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Case study

Bio-stabilising earthen houses with tannins from locally available resources

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ABSTRACT

This study presents the first-ever comparative evaluation of traditional biostabilisation practices for housing employed in Northern Ghana. Such a comparative evaluation is crucial in understanding and addressing the increased risk of flooding in the region due to a combination of climate change and land use changes. Given the environmental conditions and material availability that shape construction techniques in this area, it is imperative to assess the effectiveness of these practices in mitigating flood risks. The investigation focuses on readily available resources from the Wa and Tamale regions, specifically *dawadawa* (D), *beini* (B), and rice husk (R). These biostabilisers were subjected to rigorous testing to assess their efficacy. Earth mortar samples were created using sieved plain local soil (P) with or without the addition of rice husk, which is a local practice, and *dawadawa* and *beini* solutions were tested as a water replacement (+ wD or + wB, added during material manufacture) or as a surface cover (+ coverD or + coverB). The effects are examined in terms of microstructure modifications detected through tannins type and presence, SEM/EDS, water absorption via capillary uptake, and compressive and flexural strength for two different types of application: embedded in the mixture or covering the surface. Overall, solutions containing *dawadawa* were superior to those containing *beini* for the tested soil. Both coverD and + coverB decreased the water absorption capacity of the earth mortars and provided almost complete protection for 15 min. After three days, all mortars mixed with the dawadawa or beini solutions (P + wD, PR + wD and PR + wB) displayed lower absorption than the P material. Condensed tannins were identified in *dawadawa*, but only small precipitation in *beini* and no precipitation in the rice husk. This indicates that dawadawa has a greater degree of polymerisation (compared to rice and beini), developing a polymerisation tannin-iron complex in contact with oxygen from the air, which explains the macrostructure results. SEM/EDS results indicated polymeric condensed tannins and hydrolysable tannins and that complex accumulation and subsequent oxidation are the main reasons for improving water resistance. The laboratory tests, therefore, support the traditional methods of using *dawadawa*,

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beini, and, to a lesser extent, rice husk to improve the resilience of earthen houses and structures to water damage and can be used to encourage agro-industry in Northern Ghana to preserve and promote *dawadawa* and *beini* resources.

1. Introduction

Northern Ghana faces significant challenges attributed to increased flooding due to extreme precipitation events and alterations in land use and land cover, notably deforestation [1]. The prevalence of earth construction in the Northern Region, over 70 % of the outer walls of the houses are constructed with earth according to the 2010 Population and Housing Census [1,2], highlights the significant reliance on traditional buildings in the region. However, the susceptibility of earthen infrastructure to water-related issues poses a considerable challenge to the resilience of these structures. Water infiltration through various pathways, such as capillary rise from the foundations, direct exposure to rainfall, and ambient humidity, can compromise the integrity of earthen walls, leading to reduced cohesion and potential structural failure. Moreover, these traditional construction materials cannot withstand the impact of flood waters, leading to structural collapse and loss of livelihoods [3].

The increasing concentration of people, buildings, and infrastructure heightens vulnerability to climate-induced hydro-hazards, notably floods. This is because dense urban areas have limited natural drainage systems, increased impervious surfaces, and, in the case of rapidly growing cities in developing countries, informal settlements and inadequate infrastructure to manage heavy rainfall events. Additionally, construction activities contribute 40 % of anthropogenic greenhouse gas emissions, with half associated with embodied carbon in materials and construction processes [4]. Although society is turning to high-tech solutions such as 3D printing or AI-optimised construction to reduce construction material use and waste, their large-scale implementation faces challenges due to high costs and technical complexity [4,5]. Instead, the focus is shifting towards improving construction materials' properties while reducing their environmental footprint, especially in developing regions. Nature-based materials and circular economy principles are seen as key strategies to mitigate the impact of flood waters on housing [6,7]. One promising approach is the use of biostabilisation methods, which involve incorporating biopolymers, bio-fibres, and bacteria-based techniques into construction materials. Moreover, using locally available earth and waste materials for construction helps shorten the supply chain of raw materials, reducing resource depletion [2,8–10].

1.1. Common biopolymers to stabilise soils

Biostabilisers can have a diverse composition depending on the source of the plant material and the processing method. Biostabilisers can contain a mixture of organic compounds such as polyphenols, carbohydrates, lignins, flavonoids, tannins, and others. The specific composition of a biostabiliser depends on the plant species and the extraction method used to obtain the biostabiliser from the plant material. Additionally, the presence of other substances, such as enzymes, proteins, and mineral nutrients, can also influence the composition and properties of the biostabiliser [11].

Common biopolymers used in biostabilisation include agar gum, guar gum, xanthan gum, and gellan gum [12–15]. These biopolymers can be made from natural resources like polysaccharides, proteins, lipids, and complex molecules from vegetable and fruit residues. The use of biopolymers in earth stabilisation can change their performance by modifying the porosity and porosity distribution of materials, as shown in recent studies where polysaccharides such as cellulose, proteins like gelatine, casein, albumin, keratin, and silk, lipids such as oils and fats, and vegetable and fruit residues like beetroot and tomatoes have been used in the stabilisation process [12–15].

Guar and xanthan gums are two biopolymers resistant to temperature and pH changes. These gums are effective in changing the pore size distribution of soil by filling the smallest pores and improving the bonding of soil particles. Xanthan gum, produced by the bacterium *Xanthomonas Campestris*, is a water-soluble gum used in food and pharmaceutical applications. It is more effective with fine particles due to hydrogen bonding, which helps the fine clay particles and biopolymer matrix behave like a cementitious binder connecting coarse particles [15–18]. Latifi et al. [19] conducted a series of experiments to study the mechanisms of stabilisation of xanthan gum in soil. They found that chemical reactions between xanthan gum and soil particles form a new cementitious product. The study also found that the soil composition is important for chemical bonding and mechanical friction. The use of biopolymers for soil stabilisation was studied using two different clays, bentonite and kaolin, and the researchers found different optimum additions for each soil. This highlights the importance of considering soil composition when using biopolymers for soil stabilisation [17].

1.2. Tannins and natural fibres to stabilise/reinforce earthen materials

Fieldwork carried out by the authors in Northern Ghana (Appeaning Addo et al.) showed that the local communities employ biostabilisers to improve the resilience of their houses to water. These local communities heavily depend on climate-sensitive sectors, e.g. agriculture, and cannot adopt more expensive construction materials [1]. The biostabilisers are solutions formed from the husk of the African locust bean (*Parkia biglobosa,* locally called *dawadawa*) and the roots of the *beini* plant (*Acroceras spp.* family), both of which are sources of tannins [20,21]. Locals also add rice husk to the soil to improve its performance through fibrous reinforcement. These plant-based mixtures are used to improve the water-resistance of earth-based construction materials. However, variations in performance when these biostabilisers are used necessitate further research to pinpoint the underlying reasons. This practice is also threatened by deforestation and increasing flooding, reducing the supply but rising demand for these natural biostabilisers.

Natural fibres have been found to improve the mechanical strength of earth-based materials in construction. Olacia et al. [22] found that using Posidonia oceanica sea-plant fibres improved the mechanical strength by 50 % when the content was 1.5 wt%. Similarly,

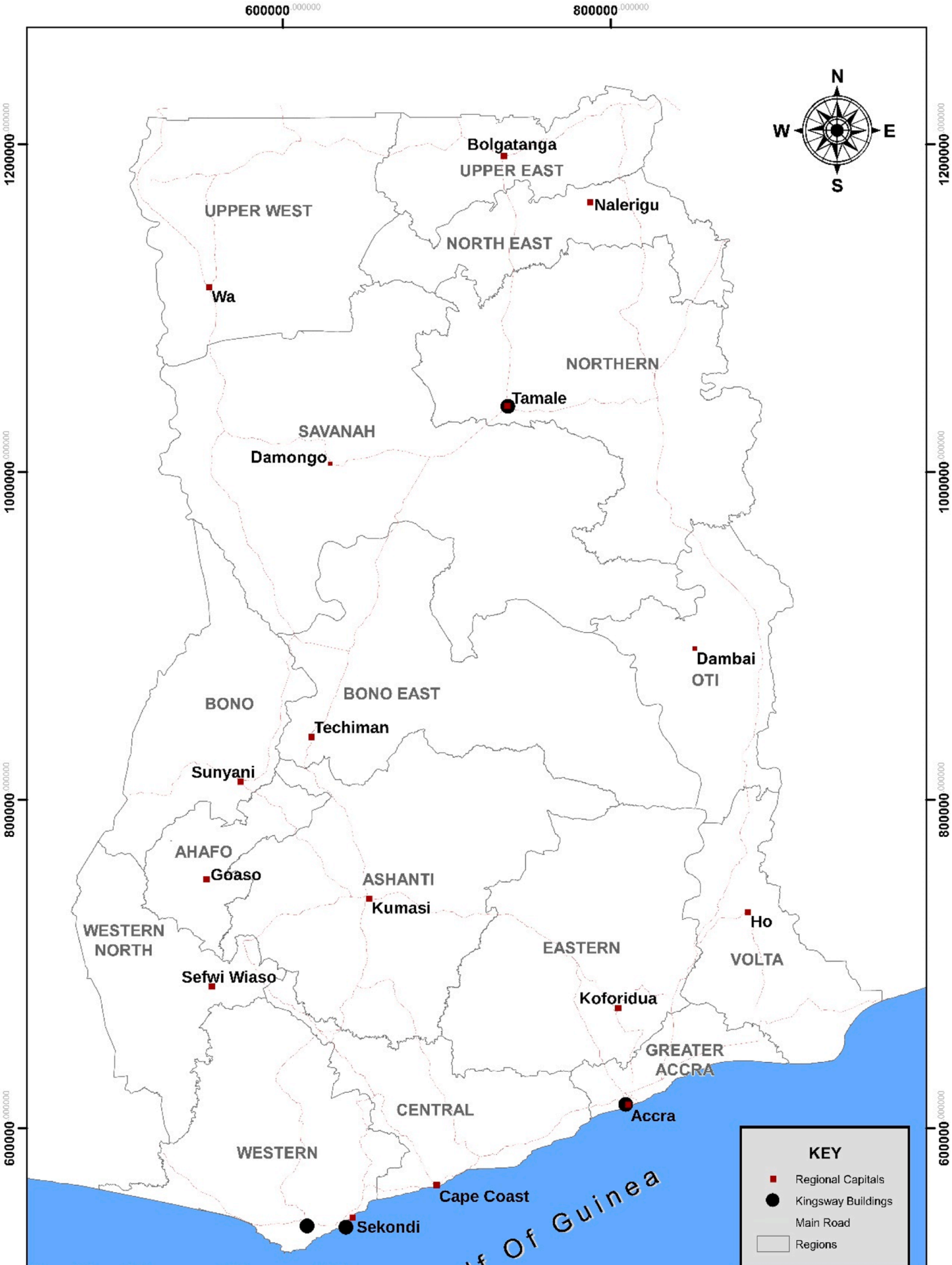


Fig. 1. Map of Ghana depicting the Tamale and Wa regions. Map prepared by Francis Andorful, Remote Sensing and GIS Laboratory, University of Ghana, 2022.

using palm fibre and straw raised the compressive strength by 156 % and 35 %, respectively, while using rice husk decreased the strength by 41 % compared to control specimens [23]. Further research is needed, however, on the impact of sustainable techniques in the production process, mixture, and curing [20,21]. The main challenge with natural fibres is their hydrophilic and biodegradable characteristics, which affect their durability [24,25]. Additionally, the shrink-swell behaviour of fibres can lead to slipping and failures at the fibre-soil contact zones. This issue can be addressed by modifying the surfaces of natural fibres, such as through treatment with boric acid, carbon tetrachloride, or sodium hydroxide.

Tannins from various plant sources, such as the African locust bean tree, can be used as biostabilisers [20,21], which can be incorporated into soil through bio-polymerisation. In wood types, tannins can make up more than 20 % of the total dry weight [26]. Tannins are considered biopolymers as they are natural organic compounds composed of many repeating subunits and can form large and complex structures through polymerisation. Tannins are commonly found in plants and have various functions, such as defence against pathogens and herbivores. They are also utilised in multiple applications, such as food, medicine, and soil stabilisation. Tannins, being natural polyphenols, play a significant role in soil stabilisation as biostabilisers. They can improve soil properties and prevent soil erosion by forming complex substances with soil particles. By cross-linking and binding soil particles together, tannins can enhance soil aggregation and structure, improving soil stability. Furthermore, tannins can improve the soil's water retention capacity (for agriculture, i.e., increase the amount of water held within the soil for a given soil suction) and reduce soil crusting, enhancing soil fertility [26–29]. This improved soil structure and fertility can increase plant growth, leading to a more resilient ecosystem and food security. These properties justify the study of plant sources rich in tannins for the construction sector.

Matin [30] showed that tannin-based treatments improved soils' mechanical and hydraulic behaviour, particularly those with high organic matter content. This suggests that tannins can be a viable option for stabilising soil in various applications. Erktan et al. [31] also explored the influence of tannins on soil aggregate stability through their interaction with proteins and root mucilage. They found that when combined with proteins, tannins can enhance aggregate stability by forming complexes that bind soil particles together. However, tannins can also have a negative effect on aggregate stability when they interact with root mucilage, disrupting its gelling properties. In their review, Kraus et al. [32] provide a broader overview of tannins' role in forest ecosystems, including their impact on soil properties. It highlights the complex interactions between tannins and other soil components and the need for further research to understand their role in soil stabilisation fully.

There are two main types of tannins: condensed tannins and hydrolysable tannins. Condensed tannins are readily available in plants and wood of various trees compared to hydrolysable tannins and are characterised by greater resistance to microbial degradation. Condensed tannins have a higher degree of polymerisation compared to hydrolysable tannins. When exposed to oxygen, condensed tannins can undergo oxidative polymerisation, forming tannin-iron complexes. These complexes can crosslink and bind with other molecules, including wood, leather, or other natural fibres, enhancing their water resistance and durability. The presence of free hydroxyl groups enables the ease of accessibility and the feasibility for modification, hence facilitating chemical modification on tannin [33–36]. Invariably, between the hydrolysable and condensing units, condensed tannins reduce the formaldehyde emission level due to their higher reactivity with formaldehyde and the presence of catechol groups [33,34,37].

Bio-based soil stabilisation technologies and bio-polymer treatments have been studied to determine their impact on the engineering characteristics of stabilised soils. Still, more research is needed to understand their potential fully. Variability in soil physical properties and testing methods has limited progress in developing unique and effective soil development approaches [3]. The development of effective vulnerability reduction strategies also requires an understanding of local resources and building practices. Using fast-growing biogenic materials in construction products can result in carbon-neutral or even carbon-negative products and provide more significant greenhouse gas savings than their use in other sectors, such as biofuels [20]. The fast gestation period of these materials also allows for quick scaling of their use for housing resilience.

This paper examines how traditional biostabilisation methods can improve the resistance of earth-based construction to damage

Fig. 2. Reddish Clayish soil used for plaster and blocks preparation in Wa, 2022 (photograph by the authors).

relating to pooling water. The study focuses on Northern Ghana, specifically Wa in the Upper West Region and Tamale in the Northern Region (Fig. 1), where the locally available food- and/or plant-based biostabilisers *dawadawa*, *beini*, and rice husk have commonly been used for housing construction. It is crucial to understand how these biostabilisers function and to demonstrate their merit in protecting and preserving natural resources and preventing a greater transition to inappropriate cementitious materials.

2. Materials and methods

2.1. Earth

Information on the mixing procedure for earth construction and plastering was collected via interviews done onsite in Wa and Tamale with traditional builders and residents (reported in Addo *et al.* forthcoming). In Wa, a reddish clay soil was used to plaster and mould blocks to construct earth houses (Fig. 2). An equivalent soil was sourced in the UK for laboratory testing, based on characterisations performed in Ghana [38], to avoid the carbon impact of transporting such a heavy material over large distances. The site soil was reproduced using red clay powder from Bath Potters' Supplies (Fig. 3). The clay is 54–62 % kaolinite, 22–26 % micaceous minerals, and 8–12 % silica (quartz). The optimum moisture content of the clay was 14 %, and the maximum dry density was 2320 kg/m^3 using the Standard proctor compaction test. The clay had a plastic limit of 19 % water content and a liquid limit of 31 % (medium plasticity). The soil was sieved through a 2 mm sieve and stored in the laboratory at room temperature until it was used to manufacture the earthen specimens. The small particle size was necessary to permit smaller specimens for testing. Given that the particle size used in the laboratory was smaller than that *in situ*, we refer here to our material as a "mortar". However, we are not exploring utilising this material to bind earth bricks, as the term "mortar" may suggest.

2.2. Biostabilisers

The *dawadawa*, *beini*, and rice husk used in this study were provided by the University for Development Studies in Tamale, Ghana. The materials were used for the experimental programme within one month of harvesting to ensure they represented the same state used in local construction. According to an on-site survey in Tamale and Wa, these types of earth-based construction take two months to be ready for use. Therefore, the laboratory tests were done at 60 days to represent the current building use reality.

2.2.1. Dawadawa solution

Locally called *dawadawa*, the African locust bean tree (*Parkia biglobosa*, also called *Néré* in Nigeria [39,40]) is an important socio-economic tree that grows in the Sudan and Guinea Savanna vegetation zones of Sub-Saharan Africa. The pods of the tree, commonly called locust beans, are initially pink and turn a dark brown when fully mature. According to site visits performed by the team in 2022 in Wa and Tamale and [40,41], the pod hosting the locust bean is an important biostabiliser used in housing construction. A healthy and good-yielding locust bean tree can produce up to 35–40 kg of locust beans annually to process *dawadawa*. The tree is a fire-resistant heliophyte with a thick dark grey-brown bark. Eight to ten kilograms of the pod are mixed in 225 l of water for construction purposes. Fig. 4 shows the *dawadawa* tree in Wa and Tamale, and Fig. 5 shows the bean husk.

2.2.2. Beini solution

Beini is a plant-based biostabiliser from the family of *Acroceras spp.*, which is widely used for house building in Northern Ghana. The plant grows in the wild in the Guinea and Sudan Savanna vegetation zones. *Beini* plants do not grow into trees but remain cover plants and shrubs that spread on the ground and along the branches of trees. The root of the plant, shown in Fig. 6, is harvested and used as a biostabiliser in housing construction. Up to 10 kg of plant roots can be harvested from a single *beini* plant. The crushed roots are mixed with about 900 litres of water to create a solution in the approximate ratio of 1:20 of *beini* to water by mass, as shown in Fig. 7.

2.2.3. Rice husk

The rice husk used for this study is shown in Fig. 8. Its chemical composition is presented in Table 2. To determine the bulk density of the rice husk, the sample was first dried at 60 °C until the weight was constant, with variations lower than 0.1 % between two weightings 24 h apart. The bulk density of the rice husk is 85 kg/m^3.

Fig. 3. Earth is used for mortar preparation (photograph by the authors).

Fig. 4. *Dawadawa* trees in the outskirts of Wa and Tamale (photographs by the authors).

Fig. 5. *Dawadawa* husk (photograph by the authors).

Fig. 6. *Beini* plant in Tamale (left) and Wa (right) (photographs by the authors).

Fig. 7. Mixing shredded *beini* roots in water to prepare the biostabiliser solution (photograph by the authors).

Fig. 8. Rice husk was used for mortar preparation (photograph by the authors).

Table 1
Chemical composition of the earth used (based on [38]).

Chemical compounds (%)	
SiO_2	41.46
Al_2O_3	15.21
Fe_2O_3	8.1
MgO	5.11
K_2O	1.64
TiO_2	1.41
Na_2O	1.027
CaO	0.633
BaO	0.22
SO_3	0.05
MnO	0.04

Table 2
Chemical composition of rice husk.

Element	Weight (%)	Atomic (%)
C	27.41	39.14
O	46.71	50.06
Mg	3.12	2.2
Si	8.9	5.43
K	2.24	0.98
Zr	11.62	2.18
Totals	100	100

2.3. Mix design using traditional recipes

Information on the traditional mixing procedure for plastering was collected via interviews done onsite in Wa and Tamale with local builders and residents (to be discussed in Addo et al.). Observing the onsite procedures, earth-based plain mortars were formed by pouring water on the soil and getting it moderately soaked, moulding soil balls. Mixing was performed manually for about 3 min. When moulding the soil balls, the soil is sufficiently wet and starchy. However, water is sprinkled on it for remixing when some dryness is observed. This was called the plain mortar composition, "P".

Two approaches were explored to apply the biostabilisers:

1. Water replacement. Replacement of the mixing water by the solution of *dawadawa* (D) or *beini* (B) is called P + wD mortar or P + wB, respectively. The dawadawa solution contains 1 kg of dawadawa husk to 10 l of water for earth-based mortar composition. The *beini* solution contains 1 kg of roots to 20 kg of water.
2. As a cover to the surface of the mortar specimen. The on-site interviews revealed that the *dawadawa* solution is also applied onto walls after plastering as a surface treatment. This is identified as P + coverD. *Despite not being a traditional practice, the Beini solution was also explored as a surface treatment (+ coverB).*

The interviews also revealed that rice husk is sometimes added to the soil mix. Rice husk was added to the soil before mixing with water, dawadawa, or *beini* solution. This mixture is referred to herein as "PR" for a mixture of rice husk in an earth-based mortar, i.e. PR + wD signifies a plain mortar comprising rice husk with the water replaced with *dawadawa* solution. Therefore, eight types of mortars were prepared in total, as shown in Table 3.

All specimens were cured for 60 days in a laboratory environment (temperature = 21 °C, relative humidity = 53 %). Three specimens were prepared per mix and test (compressive, three-point bending test, water absorption via capillary, and SEM/EDS, as discussed in the following sections). Fig. 9 presents samples of the tested earth-based mortars. Figs. 10 and 11 present the solution of *dawadawa* and *beini* used for the earth-based mortars.

2.4. Mechanical and durability tests for mortars

It is well known that an increase in the water content of an earthen material, from whatever exposure method, reduces its mechanical strength [3]. Therefore, it is critical to understand the effect of any action to protect against damage due to water on the strength of the material, to understand the likely performance of the structure pre- and post-treatment and the subsequent factors of safety. It is also essential to know for how long a material might be protected and to understand after what time the mechanical properties might begin to degrade.

Mortar specimens were tested according to the following procedures (Table 4). Two half-size specimens were obtained for each flexural strength test: one for water absorption via capillary rise and the other for the compressive strength test. Scanning electron micrographs of earth mortars with and without biostabiliser were obtained using the remaining crushed fragments after the compressive strength test.

Table 3
Earth-based samples mix design.

Mortar mix	Earth (g/cm^3 of mortar)	Water (g/cm^3 of mortar)	*Dawadawa* (g/cm^3 of mortar)	*Beini* (g/cm^3 of mortar)	Rice husk (g/cm^3 of mortar)
P	0.98	0.20	-	-	-
P + coverD	0.98	0.20	0.01	-	-
P + coverB	0.98	0.20	-	0.01	-
P + wD	0.98	-	0.20	-	-
PR	0.96	0.20	-	-	0.01
PR + coverD	0.96	0.20	0.01	-	0.01
PR + wD	0.96	-	0.20	-	0.01
PR + wB	0.96	-	-	0.20	0.01

Fig. 9. Samples of the tested earth-based mortars (photograph by the authors).

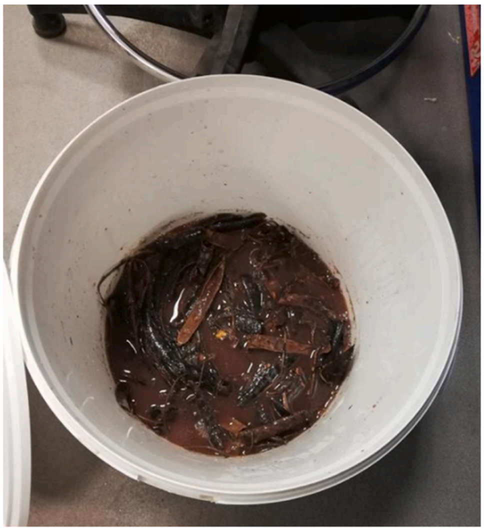


Fig. 10. Solution of *dawadawa* used for the earth-based mortars (photograph by the authors).

All samples were cured in the lab environment for 60 days. For capillary rise testing, the weight of the samples was registered at 0', 5', 15', 30', 1 h, 2 h, 3 h, 24 h, and 3 days.

2.5. Tests to determine the presence of tannins

Dawadawa, *beini* and rice husk solution samples were analysed for suspected tannins using the ferric chloride test, the Stiasny method (gelatine in sodium chloride test), and the lead acetate test.

Fig. 11. Solution of *beini* used for the earth-based mortars (photograph by the authors).

2.5.1. Ferric chloride test

This test takes advantage of the ability of hydrolysable tannins to form coloured complexes with ferric ions. Extract the tannins from the sample by macerating the material in a suitable solvent (e.g., water) and filtering the solution. Pipette 2 ml of sample containing suspected tannins into a test tube or glass vial. Add a few drops of the 5 % ferric chloride solution to the sample in the test tube (enough to cover the sample). Suppose the sample contains hydrolysable tannins; a colour change will occur, ranging from greenish-blue to blackish-blue or brownish-black, depending on the concentration of tannins and the type present in the sample. In that case, greenish-blue indicates condensed tannin, while blackish-blue indicates hydrolysable tannin.

2.5.2. Stiasny method

This method takes advantage of the ability of tannins to form complexes with proteins, leading to protein precipitation [47,48]. Extract tannins from the sample by macerating the material in a suitable solvent (e.g., water) and filtering the solution. Pipette 2 ml of the prepared sample containing tannins and place it into a test tube or glass vial. Prepare a 1 % gelatine solution containing 10 % NaCl and add some drops to the sample in the test tube. Observe the formation of any precipitates or turbidity in the solution; the appearance of a precipitate shows the existence of condensed tannins. In this study, the resulting mixture was tested in two ways: at an environmental temperature and heated at 90 °C for 15 min.

2.5.3. Lead acetate test

This test confirmed the results obtained using the Stiasny method (Section 2.5.2). The lead acetate method also takes advantage of the ability of tannins to form complexes with proteins, leading to protein precipitation. Using the same solutions prepared for the Stiasny test, pipette 2 ml of the prepared solution sample containing tannins into a test tube or glass vial. Add some drops of a 10 % lead acetate solution to the sample in the test tube and observe the formation of any precipitates or turbidity. The sample containing tannins will form a precipitate with the lead acetate.

2.6. SEM/EDS

Mortar samples were detached from the main body after compressive testing via Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS). The fragments were coated with 6 nm gold to investigate the bonding characteristic between the soil and the biostabilisers on the surface of the earth-based mortars.

3. Results and discussion

3.1. Tannins identification

Hydrolysable and condensed tannins were tested in *dawadawa*, *beini* and rice husk solutions. The results are presented in Table 5 and Figs. 12–15. Condensed tannins were identified in *dawadawa,* but only small precipitation in *beini* and no precipitation in the rice husk. This indicates that *dawadawa* has a greater degree of polymerisation (compared to rice and *beini*), developing a polymerisation tannin-iron complex in contact with oxygen from the air.

Tannins can act as natural glues, binding soil particles together or strengthening the structure of earthen materials they impregnate. This can improve resistance to erosion. The presence of tannins in the bio-stabilisers can delay the initial stages of certain processes, particularly in the context of mortar stabilisation [49]. This might benefit mortars containing *dawadawa* but not so much those with *beini* and rice husk. However, since tannins are organic, they are susceptible to decomposition by microorganisms over time. This can ultimately limit the long-term durability of materials treated with them. This will be analysed in the future.

Table 4
Testing procedures adopted in this study.

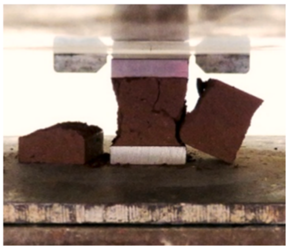
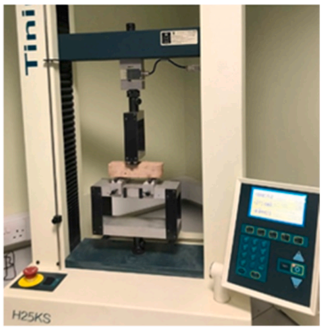
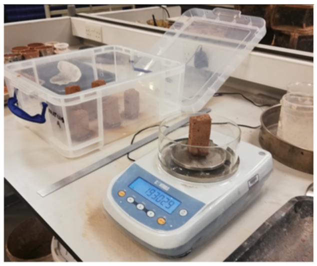
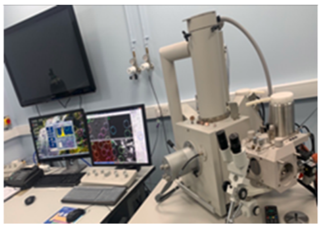
Tests performed	Standard	Picture (photographs by the authors)
Bulk Density	EN 1015-6 [42]	N/A
Compressive strength	BS EN 826 [43] and EN 1015-11 [44]	
Three-point flexural strength	EN 12089 [45]	
Water absorption via capillary	EN 1015-18 [46] and EN 15801 [47]	
Scanning electron microscopy coupled energy-dispersive x-ray spectroscopy (SEM-EDS)	FEI Inspect S SEM variable vacuum. Kv range 0.1–30 kv used	
Colorimetric test and Stiasny method for tannin detection	This includes the ferric chloride test, gelatine in sodium chloride test and the Lead Acetate test.	

Table 5
Testing results for tannins identification and pH for each solution.

Test	Solution		
	Dawadawa	***Beini***	**Rice husk**
Ferric chloride (FeCl3)	dark blue	disappearing green	No colour changes
Stiasny (gelatine)	white precipitate	small precipitation	No precipitation
Lead Acetate	white precipitate	No precipitation	No precipitation
pH	5.48	7.06	5.33

Fig. 12. Filtered solutions of macerated *dawadawa*, *beini* and rice husk (photograph by the authors).

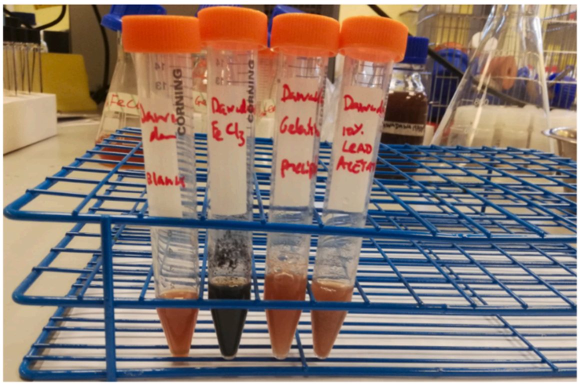


Fig. 13. Results for *dawadawa*. Leftmost: blank solution; second from left: ferric chloride test; second from the right: Stiasny test; rightmost: lead acetate (photograph by the authors).

3.2. Mechanical strength

Compressive and three-point flexural test results are presented in Fig. 16. ANOVA single-factor parameters are given in Table 6.

No statistically significant variation was observed between the P and PR mixes in compression. However, the overall difference between the P mixes and those containing PR was statistically significant at the 95 % confidence level, with PR mixes achieving lower compressive strengths by 20 % overall. Notably, P + coverD appeared to achieve the highest average compressive strength. However, these two sets' differences are insignificant ($F = 0.84$, $p = 0.41$). Given that a surface coating should not influence the material cross-section, finding that there is no significant difference between or within these groups is sensible, and the disparity here likely arises from the change in stiffness between the matrix and the coating (i.e. it is likely to be a peculiarity of the test and not the material). Given that this study focuses on the resistance to water ingress, a further investigation of the compressive strength variation is outside of the scope of this work.

As all specimens were cured under identical conditions, it is unlikely that the loss of compressive strength on incorporating rice husk is due to changes in soil suction (at these strengths, the contribution of suction to strength is likely to be considerable [50]). Beckett et al. [51] examined the effect of adding rice husk fibres on the mechanical properties of compressed earth bricks. They also found that increasing the rice husk content reduced the compressive strength and argued that the loss of strength was due to the lower

Fig. 14. Results for *beini*. Leftmost: blank solution; second from left: ferric chloride test; second from the right: Stiasny test; rightmost: lead acetate. The results show small amounts of tannins (photograph by the authors).

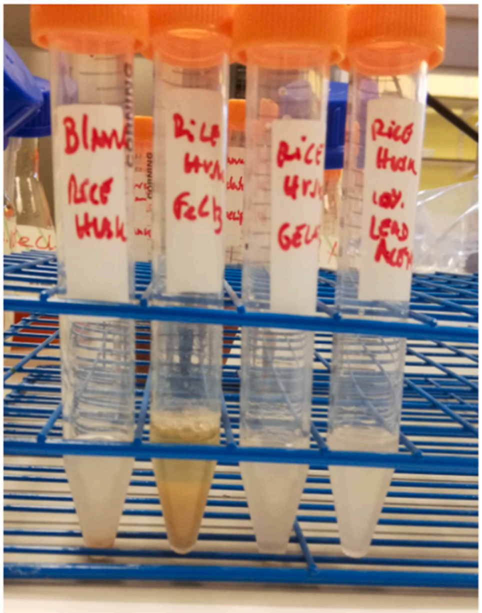


Fig. 15. Results for rice husk. Leftmost: blank solution; second from left: ferric chloride test; second from the right: Stiasny test; rightmost: lead acetate. All tests show a negative result for tannins (photograph by the authors).

density of the bricks. Although density is a governing property of the strength of earthen materials [50], the effect of strength of variations in density due to fibrous inclusions cannot be predicted *a priori* due to the concurrent changes (amongst others) in stiffness and water retention due to fibre clustering and the fibre's microstructure respectively [52]. Detailed examinations of the microstructure, water retention behaviour, and pore size distributions of the mortars presented in Fig. 16 are outside of the scope of this work. However, it is reasonable (from [51,52]) that adding rice husk to the plain soil resulted in a weakly significant reduction in strength due to the inclusion of weaker material. Furthermore, it should be noted that although the compressive strength marginally reduced, the compressive strengths of all tested mixes are above the minimum recommendations for construction [53].

No significant variation was observed between the P mix flexural strengths. The variation between the PR mixes was significant but arose due to the slight variance found for PR + wD rather than due to one mix outperforming its peers. The means for all P and PR mixes were similar. Beckett et al. [51] observed increased flexural strength with increasing rice husk addition, as the fibres reduced crack formation and permitted greater deflections (mobilising the fibre tensile strengths). However, the drying time was not consistent in that work, which may have affected internal suction, given the large size of their specimens (1980 × 300 × 150 mm). Our result, therefore, agrees with the local practice of incorporating rice husk to counter shrinkage cracking. Overall, the results presented in

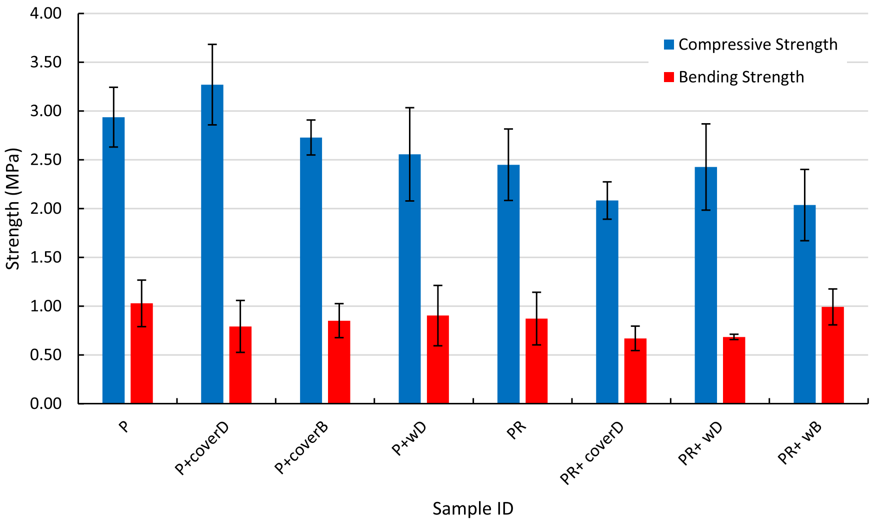


Fig. 16. Compressive strength and bending strength of the earth-based mortars at 60 days. Error bars show plus or minus one standard deviation.

Table 6
ANOVA results for compressive and flexural strength testing.

Set	F	F_{crit}	p	Interpretation	
Compressive					
P mixes	1.440	4.066	0.302	-	No significant variation
PR mixes	0.772	4.066	0.542	-	No significant variation
P versus all PR	11.818	2.657	0.002	**	Significant variation ($p < 0.01$)
All mixes	2.696	4.301	0.048	*	Weakly significant variation ($p < 0.05$)
Flexural					
P mixes	2.105	4.066	0.178	-	No significant variation
PR mixes	6.261	4.066	0.017	*	Weakly significant variation ($p < 0.05$)
P versus all PR	0.062	2.657	0.806	-	No significant variation
All mixes	2.982	4.301	0.033	*	Weakly significant variation ($p < 0.05$)

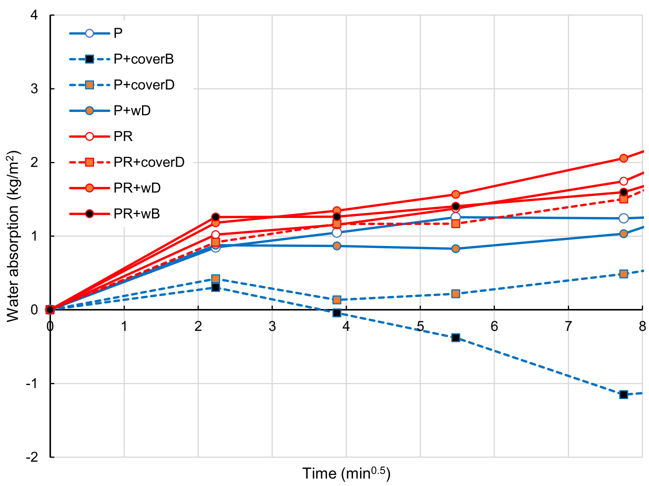


Fig. 17. Water absorption via capillary during the first hour.

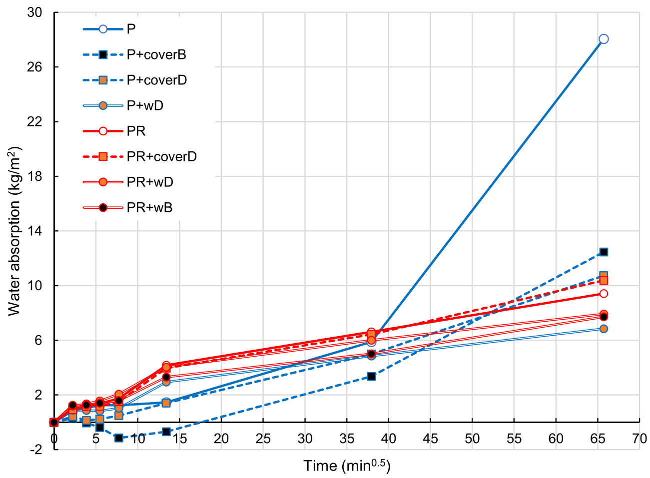


Fig. 18. Water absorption via capillary during the first three days.

Fig. 16 provide sufficient confidence that adding dawadawa, beini, or rice husk does not significantly improve the mechanical properties of the plain soil and that the practices are not detrimental.

3.3. Water absorption via capillary

Figs. 17 and 18 present the capillary water absorption for earth-based mortars after one hour and three days of testing, respectively.

Fig. 17 shows that the plain soil prepared with a *dawadawa* or *beini* cover (+ coverD or + coverB) successfully resisted capillary absorption for the first 15 min (approx. 4 $min^{0.5}$) of the test. As the test is based on mass measurements, the mass increased and decreased for both materials, indicating that some material may have been lost when transferring the samples from the water baths to the balances; this effect was more pronounced for P + coverB. Table 4 indicates that the tannins concentration in P + coverB is less than that in P + coverD, i.e. either the curing time or the tannins in P + coverB insufficient to form complexes with iron and the formation of a compact film structure that would protect the mortar. A poor bond between the cover and the mortar may have led to an instability of the surface cover and increased the likelihood of the cover debonding from the substrate and subsequent mass loss. Therefore, the results for P + coverB should be viewed as not having significant water ingress rather than water egress. It should be noted that, from our on-site interviews, *beini* is not used to cover wall surfaces; i.e. our results support the traditional knowledge of the local community. However, it is clear from Fig. 17 that applying *dawadawa* or *beini* as a surface cover can protect the underlying material during a short saturation period, for example, during heavy rain.

Notably, the results for P + wD closely match those found for the P material for the first hour of testing. The same was found for the PR mixes; incorporating *dawadawa* or *beini* within the material made no significant difference to capillary uptake. Yi et al. [39] demonstrated that tannin causes deflocculation of the clay matrix, which, combined with blocking soil pores with the iron-tannin complexes, reduces the absorption rate. That no improvement was found here on adding biostabilisers indicates that the distribution of the biostabilisers within the material matrix arising from the traditionally used concentrations of these solutions could not

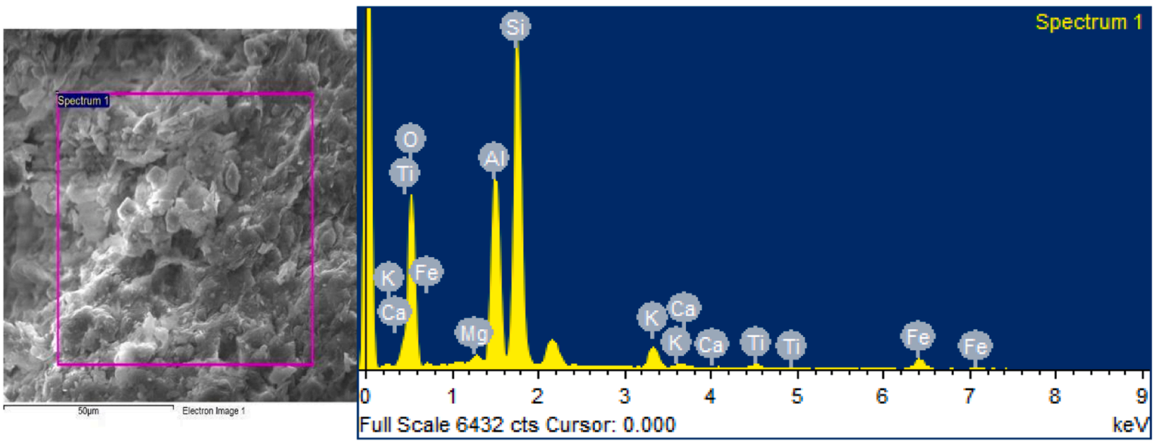


Fig. 19. SEM/EDS for plain mortar.

prevent water from imbibing through unstabilised pore channels. Increasing the concentration could improve this performance. However, we must note the associated cost in time and effort of harvesting more raw material and the greater fluid viscosity, which may delay or prevent mixing if relying on manual methods. Given these concerns, mixes incorporating *dawadawa* or *beini* in the solution (+ wD and + wB) were not examined further.

Figs. 17 and 18 show that all of the PR mixes behaved similarly. Table 4 shows that rice husk contains no tannins and cannot contribute to stabilisation. It is, therefore, likely that the presence of rice husk interfered with any stabilising or waterproofing reaction between the dawadawa or beini and the clay, for example, if the rice husk fibres absorbed the *dawadawa* and *beini* solutions, reducing the tannin-iron complex availability for polymerisation. Consequently, all PR mixes shared the same behaviour and could not benefit from the surface protection observed for P + coverD or P + coverB [37]. Although all PR mixes displayed greater capillary absorption in the first hour of testing (Fig. 17), the performance after three days resembled that of the plain mixes either with coverings (+ coverD or + coverB) or with a solution substitution (+ wD). Incorporating rice husk may, therefore, provide some form of longer-term protection from water absorption than plain soil. Notably, Fig. 18 shows that all of the mixes prepared with *dawadawa*, *beini*, and/or rice husk surpassed the performance of the plain mix after three days of absorption. However, We should note that adequate drainage must also be present, as none of the treatments could resist water entirely, and a wet earth material may be prone to structural failure [3].

3.4. SEM/EDS

The mixes using *dawadawa* or *beini* as surface covers (i.e., those that showed improved resistance to water ingress) were selected for further testing using SEM/EDS compared to the P mortar and the PR mortar. SEM micrographs and the EDS spectra are shown in Figs. 19–22, and the resulting elemental distributions are given in Table 6.

The SEM analyses reveal the existence of a crystalline structure for all specimens. However, voids are apparent within the structure of P + coverB (Fig. 21), which seem to be absent from P, P + coverD, and PR. Voids within the surface structure likely contributed to the poorer absorption performance and debonding of the surface treatment for P + coverB versus P + coverD, as a greater cross-section of open void space was available for imbibition.

The results presented in Table 7 show similar elemental distributions for each mix ($p = 1$). An overall similarity is expected, as each mix differs only in the presence of a small amount of biostabiliser, and each biostabiliser utilises a similar stabilisation mechanism. Here, the similarity indicates that the variation in capillary absorption and mechanical performance was not associated with a change in the properties of the underlying mortar.

Table 7 shows that the amount of Si was reduced between the plain and biostabilised mixes. According to [7], the presence of water can lead to the dissolution of silicate structures. This dissociation is also favoured in the presence of OH^- groups, which were more prevalent in the *beini* solution (pH 7.06 versus pH levels c.5 for the other materials, Table 4).

The amount of O also increased, principally for P + coverB. However, the Fe content is higher in the P + coverD samples and lower in P + coverB in comparison to the plain and PR mortars, indicating that *dawadawa* was more successful than *beini* in creating the iron-tannin complexes in contact with oxygen required to bind the material and reduce water absorption. This supports the discussion presented above regarding the likely loss of binding between the *beini* cover and the mortar. The amount of Fe present in PR was also similar to that in the plain mix, i.e. what iron was present may have been involved in reactions with the rice husk and, subsequently, was not available to create complexes on the addition of *dawadawa* or *beini*, again as postulated in the previous section. Based on the results, it can be suggested that complex accumulation and subsequent oxidation are the main reasons for improving water resistance.

4. Conclusions

Earth construction prevails in Northern Ghana. However, the susceptibility of earthen infrastructure to water-related issues poses a considerable challenge to the resilience of these structures, particularly in view of increased flooding due to a combination of climate

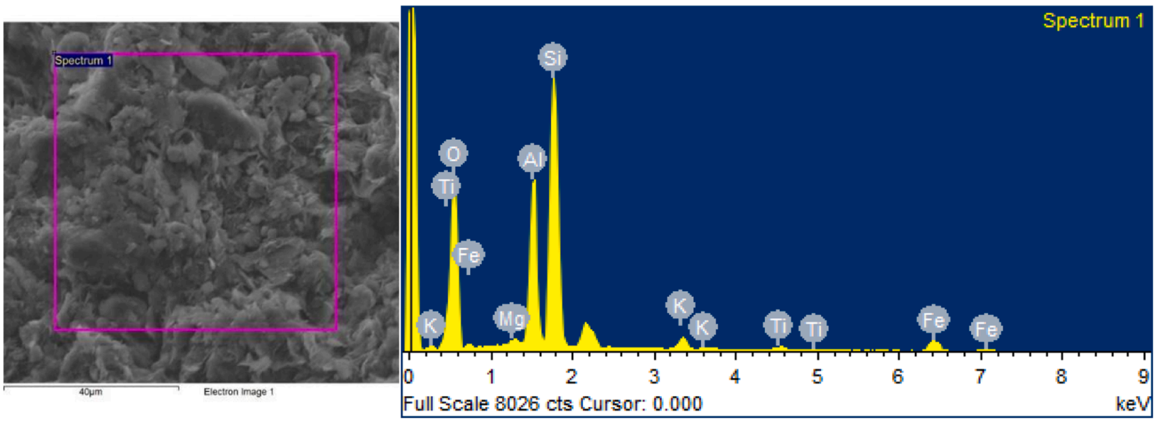


Fig. 20. SEM/EDS for P + coverD.

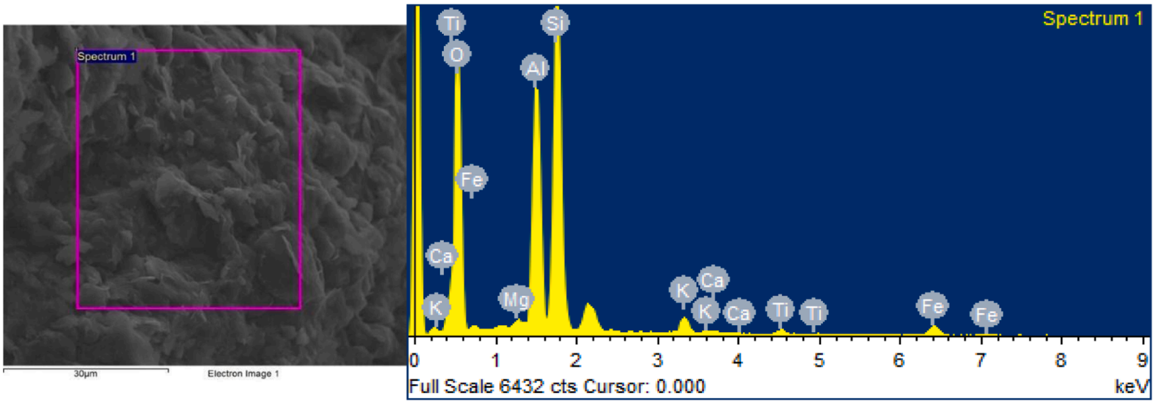


Fig. 21. SEM/EDS for P + coverB.

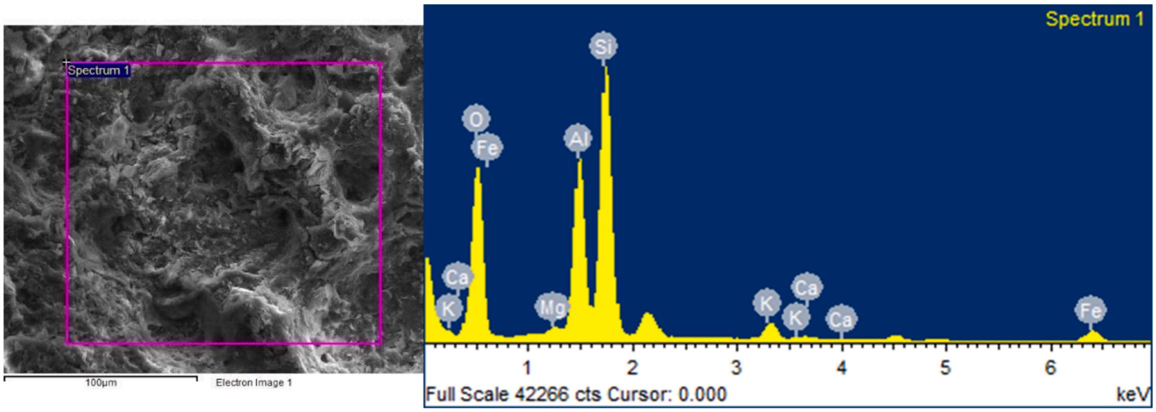


Fig. 22. SEM/EDS for PR.

Table 7
EDS analysis of plain, P + coverD, P + coverB and PR mortars.

Plain mortar			P + coverD			P + coverB			PR		
Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%	Element	Weight%	Atomic%
O	51	65.68	O	53.1	67.56	O	56.6	70.27	O	54.3	68.41
Mg	0.57	0.49	Mg	0.56	0.47	Mg	0.44	0.36	Mg	0.67	0.55
Al	13.2	10.09	Al	13.7	10.3	Al	12.8	9.38	Al	13.9	10.41
Si	28.2	20.65	Si	26.3	19.07	Si	25.5	18.06	Si	25.5	18.27
K	2.49	1.31	K	1.53	0.8	K	1.36	0.69	K	1.96	1.01
Ca	0.26	0.14	Ca	0	0	Ca	0.2	0.1	Ca	0.26	0.13
Ti	0.81	0.35	Ti	0.7	0.3	Ti	0.6	0.25	Ti	0	0
Fe	3.5	1.29	Fe	4.12	1.5	Fe	2.52	0.89	Fe	3.38	1.22
Totals	100		Totals	100		Totals	100		Totals	100	

change and changes in land use, such as deforestation. Adopting sustainable construction practices that utilise nature-based materials can play a crucial role in increasing the resilience of these traditional buildings. Moreover, earthen buildings have lower embodied carbon than modern construction materials like concrete. Using locally available earth and waste materials for construction helps shorten the supply chain of raw materials, reducing resource depletion.

One nature-based approach to improving the water resistance of earth-based construction materials is using biostabilisers. Solutions formed from the husk of the African locust bean, locally called *dawadawa*, and the roots of the *beini* plant, both of which are sources of tannins, are commonly used biostabilisers in the region. Locals also add rice husk to the soil to improve its performance through fibrous reinforcement. However, the literature highlights variations in performance when these biostabilisers are used. This study evaluated the efficacy of traditional biostabilisation practices from Wa and Tamale using *dawadawa* (D), *beini* (B), and rice husk (R). In addition, replacing the water component of an earth mix was also explored (+ wD and + wB), alongside the traditional use of the biostabilisers as a surface treatment (+ coverD and + coverB).

Dawadawa was found to have a higher degree of polymerisation compared to rice husk and *beini*. Testing also revealed no significant changes to the compressive strength between the plain mix and those containing or covered with *dawadawa* or *beini*. Results showed an overall reduction in compressive strength by 20% when adding rice husk (PR). The flexural strengths for all mixes were similar, as the weaker rice husk (in compression) could resist cracking under flexure. Traditional biostabilisers are, therefore, not detrimental to mechanical performance but cannot improve it.

Water absorption via capillarity testing demonstrated that samples coated with either *dawadawa* or *beini* solution (P + coverD, P + coverB) were successfully able to resist water ingress for 15 min, as might occur during heavy rain, and consistently outperformed the other mixes tested. The P + coverD mix surpassed P + coverB as the latter was more porous and was less able to create iron-tannin complexes, resulting in poorer binding between the treatment and the soil and mass loss from the treated surface. It must be noted, however, that none of the tested mixes resisted water ingress entirely, i.e., adequate drainage must be present to protect the walls, and a surface treatment must be used.

Mixes where *dawadawa* or *beini* solutions were used to replace the water exhibited similar absorption behaviour to the unmodified mixes. Adding rice husk to the material counteracted the advantage of a *dawadawa* or *beini* surface treatment; EDS testing demonstrated that the rice husk interfered with forming iron-tannin complexes. Therefore, complex accumulation and subsequent oxidation are the main reasons for improving water resistance. For the local communities, the results presented here indicate that omitting rice husks may improve local practices if aiming for greater water resistance. However, no other advantages of including rice husk, such as reduced shrinkage on drying, have been explored in this work.

The results presented in this paper support the local knowledge and practices in Northern Ghana of using *dawadawa*, *beini*, and rice husk to improve the resilience of earthen structures to water damage. As *dawadawa* proved the most successful, promoting *dawadawa* for construction may encourage agro-industry in the region.

CRediT authorship contribution statement

Hazha Mohammed: Formal analysis, Investigation. **Ibrahim Yakubu:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Ibijoke Idowu:** Formal analysis, Investigation, Validation. **Irene Appeaning Addo:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Christopher T.S. Beckett:** Funding acquisition, Formal analysis, Data curation, Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Ana Brás:** Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization, Validation, Visualization, Writing – original draft, Writing – review & editing. **Alexandre S. Gagnon:** Writing – review & editing, Formal analysis, Investigation, Validation, Writing – original draft. **Rosalind Jones:** Formal analysis, Investigation, Writing – review & editing. **Yuner Huang:** Writing – original draft, Validation, Methodology, Investigation. **Fred Owusu-Nimo:** Writing – original draft, Methodology, Investigation.

Declaration of Competing Interest

Ana Bras reports financial support was provided by Liverpool John Moores University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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