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Research article

Dimensionnal stability and strength appraisal of termite hill soil stabilisation using hybrid bio-waste and cement for eco-friendly housing

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ABSTRACT

Dimensional stability and compressive strength are key factors to consider when modelling earth-based materials. It defines the volumetric performance of earth-based materials upon wet and dry environment. Meanwhile, the deformation under compression loading is accessed with the compressive strength testing. This study is aimed to use locally available materials considered as waste to model sustainable construction materials through soil stabilisation technique. The utilization of biowaste in this study is aimed to reduce the amount of waste produced in the agricultural sector in addition to the promotion of this material locally in the construction field. Cement was used as stabilizer to establish the performances of the waste-based stabilizer when mixed with conventional stabilizer or partnerless. Borassus fruit ash and cement were used both in solo, and hybrid mix (5wt%, 10wt%) to stabilize termite mound soil in the mix design. The mix design was analyzed microstructurally with scanning electron microscopy (SEM)-energy dispersive spectroscopy (EDS) to understand the effect of each stabilizer on the microstructural level. Fourier transform infra-red (FTIR) was conducted to identify the functional group present in each mix design to establish the influence of both stabilisers on the bonding mechanism. The mix design was also tested for water sensitivity, linear shrinkage, and compressive strength. From the results, samples containing 10wt% hybrid borassus fruit ash/cement exhibited higher content of Silicon, Aluminum, and Iron consequently satisfactory compressive strength. For hybrid stabilisation of earth-based materials, preference is given to 10wt% stabilisation level. The results of this study are analyzed to reduce the footprint of agricultural waste and to model locally available materials into sustainable housing materials.

1. Introduction

Engineering locally available through sustainable technologies in construction is considered as one of the major strategies to support green materials' development and lower the energy consumption rate in construction (from the raw material processing until the buildings' life service). Among the locally available materials, earth-based materials have been intensively used because of their various properties. Earth based materials have shown low thermal conductivity [1], no carbon emission [2] from their processing until their life-service. Thus, they are attractive "green" alternatives to conventional building materials to address the environmental [3] problems related to the greenhouse emission. However, durability, strength and hygroscopicity constitute the main drawbacks to their utilization [4]. On that account, earth-based materials were ignored in the construction field during the previous decades in most regions. However, the "green" concept has become the center of interest in the construction field ascribed to environmental concerns. These environmental concerns are related with the manufacturing of conventional building materials (CO_2 emission, high energy consumption, raw materials depletion, etc.) [5] resulting in very expensive and detrimental materials. The conventional construction materials are not accessible and affordable in some eroded regions [6] (some sub-Saharan African countries). Consequently, these precited problems motivate to consider/promote the development of eco-friendly materials. Earth-based construction has been used empirically. However, it's necessary to develop technologies [7] to transform earth-based materials into strong and durable construction materials [8] and search for alternatives materials to serve as binder [9, 10]. The alternatives are preferably industrial [11] or agro-waste [12] materials, as their disposal constitutes a considerable factor in the ecosystem's stability [13]. According to the World Bank's

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report, about 2.01 billion tons of solid waste are generated worldwide in 2016 and this is expected to increase by 70% in 2050 [14]. Many schemes have been drawn to manage agricultural waste, but these strategies were proven inadequate due to the lack of data related to the nature/-characteristics of the agricultural waste. One of the beneficial schemes is to transform and utilize the agricultural waste as construction material. Henceforth, a number of studies have been conducted on the utilization of agricultural waste as stabilizer [11, 12, 15]. Agricultural waste is the residue or undesirable outcome generated from the cultivation and processing of raw agricultural products such as crops, fruits, etc. [16]. Borassus fruit is an agricultural product which is abundantly available (In Africa and Asia [17]) but considered as waste in sub-Saharan Africa as the leave and trunk are the only part used traditionally. Borassus tree is a palm specie that withstands conditions in dry, low precipitations and moist climates with high potential grow rate, fast renewability and sustainability [18]). The palm oil industry produces important amount of waste. The total amount of fresh fruit produces 20% of nutshell (waste), plus 30% of fibers and empty bunches [19]. Tay et al. used palm oil fuel ash (POFA) in concrete production. They reported that the POFA was mainly composed of high amorphous silicon dioxide (SiO_2) [19].

On the other hand, rice is one of the major food crops worldwide. The rice husk is non-edible and when landfilled it creates environmental problems [20]. Studies carried by Chandra Paul have shown that the rice husk ash (RHA) contains 90–96% amorphous silica (SiO_2) thus it constitutes a good alternative binder [12]. Other studies explored the use of sugarcane bagasse ash (SCBA). It was recorded that planted sugarcane produces 52% of solid waste [21]. It was also reported that the inclusion of SCBA has a positive effect on concrete durability [3].

Other studies explored the use of bamboo leaf ash (BLA) [22], it was reported that the mechanical properties of the concrete reduced with the addition of BLA while the durability have considerably improved [23]. Investigations carried by Shazim et al. used corn cob ash blended with cement as an eco-friendly option [24]. Moreover, the results reported from various studies have proven that the soil's properties (variable in each study) have improved upon stabilisation. The problems faced by soil without stabilisation, among many, are insufficient strength to support the loads imposed on it in construction or during the service life for the various applications for which they have been designed and low volumetric stability. As defined by the ASTM, soil stabilisation is a technique to improve soil's strength and permeability to increase its load-bearing capacity [25].

It's noteworthy to recall that soil stabilization primarily depends on chemical reaction between stabilizer (cementitious material) and soil minerals [15]. Additionally, soil stabilisation is a technique that requires low energy and less time during manufacturing.

As per author's knowledge, comprehensive and fastidious studies have not been carried on the use of borassus fruit ash (BFA) in soil stabilisation as construction materials. Therefore, this study was carried out to appraise the effect of the BFA on the dimensional stability of termite hill soil. To attain that objective, the BFA was used as stabilizer alone and mixed with cement to understand clearly and compare its binding mechanism.

1.1. Statement of originality

This study constitutes one of the pioneer investigations to examine and corelate the microstructure and dimensional stability of termite mound soil with hybrid stabilizers, to transform borassus fruit from biowaste into opulent construction materials with eco-friendly matrice. It also uses simple and sustainable manufacturing technology to promote the use of these unconventional building materials in least developed regions.

2. Materials

2.1. Termite hill soil

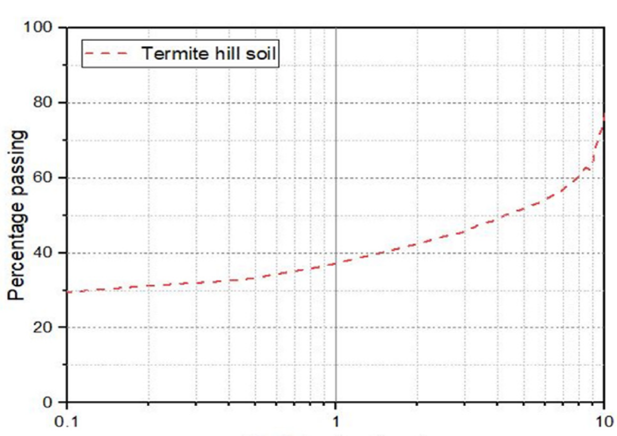
The processing of the termite hill's soil and the results of its Atterberg limits, particle size distribution, moisture content, density are presented in Figure 1. Meanwhile its chemical composition is reported elsewhere [6].

2.2. Borassus fruit ash

In the ash's obtention sequence, the shell of ripened borassus fruits was removed, sun dried and burned in open air until calcination before grinding the product into powder form as seen in Figure 2. The dark color of the borassus ash represents more unburnt carbon, as the whitish color indicates removal of unwanted fixed carbon [26] in this study the ash was used in its dark color state to optimize the reaction of the unburnt carbon with the soil's components. The ash was sieved in order to remove the organic and uncombusted matter.

2.3. Cement

Ordinary Portland Cement (OPC) was used in this investigation to serve as hydraulic binder in the bio-composite. The OPC is used as first stabilizer because it's a conventional material that is widely used, its effects as a stabilizer were examined alone, then mixed with the BFA. Although there is no published literature related to the usage of BFA as stabilizer, the BFA is used as the second stabilizer. It has been used alone, afterwards mixed with the OPC. The main purpose of using OPC as stabilizer is to serve as reference. The OPC used in this study was produced by Dangote limestone cement. It is the type I for general construction



Termite hill soil physical properties

- **Atterberg Limits:**
  Liquid Limit (35.2%)
  Plastic Limit (22.5%)
- **Moisture content 3.0%**
- **Specific gravity 2,60**
- **Density 0.385 g/cm^3**

Figure 1. Physical characteristics of the termite hill soil.

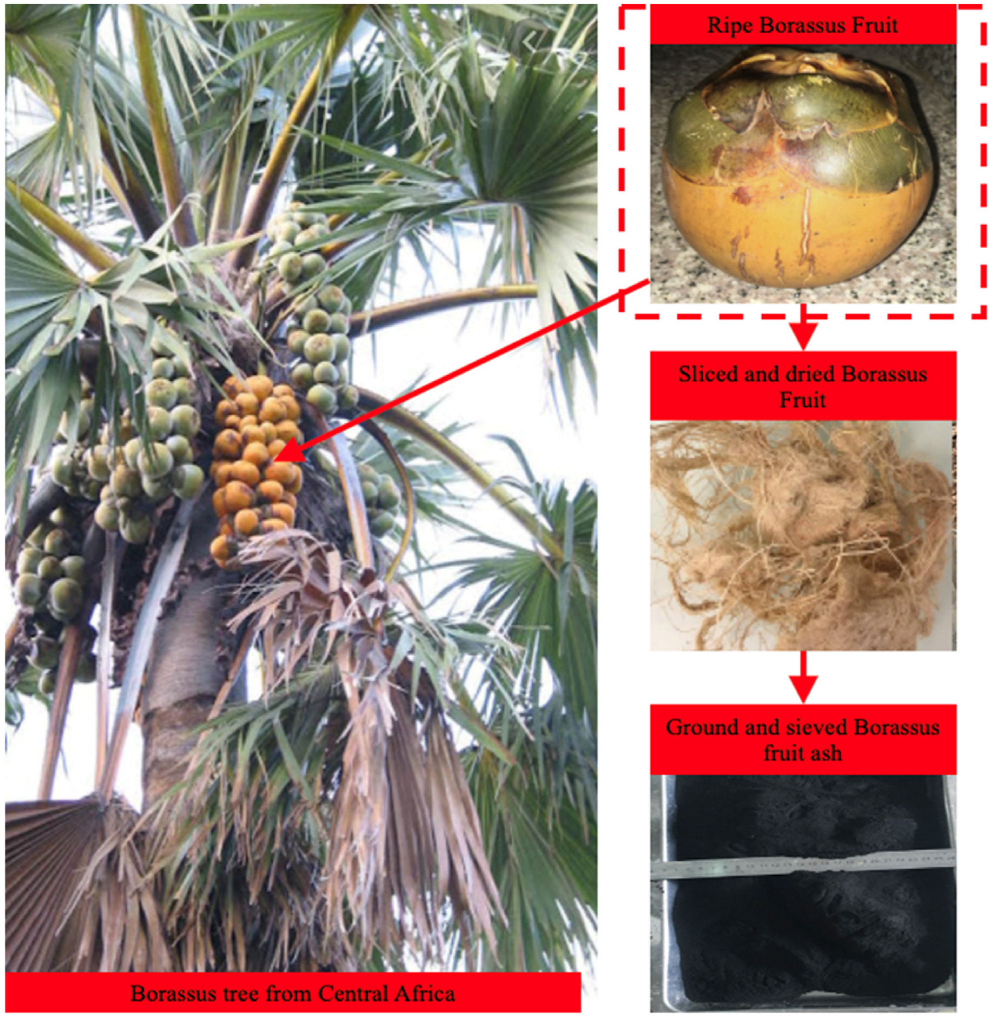


Figure 2. Different steps in the borassus fruit ash obtention.

purposes with 75wt% of calcium silicate minerals and particles sizes of 80 μm according to the supplier.

2.4. Bricks manufacturing

During the manufacturing, metallic moulds of 50 mm × 50 mm x 50 mm were used for the compressive testing according with EN 206 [27]. In the manufacturing sequence, the different materials were mixed based on the different stabilisation level as shown in Table 1. The stabilisation level of the cement was conducted based on previous work [15] as the effective cement stabilisation was reported to be less than 15%. Subsequently, in this study the maximum concentration of cement used is 10wt% likewise the concentration of the BFA.

Each formulation was mixed in a laboratory mixer at high speed for 5 min before addition of the required quantity of distilled water (10wt%). The quantity of water was constant to examine the cementitious reactions induced by each stabiliser. The pastes were transferred into metallic moulds and were oven-dried at 60 °C for 24 h prior to demoulding. After demoulding, the samples, were left in the laboratory environment (see Figure 3) at room temperature (27 °C) for the curing periods of 7, 14 and 28 days prior to water sensitivity and mechanical testing. Room temperature curing method has previously displayed higher compressive strength compared to oven-curing and sun-drying methods [8].

Table 1. Details of the sample preparation at different stabilisation level with the various materials composition.

Samples designation/ Composition	5BFA	5C	5BAFC	10BFA	10C	10BAFC
Borassus Ash (BFA)	5wt%	0wt%	5wt%	10wt%	0wt%	10wt%
Cement (C)	0wt%	5wt%	5wt%	0wt%	10wt%	10wt%
Termite Soil (TS)	95wt%	95wt%	90wt%	90wt%	90wt%	80wt%

3. Methods

3.1. Microstructural characterizations

Examination of the microstructure for all the samples was accomplished to understand the bonding mechanism and correlate the microstructure to the bulk behavior. Hence, the morphology, chemical component and existing bonds were examined through scanning electron microscope (SEM)-energy dispersive spectroscopy (EDS) and Fourier transform infra-red (FTIR) respectively. Those characterizations have been proceeded on a Thermo Scientific Nicolet iS5 FTIR system (Thermo Scientific Nicolet, Worcester, MS, USA), Carl Zeiss Model EVO LS10 (Carl Zeiss, Pleasanton, CA, USA) for the FTIR and SEM-EDX respectively as reported elsewhere [6]. All the microstructural observations were carried out on the mechanically tested samples at 28 days.

3.2. Dimensional stability analysis

To analyze the dimensional stability, the samples were tested in a wet and dry environment via water absorption and linear shrinkage analyses

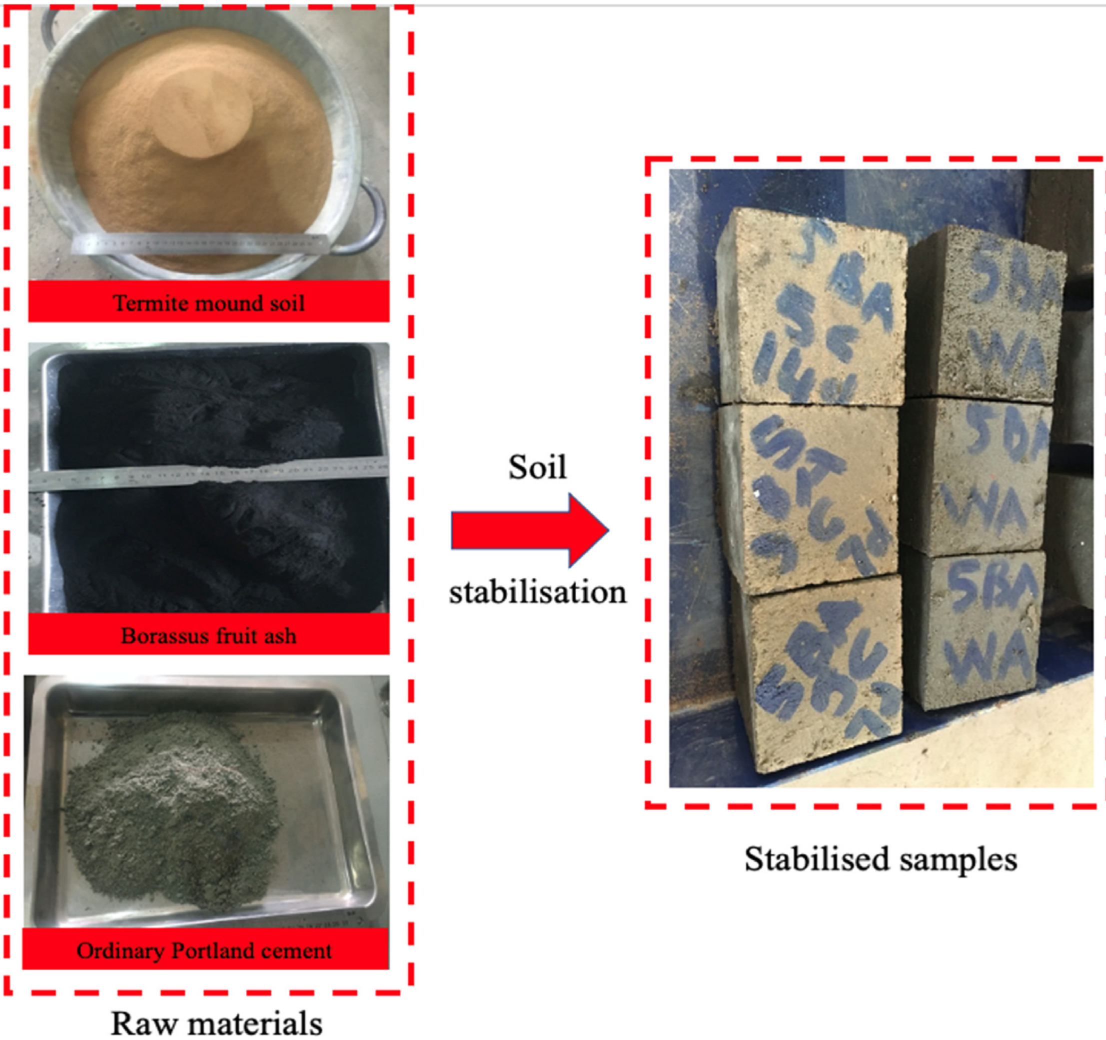


Figure 3. Manufacturing process of the mix design.

respectively. The water absorption analyze was carried out as described in Malkhanti's work [28]. The water sensitivity analysis was evaluated to ascertain the dimensional stability of the wet samples. The linear shrinkage was conducted in accordance with BS [29]. During the linear shrinkage analysis 10 mm × 50 mm x 20 mm samples were produced with three replicates per composition. The samples were air dried in the laboratory environment for 4 days at 25 °C to avoid the effects of heat on the bonding mechanism. At the 4th day the samples didn't display any change in length until day 7. Hence the analysis was carried when the constant length was noticed. The thickness and length of each sample was measured after 7 days using a vernier calipers to calculate the linear shrinkage as described in the BS (the authors have chosen the BS over other standard for accessibility reasons only), Eq. (1) was used for this purpose.

$$Ls = 1 - \frac{\textit{Length of dry sample}}{\textit{sample's initial length}} \tag{1}$$

The test was used to evaluate the effects of water evaporation on the dimensional integrity of the samples.

3.3. Mechanical characterization

The compressive deformation for all the samples was determined in accordance to EN 206 [27]. The compressive deformation constitutes a major factor in the utilization of earth-based materials in construction as those unconventional materials are preferably used in wall partitions or non-load bearing units hence likely subjected to compression loadings. The compressive testing was carried out on the samples cured at room temperature for (27 °C) for 7, 14 and 28 days. The samples were loaded in an electromechanical testing machine UTM7001 Model 4002 (Utest,

Figure 4. Samples at various stabilizations level with the different stabilisers.

Ankara, Turkey) at a loading rate of 1.2 kN/s. A Vernier calipers was used to measure the actual dimensions of the samples prior to the mechanical testing and Eq. (2) was used to determine the compressive strength:

$$\sigma = \frac{F}{Ao} \tag{2}$$

where σ is the compressive strength in megapascal (MPa), F is the force at the onset of failure in newton (N) and A_0 is the initial cross-sectional area in millimetre square (mm^2).

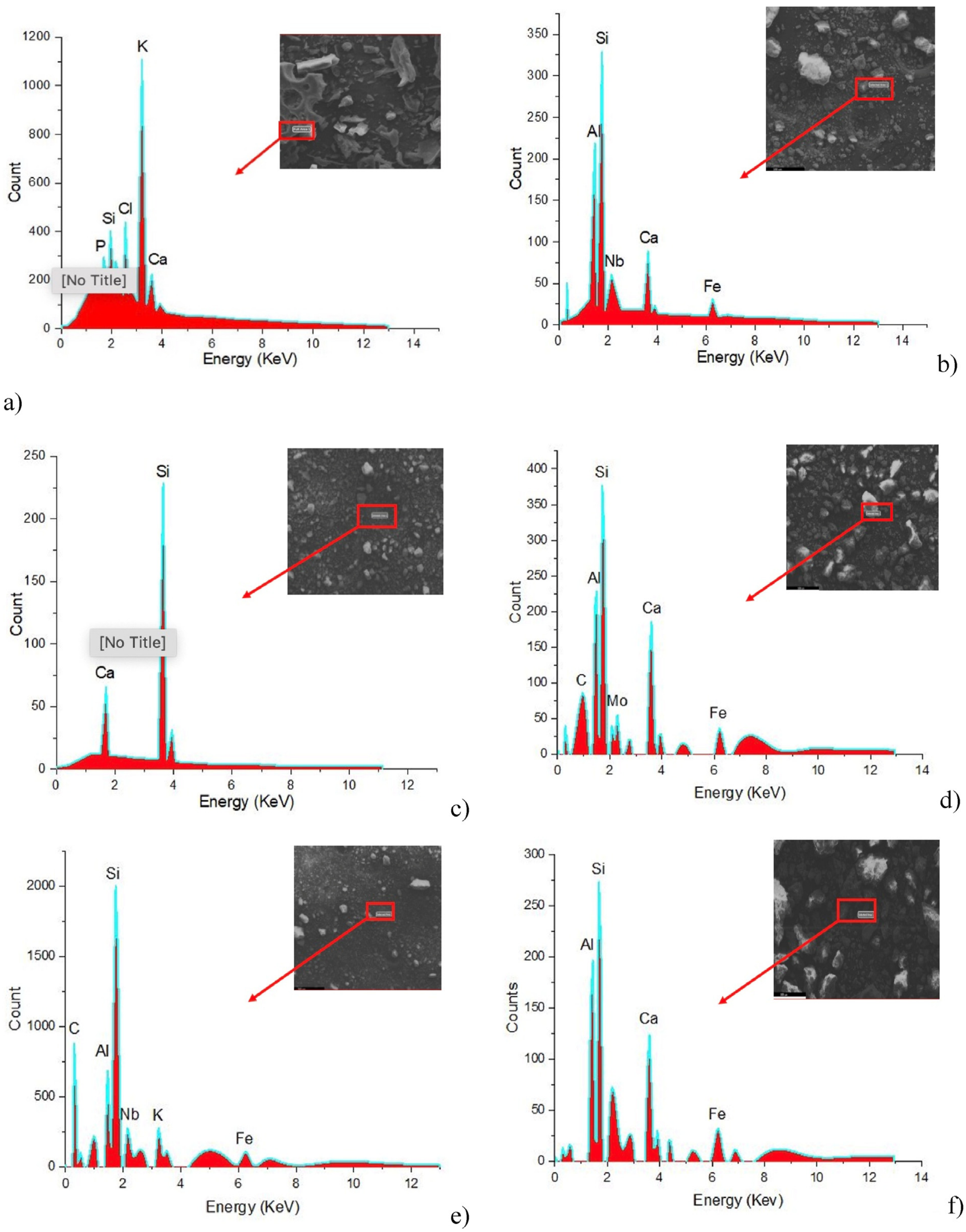


Figure 5. EDX with the SEM graphs of samples stabilized at: a) 5wt% BFA, b) 5wt% BFA-cement, c) 5 wt% cement, d) 10wt% cement, e) 10 wt% hybrid BFA and f) 10wt% hybrid BFA/cement.

4. Results

4.1. Effects of stabilizers on the physical properties

The macrostructural observation was carried out after demoulding of the oven-dried samples. The samples didn't display any significant expansion or shrinkage after extrusion from the moulds (Figure 4). The dried samples didn't exhibit noticeable cracks. The difference in coloration was noticeable based on the nature of stabilisers used: samples containing BFA alone displayed darker coloration compared to the samples containing hybrid BFA/cement and cement alone. This is attributed to the blackish color of the BFA. Macroscopically, the curing period has no effect on the samples as their morphology was intact after 7, 14 and 28 days of curing period.

4.2. Elemental variation over stabilizations level

The elemental analysis results obtained from the EDX is shown in Figure 5 and Table 2. The results show that the elemental composition of the samples differed at all the stabilisation level. The elemental variation was analyzed in terms of Silicon, Aluminum and Iron content as their component govern the pozzolanic activity of the stabilisers. The samples stabilized with 10wt% hybrid BFA/cement exhibited the highest Silicon, Aluminum, and Iron (Si + Al + Fe) content.

4.3. Morphological variation

Figure 6 shows the results of the SEM characterizations. The morphology of all the samples was nearly similar with very slight difference in terms of smoothness, grain size and pores content. The samples stabilized at 5wt% BFA, 5wt% cement and 5wt% hybrid BFA-cement demonstrated the same morphology. Similar feature was noticed at 10wt% stabilisation, both stabilisers and hybrid demonstrated the same morphology at 10wt%. Henceforth, the morphological analysis is conducted based on the stabilisation level (5 and 10wt%). The BFA exhibited a very porous surface as seen in Figure 6a. Figure 6b. It presented minuscule flake-shaped and prismatic particles, while the termite mound soil's grains had different shapes from spherical to irregular. The products resulting from the hydration process were also perceived in Figure 6c.

4.4. Bonding groups analysis

Figure 7 reveals the FTIR micrographs in which the existence of the different group is displayed. Around 3445 and 1650 cm^{-1} vibrations of bound water molecules assigned to the stretching (–OH) and bending (H–O–H) respectively were noticed in all the samples with a slight shift in the peak. The peaks displacement of the water molecules group was significant at 10wt% hybrid BFA/cement stabilisation level, these peaks are characteristics of the hydration products formation. Peaks around 537 cm^{-1} are characterized by the ring vibrations of Si–O bonds of silicate network. This network was noticed in all the samples with a variation in the intensity. Around 1030 cm^{-1} peaks characterizing the vibration of SiO/Al–O bond were displayed reflecting the generation of amorphous products.

Table 2. EDX graphs demonstrating the elemental variation of the samples under the different stabilisers used.

Elements	Different stabilisation level						
	BFA	5 BFA	10 BFA	5 C	10 C	5BFA- 5C	10BFA-10C
C	55.67	66.63	66.46	0.31	0.46	0.61	-
Al	13.32	-	3.93	-	16.98	18.91	17.82
Si	26.47	0.83	14.83	7.26	35.86	38.12	34.57
Ca	-	2.32	-	83.99	26.79	18.17	28.26
Fe	4.53	-	3.5	-	9.97	9.81	12.13
O	-	2.34	4.55	8.44	-	-	7.21
P	-	2.55	-	-	-	-	-
Mo	-	-	-	-	9.94	-	-
Nb	-	2.76	3.67	-	-	14.37	-
Cl	-	3.82	-	-	-	-	-
K	-	18.21	3.06	-	-	-	-
Ru	-	0.54	-	-	-	-	-

4.5. Effects of the stabilizers on the dimensional stability

The results obtained from the linear shrinkage and water absorption tests are shown in Figure 8. The results of the linear shrinkage in Figure 8a for the various samples show that the linear shrinkage varied

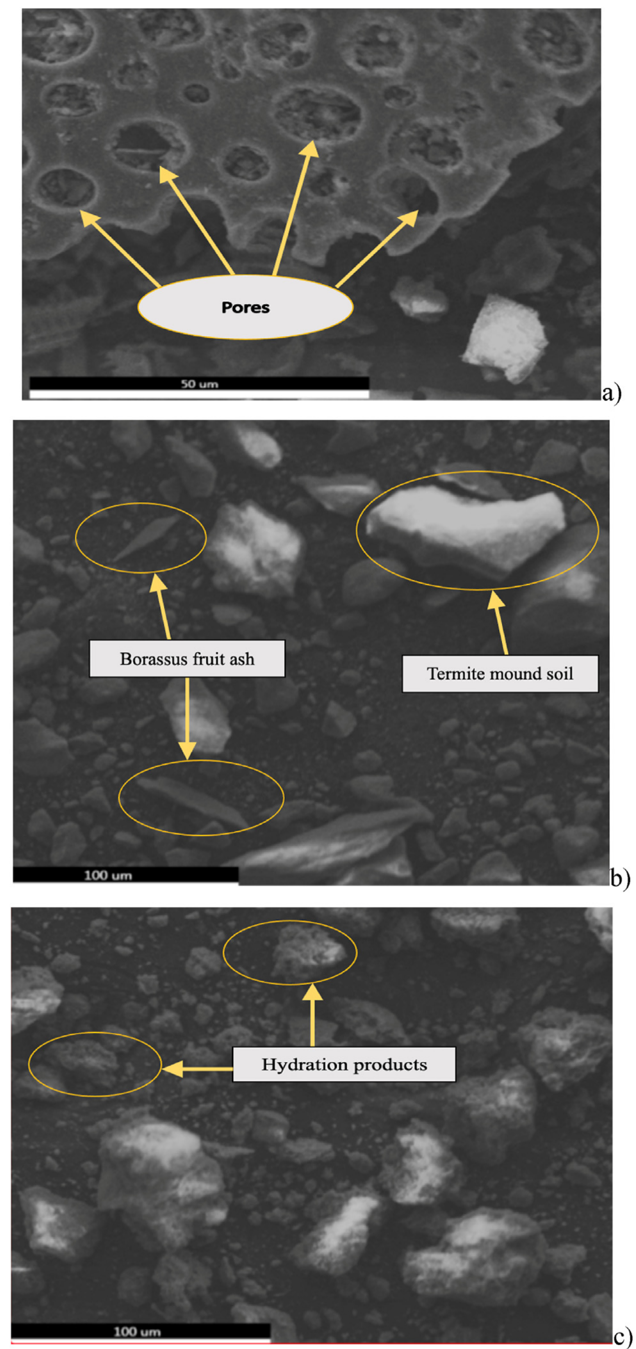


Figure 6. SEM micrographs of samples stabilized at: a) BFA, b) 5wt% hybrid BFA-cement and c) 10wt% hybrid BFA-cement.

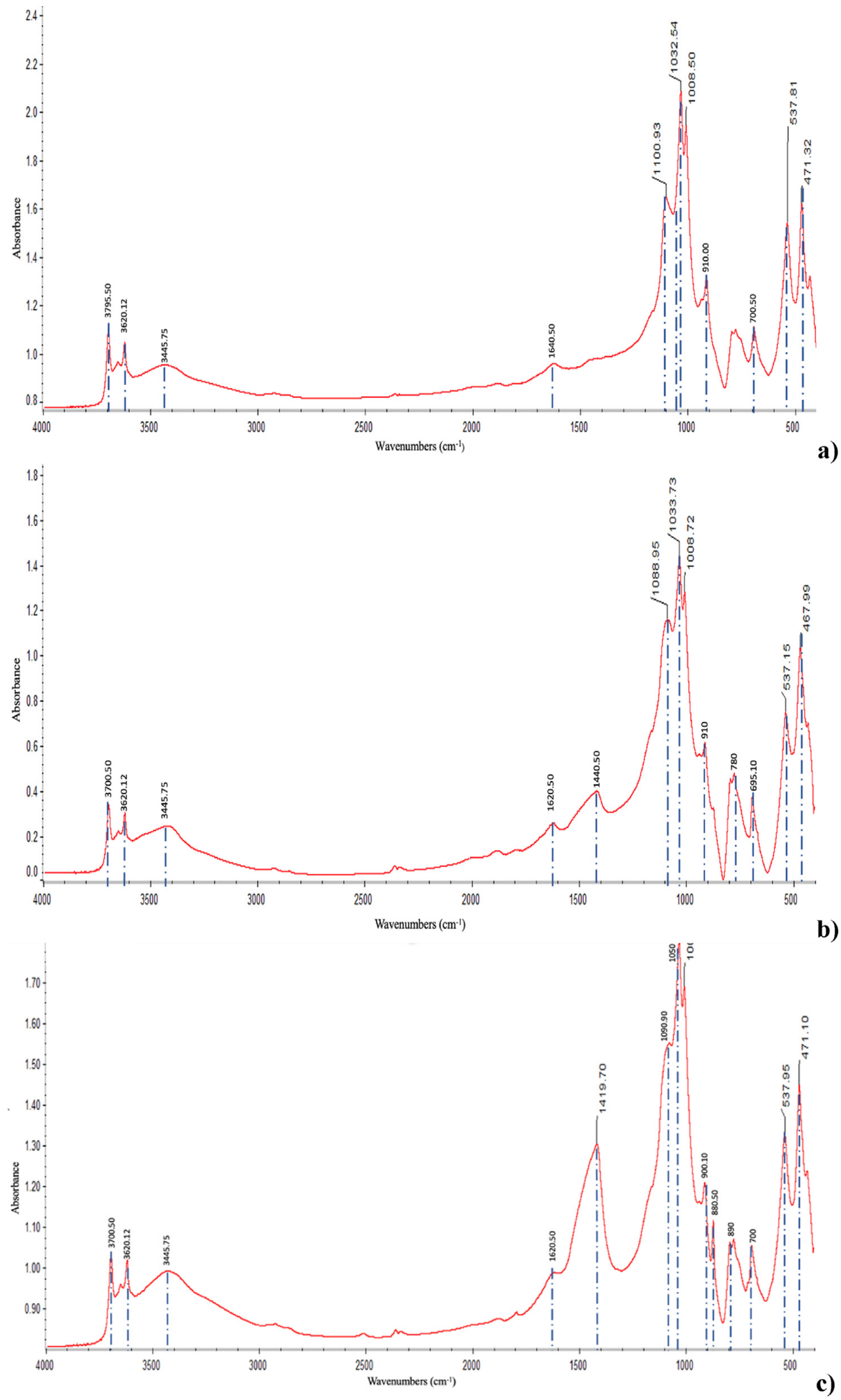


Figure 7. FTIR spectra of: a) 5-10BFA, b) 5–10 cement and c) 5–10 Hybrid BFA cement.

from 4.29% to 5% for the different samples. Samples containing 5wt% BFA, 5 and 10wt% cement exhibited all a linear shrinkage of 5% while the samples stabilized with 5wt% hybrid BFA-cement and 10wt% BFA displayed a linear shrinkage of 4.29%. Lastly samples stabilized with 10wt% hybrid BFA-cement displayed the highest linear shrinkage (5.71%).

The integrity of the samples in wet environment has shown (Figure 8b) that the samples containing only BFA displayed an average water absorption level of 17% when the ash was used at 5wt% while the absorption rate has increased proportionally with the ash content (the water absorption increased up to 19.04% when the samples were stabilized with 10wt% BFA). Moreover, the samples containing only

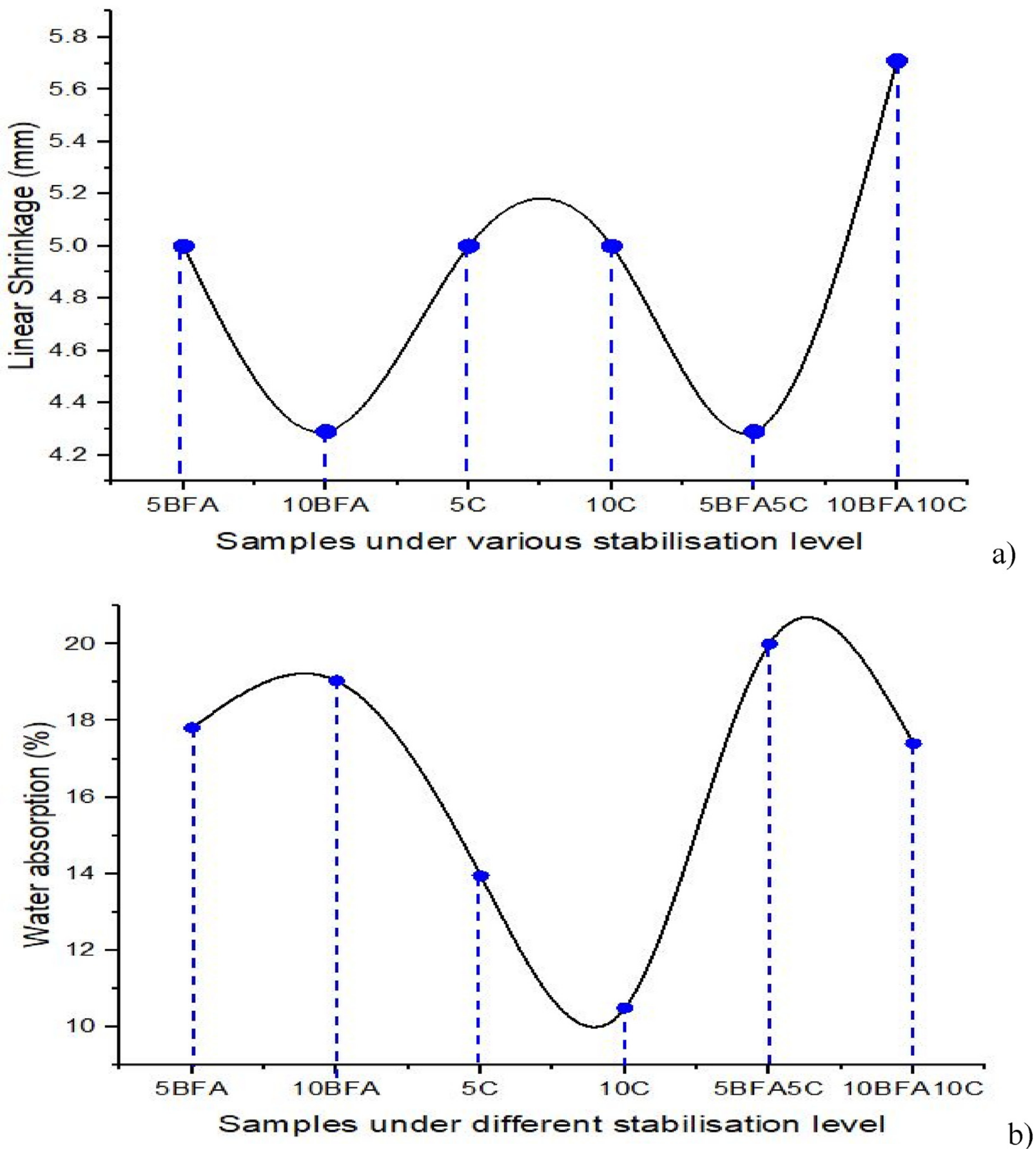


Figure 8. a) Linear shrinkage of the samples, b) water absorption of the various samples.

cement as stabilizer displayed lower water absorption rate of 13.4% and 10.5% for 5wt% and 10wt% cement respectively. However, a maximum absorption level of 20% was observed when the hybrid BFA/cement was used at 5wt% but this absorption level has decreased to 17.4% when the hybrid stabilisation level has increased up to 10wt%.

4.6. Performance under compression

Figure 9 presents the results of the compressive strength testing for the samples stabilized at different level. The compressive strength for the different samples varied with curing days. At 7 days samples containing 5wt% BFA, 10 wt% BFA, 5wt% cement and 10wt% cement had a compressive strength of 1.1, 1.2, 1.4 and 1MPa respectively. While, samples containing 5 and 10wt% hybrid BFA-cement displayed compressive strength of 1.8 and 2.4 MPa respectively. However, at 14 days samples containing 5wt% BFA, 10 wt% BFA, 5wt% cement and 10wt% cement exhibited compressive strength of 2.2, 1.8, 2.2 and 2.6 MPa respectively. Lastly, at 28 days samples containing 5wt% BFA, 10 wt % BFA, 5wt% cement and 10wt% cement displayed compressive strength of 3, 1.9, 1.1Mpa while for 5wt% of BFA, 10 wt% BFA and 5-10wt% cement respectively. That demonstrates the increase in compressive performance with curing days. During loading, the samples failed after formation of nearly vertical cracks initiated collaterally to the loading direction. However, the sides of the samples disintegrated first while the central sides remained sticked together confirming the plastic deformation mode in that region.

5. Discussions

The coloration of the ash obtained from the borassus fruit is indicative of the elements present in the material confirming results from previous work [26]. However, the presence of unburnt elements is evidenced by the presence of black particles [30]. Also, the samples' color variation is mainly due to the quantity of oxides apported by both stabilisers. The particles shape microstructurally analyzed in this study are confirming previous work carried by Obianyo et al in which they reported the presence of similar particles in palm bunch ash [31]. It's noteworthy to recall the similarity of the borassus and palm fruit as they are from the same botanic species.

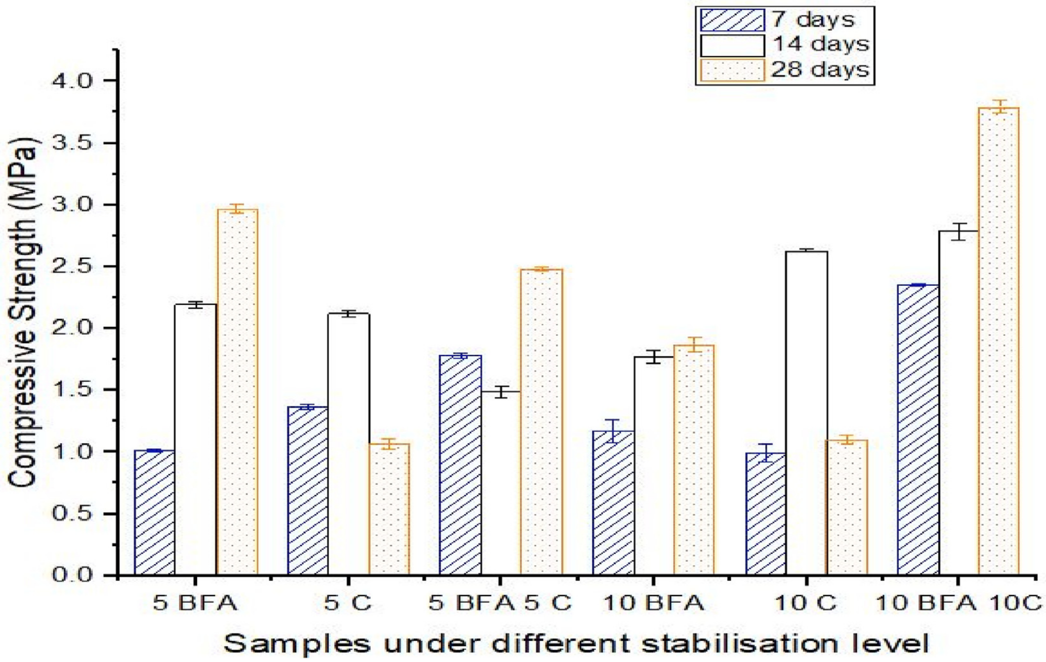


Figure 9. Compressive strength of the samples at the various stabilizations level with the different stabilisers.

The maximum water absorption was observed when the stabilisation level was 5wt% hybrid BFA/cement followed by the samples with 10wt% BFA. This trend can be explained by the induction of pores present in the BFA as seen from the morphological examination; the BFA displayed a very porous surface. In similar work, the average water absorption rate was much higher compared to the present work when coal ash stabilizer was used at 10wt% [32]. However, the observed water absorption in the present work is a function of particles size and cement content [33] as all the samples containing cement displayed lower water absorption rate than the samples without cement. The use of cement induces more pozzolanic reaction responsible for hydration and strengthening processes. These processes tend to densify [34] the samples making them more resistant to water exposure.

In the observed linear shrinkage trend, samples containing 5wt% hybrid BFA/cement exhibited the lowest linear shrinkage compared to the other samples. Meanwhile, the maximum linear shrinkage was observed for 10wt% hybrid BFA/cement. This confirms our EDX results where the highest pozzolanic content was observed at 10wt% hybrid BFA/cement. It was expected that the samples displaying higher water absorption rate would exhibit higher shrinkage. However, the results of the present study are conforming the findings of Ashour et al. [35]. They concluded that lower curing temperature affects positively the shrinkage. Nonetheless, the difference of the present results is probably due to the high porosity and particles size of the BFA. In Sangma's work they observed that the shrinkage increased with increasing in cement content which was at its maximum when the cement content was 10wt%. However, samples containing cement displayed higher shrinkage compared to fiber reinforced samples [36]. In the previous work the authors also elucidated the effect of temperature on the shrinkage. Shrinkage increases as the temperature increases however in the present work only one curing temperature was considered.

The maximum compressive strength was attained at 10wt% hybrid BFA/cement at all curing days. In the case of samples stabilized with only BFA, the compressive strength demonstrated a stable increase from the early curing days of 7 until 28. However, that is not the case of the samples stabilized with cement only. In these samples, the compressive strength increased in the early curing days and decreased in the late curing days. That can be interpreted by the lower hydration reaction rate during the late curing period. This is also displayed by the FTIR spectra in which broadening of peaks were observed when the samples are stabilized with cement only. In previous work where palm oil fuel ash was used, it was reported that the palm oil fuel ash slowed down the hydration process resulting in poor bonding between the particles present in the matrix [37]. Also, in the present study the compressive strength is confirming the EDX, linear shrinkage and water absorption results. As expected, the samples stabilized with hybrid stabilisers produced components that influence majorly the dimensional stability and compressive strength. These components resulted from the pozzolanic reaction taking place during the hydration reaction. Chen et al. demonstrated that the compressive strength of earth-based materials increases with curing age [38]. The samples which displayed lower compressive strength displayed poor bonding between the particles that can be caused by the porous BFA as evidenced by the peaks around 1420 cm^{-1} (Figure 6c), corresponding to the stretching vibrations of O–C–O. It's noteworthy to recall that this peak exists only in the samples containing 10wt% hybrid BFA/cement thus it contributes majorly to its notable strength.

6. Conclusions

Agro-wastes are considered as potential construction materials due to their sustainability, pozzolanic characteristics, low cost, low carbon-print and high renewability rate. Thus, the transformation of agricultural and industrial waste into produce added-value products has become progressively important in the last decade.

This study has investigated the effect of biowaste, cement and hybrid biowaste/conventional stabilisers on the dimensional integrity and compressive deformation of termite mound soil. Indeed, dimensional stability is an important characteristic to be considered when modelling earth-based materials. The dimensional stability defines the earth-based structures' performance under wet and dry environment. Based on the results obtained from this study, the following conclusions can be drawn:

– The porous nature of the Borassus Fruit Ash (BFA) significantly affects the water absorption level. Therefore, it is recommended to limit the use of BFA content for applications where lower water absorption is needed. However, for applications requiring high water absorption level, BFA content can be maximized.

– Internal stresses and chemical component govern the linear shrinkage tendency. Therefore, the chemical reactions taking place during the curing period should be investigated carefully when hybrid stabilisers are used. If the hybrid stabilisers generate instable reactions subsequently the linear shrinkage will be considerable.
– The intrinsic properties of the various materials used govern the overall macrostructure of the samples. Moreover, the microstructure governs the performance of the samples (compressive strength for instance). Thus, the necessity of analyzing the raw materials' intrinsic properties before producing the mixed design.
– Al, Si and Fe dictates the pozzolanic activity within the mixed design, henceforth this chemical content imparts greatly the compressive strength. For application requiring higher compressive strength, the chemical composition can be altered by a third stabilizer (silicate for instance).

The results of this study are aimed to contribute to lower biowaste and promote their use in sustainable housing. Borassus fruit ash was used because of their availability in the Sub-Saharan African at very negligeable cost and considered as waste due to its non-utilization. In fact, the borassus tree is abundantly spread in the Sub-Saharan Africa (SSA), but the fruits are not exploited, while only the stem and leave have been used in traditional construction or craft. Moreover, the use of waste in the construction field has increased. But, in most cases the waste incorporated construction materials are produced according to specific relevant standard. But these standards are established based on conventional materials properties. Therefore, the establishment of standards is required for the development of unconventional construction materials. Also, more studies should be directed towards the long-term properties, production technology, quality control and renewability of the earth-based materials. The use of waste in the construction field will address the problem related to waste management in many countries and will represent a solution for global environmental pollution.

Declarations

Author contribution statement

Assia Aboubakar Mahamat: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Abubakar Dayyabu, Abdulganiyu Sanusi, Mohammed Ado: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Ifeyinwa Ijeoma Obianyo, Tido Tiwa Stanislas, Numfor Linda Bih: Conceived and designed the experiments; Performed the experiments.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

[1] M. Lamrani, M. Mansour, N. Laaroussi, M. Khalfaoui, Thermal study of clay bricks reinforced by three ecological materials in south of Morocco, Energy Proc. 156 (2019) 273–277.
[2] D. Daudon, Y. Sieffert, O. Albarracín, L.G. Libardi, G. Navarta, Adobe construction modeling by discrete element method: first methodological steps, Procedia Econ. Finance 18 (2014) 247–254.
[3] O.B. Adegun, Y.M.D. Adedeji, Review of economic and environmental benefits of earthen materials for housing in Africa, Front. Architect. Res. 6 (4) (Dec. 01, 2017) 519–528. Higher Education Press Limited Company.
[4] W. Xu, et al., Effect of rice husk ash fineness on porosity and hydration reaction of blended cement paste, Construct. Build. Mater. 89 (Apr. 2015) 90–101.
[5] J. Zhang, G. Liu, B. Chen, D. Song, J. Qi, X. Liu, Analysis of CO2 Emission for the cement manufacturing with alternative raw materials: a LCA-based framework, Energy Proc. 61 (2014) 2541–2545.
[6] A.A. Mahamat, N. Linda Bih, O. Ayeni, P. Azikiwe Onwualu, H. Savastano, W. Oluwole Soboyejo, Development of sustainable and eco-friendly materials from termite hill soil stabilized with cement for low-cost housing in Chad, Buildings 11 (3) (Feb. 2021) 86.
[7] A.A. Mahamat, et al., Machine learning approaches for prediction of the compressive strength of alkali activated termite mound soil, Appl. Sci. 11 (11) (May 2021) 4754.
[8] A.A. Firoozi, C. Guney Olgun, A.A. Firoozi, M.S. Baghini, Fundamentals of soil stabilization, Int. J. Geo-Eng. 8 (1) (Dec. 2017).
[9] A.A. Mahamat, et al., Alkali activation of compacted termite mound soil for eco-friendly construction materials, Heliyon 7 (3) (Mar. 2021).
[10] N. Stevulova, J. Cigasova, I. Schwarzova, A. Sicakova, J. Junak, Sustainable bio-aggregate-based composites containing hemp hurds and alternative binder, Buildings 8 (2) (Feb. 2018).
[11] N. Jannat, A. Hussien, B. Abdullah, A. Cotgrave, Application of agro and non-agro waste materials for unfired earth blocks construction: a review, Construct. Build. Mater. 254 (Sep. 10, 2020). Elsevier Ltd.
[12] S.C. Paul, P.B.K. Mbewe, S.Y. Kong, B. Šavija, Agricultural solid waste as source of supplementary cementitious materials in developing countries, Materials 12 (7) (2019). MDPI AG.
[13] G. Pardo, R. Moral, A. del Prado, SIMSWASTE-AD - a modelling framework for the environmental assessment of agricultural waste management strategies: anaerobic digestion, Sci. Total Environ. 574 (Jan. 2017) 806–817.
[14] Toggle navigation 1, Understanding Poverty 2. Topics 3, Urban Development Solid Waste Management, 2019.
[15] S. Raj S, A.K. Sharma, K.B. Anand, Performance appraisal of coal ash stabilized rammed earth, J. Build. Eng. 18 (Jul. 2018) 51–57.
[16] A. Olajide Olorunnisola, Development of sustainable building materials from agro-industrial wastes in Nigeria, in: Sustainable Construction and Building Materials, IntechOpen, 2019.
[17] P. Sudhakara, et al., Studies on Borassus fruit fiber and its composites with Polypropylene, Comp. Res. 26 (1) (Feb. 2013) 48–53.
[18] B. Medvey, G. Dobszay, Durability of stabilized earthen constructions: a review, Geotech. Geol. Eng. 38 (3) (Jun. 01, 2020) 2403–2425. Springer.
[19] J.-H. Tay, K.-Y. Show, Recycling ELSEVIER, Use of ash derived from oil-palm waste incineration as a cement replacement material, Resour. Conserv. Recycl. 13 (1995).
[20] R. Pode, Potential applications of rice husk ash waste from rice husk biomass power plant, Renew. Sustain. Energy Rev. 53 (Jan. 01, 2016) 1468–1485. Elsevier Ltd.
[21] P.A.O. George, J.J.C. Eras, A.S. Gutierrez, L. Hens, C. Vandecasteele, Residue from sugarcane juice filtration (filter cake): energy use at the sugar factory, Waste Biomass Valorizat. 1 (4) (Dec. 2010) 407–413.
[22] OlutogeFA, O.M. Oladunmoye, Bamboo leaf ash as supplementary cementitious material, Am. J. Eng. Res. 14 (2017) [Online]. Available: www.ajer.org.
[23] P. Asha, A. Salman, R.A. Kumar, Experimental Study on Concrete with Bamboo Leaf Ash, 2014.
[24] S.A. Memon, M.K. Khan, Ash blended cement composites: eco-friendly and sustainable option for utilization of corncob ash, J. Clean. Prod. 175 (Feb. 2018) 442–455.
[25] American Society for Testing Materials C129, Non load-bearing masonry, "ASTM C129." [Online]. Available: https://www.astm.org/Standards/D854. (Accessed 6 March 2020).
[26] M.N. Amin, T. Murtaza, K. Shahzada, K. Khan, M. Adil, Pozzolanic potential and mechanical performance of wheat straw ash incorporated sustainable concrete, Sustainability 11 (2) (Jan. 2019).
[27] performance, production and conformit Concrete -Specification, European Standard EN 206-2013+A1-2016, European standard, 2016.
[28] S.N. Malkanthi, N. Balthazaar, A.A.D.A.J. Perera, Lime stabilization for compressed stabilized earth blocks with reduced clay and silt, Case Stud. Constr. Mater. 12 (Jun. 2020).
[29] British Standards Institution, British Standard Methods of Test for Soils for Civil Engineering Purposes, British Standards Institution, 1990.

[30] S.A. Memon, I. Wahid, M.K. Khan, M.A. Tanoli, M. Bimaganbetova, Environmentally friendly utilization of wheat straw ash in cement-based composites, Sustainability 10 (5) (May 2018).
[31] I.I. Obianyo, et al., Performance of lateritic soil stabilized with combination of bone and palm bunch ash for sustainable building applications, Cogent Eng. 8 (1) (Jan. 2021) 1921673.
[32] S. Masuka, W. Gwenzi, T. Rukuni, Development, engineering properties and potential applications of unfired earth bricks reinforced by coal fly ash, lime and wood aggregates, J. Build. Eng. 18 (Jul. 2018) 312–320.
[33] J.E. Oti, J.M. Kinuthia, J. Bai, Engineering properties of unfired clay masonry bricks, Eng. Geol. 107 (3–4) (Aug. 2009) 130–139.
[34] K. Onyelowe, D. Bui Van, C. Igboayaka, F. Orji, H. Ugwuanyi, Rheology of mechanical properties of soft soil and stabilization protocols in the developing countries-Nigeria, Mater. Sci. Energy Technol. 2 (1) (Apr. 2019) 8–14.
[35] T. Ashour, W. Wu, An experimental study on shrinkage of earth plaster with natural fibres for straw bale buildings, Int. J. Sustain. Eng. 3 (4) (Dec. 2010) 299–304.
[36] S. Sangma, D.D. Tripura, Experimental study on shrinkage behaviour of earth walling materials with fibers and stabilizer for cob building, Construct. Build. Mater. 256 (Sep. 2020).
[37] M.M. Ul Islam, K.H. Mo, U.J. Alengaram, M.Z. Jumaat, Durability properties of sustainable concrete containing high volume palm oil waste materials, J. Clean. Prod. 137 (Nov. 2016) 167–177.
[38] F. Chen, K. Wu, L. Ren, J. Xu, H. Zheng, Internal curing effect and compressive strength calculation of recycled clay brick aggregate concrete, Materials 12 (11) (Jun. 2019).