinkage of Lime blended BA mixes with different measuring techniques (c): Variation of volumetric shrinkage strains of BA with clay using Python, image J and Mercury displacement method (d): Variation of volumetric shrinkage strains of lime blended clay with BA using image J and Mercury displacement method

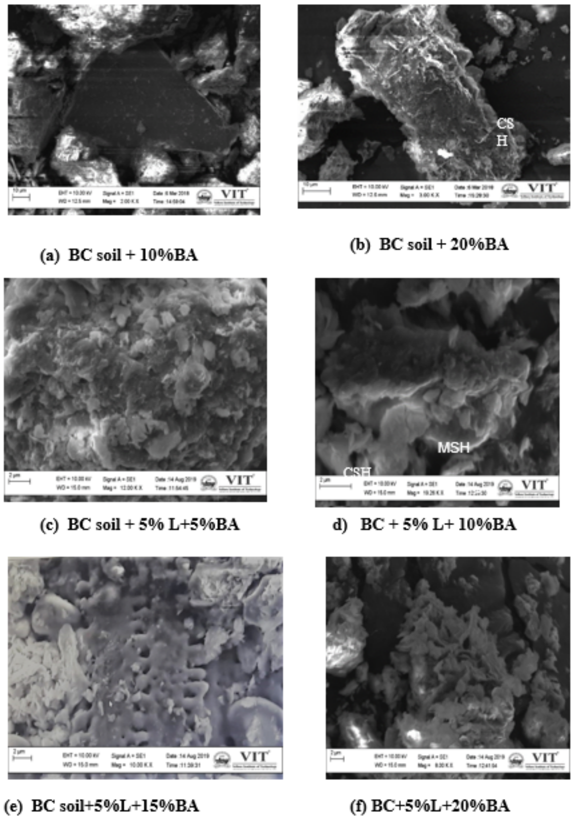


Figure 5

SEM images of the black cotton (BC) soil for different bagasse ash (BA) content and lime (L) content

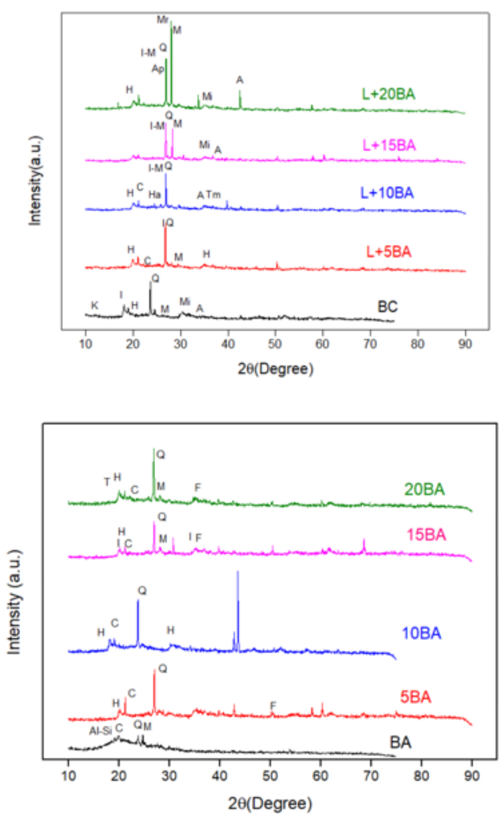


Figure 6

Mineralogical characterisation of BA and Lime blended mixes by X-Ray Diffraction analysis

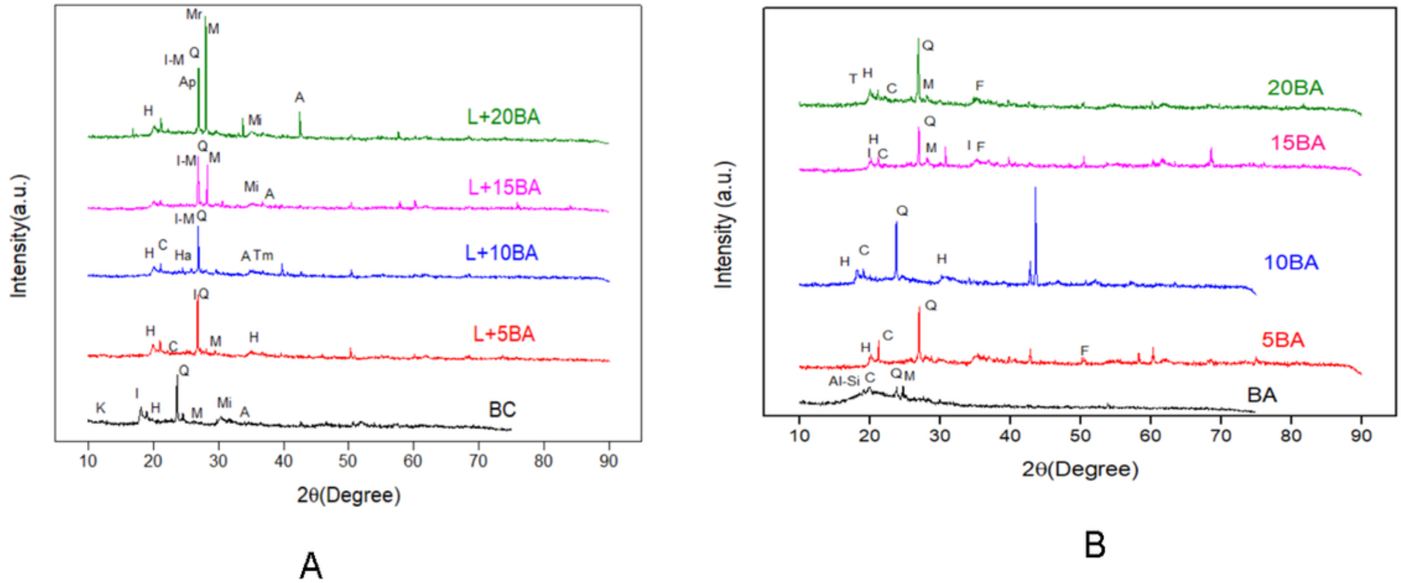


Figure 7

(a). X-Ray Diffraction analysis for mineralogical characterisation of BC soil blended with different percentages of BA (b). Mineralogical characterisation of BA and Lime blended mixes by X-Ray Diffraction analysis

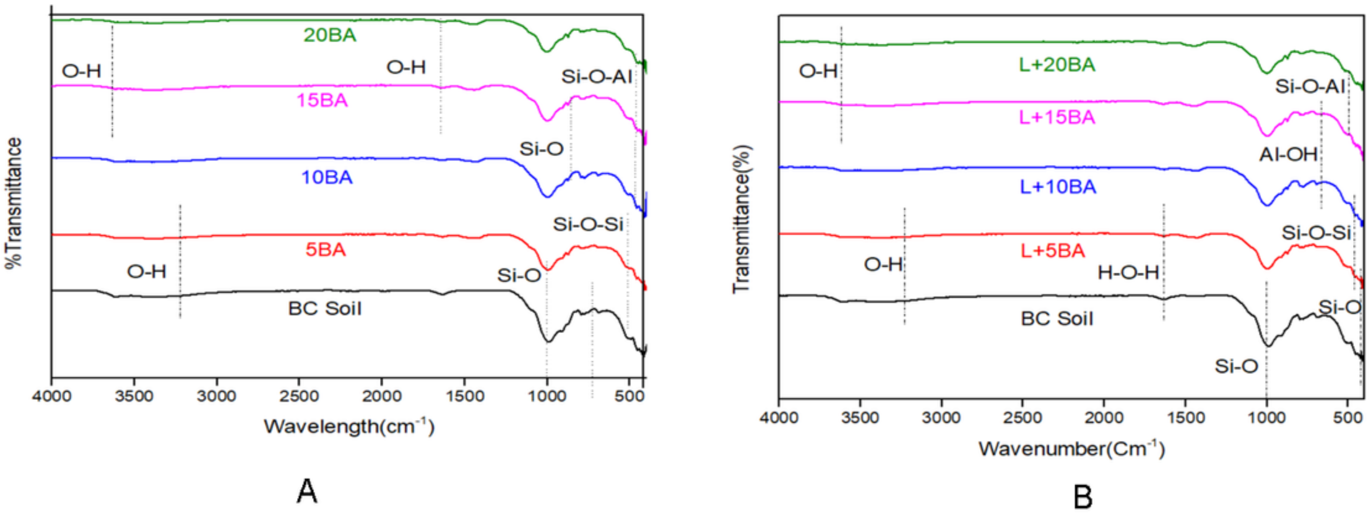
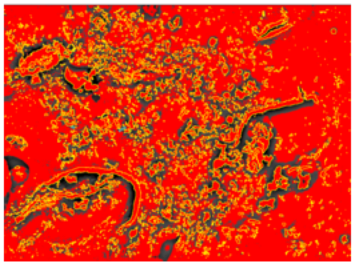
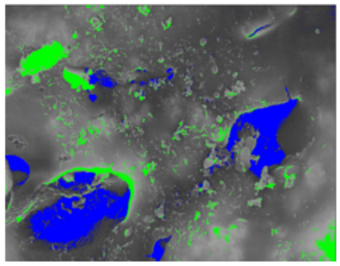


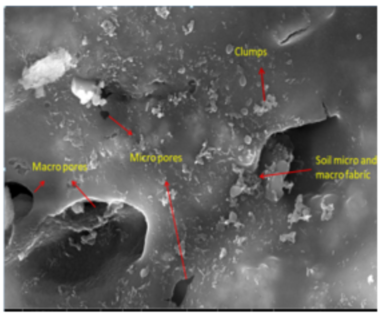
Figure 8

(a) Fourier Transform Infrared spectroscopy (FTIR) of lime treated clay with bagasse ash (b). Fourier Transform Infrared spectroscopy (FTIR) of lime treated clay with bagasse ash





9 (a) 9 (b)

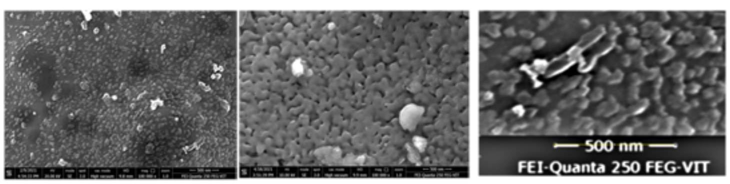


9 (c)

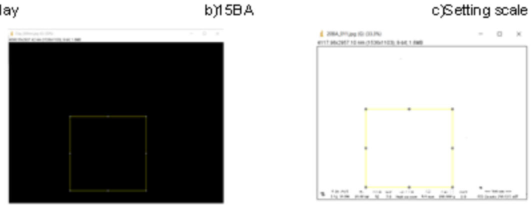
a)Adhesion of clay particles b)Voids in clay particle (blue)
c) Clay matrix forming honeycombs (Yellow)

Figure 9

Validation of clay matrix with voids through FE-SEM images



a)Clay b)15BA c)Setting scale



d)100% area with Black pixels of intensity 0 e) 0% area with white pixels of intensity 255

f) Clay particle matrix (68%pore space) g)15BA(28%pore space)

Figure 10

Representation of void reduction due to pozzolanic activity of bagasse ash

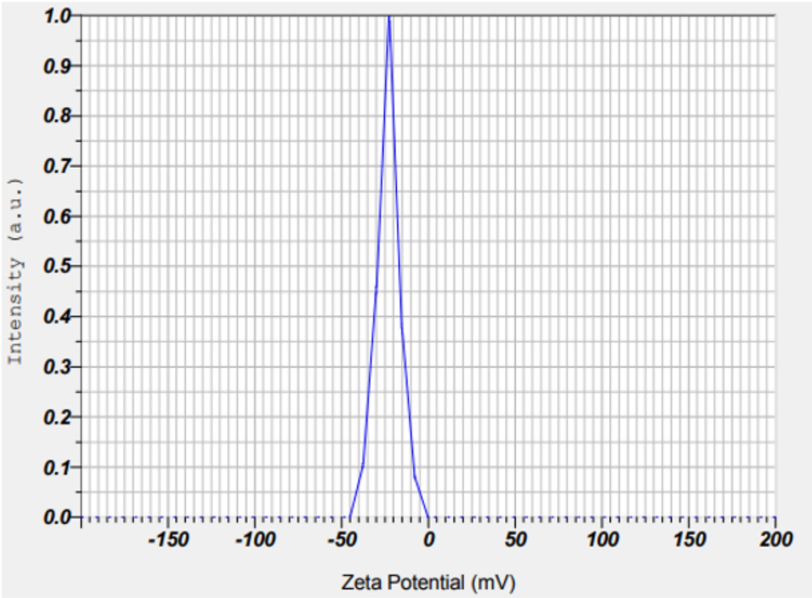


Figure 11

Zetapotential of clay particle indicating its stability and reactivity