Strength and durability of biostabilised Ghanaian mud bricks

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Abstract. Communities in northern Ghana (Tamale and Wa) rely on earthen materials to construct affordable houses. However, these traditional practices are threatened by climate change: repeated flooding is triggering a transition to using cement-based building materials, and urban expansion and loss of biodiversity threaten the source of biostabilisers traditionally used to protect structures from water damage. Local builders currently rely on cementitious or bituminous renders to protect earthen houses, but these can trap water within the walls and so increase the likelihood of failure instead of protecting the buildings from harm. Such materials are, however, viewed as being prestigious and local people race to be able to apply them to their homes, creating a vicious cycle of earthen building degradation.

This paper explores the possibility of using traditional Ghanaian biostabilisers *dawadawa* and *beini* in communities in northern Ghana to create water-resistant earth renders, to stabilise earth bricks and avoid the need for cement or bitumen. Methods used in Tamale and Wa to manufacture mud bricks were identified through field studies and used to recreate specimens in UK laboratories. The compressive strength and resistance to water (from immersion or dripping water) were tested for unstabilised bricks and bricks stabilised with a solution of *dawadawa* or *beini*. The results indicate that *dawadawa* can quadruple the resistance of mud bricks to water damage for no loss in mechanical properties, creating a strong incentive to protect and manage this resource.

Keywords: Biostabilisers, African locust bean, *dawadawa*, *beini*, Mud brick, Ghana.

1 Introduction

Mudbrick construction is a notable feature of building practices in numerous African communities, particularly in rural areas where alternative construction materials are scarce. In certain regions of Ghana, such as in Tamale and Wa in the north, mud brick construction is an essential aspect of the local architectural heritage and an economical and easily accessible building material [1,2]. However, multiple factors are driving households to shift from earth-based construction, for example: the high labour demand; the lack of access to local building materials; frequent maintenance requirements; the growing perception that earth-based buildings cannot withstand the region's recurrent floods; the desire to be 'modern'; and the desire to earn rental income (tenants demand prestigious structures) [3-5].

Climate change in northern Ghana means that the local climate is characterised by extreme weather-related events, including droughts, variable rainfall, and pluvial and fluvial flooding [6,7]. Rain and pooling water threaten the stability of earthen houses by eroding material and weakening the mechanical properties if water becomes absorbed [8]. Local communities have turned to cementitious or bituminous materials to protect their houses from water damage. Depending on the available budget, families may opt to build the lower courses of a new wall using cement or cement-sand blocks to protect a surmounting earth wall from capillary rise, surface water, and erosion via water splashing [3]. Cement mixed with sand may also be used as a wall render: a process to which locals aspire as the render covers the (purportedly) inferior earthen materials. Alternatively, sand can be mixed with bitumen and used car oil: a recent technique that households in the peri-urban zones of Tamale are beginning to adopt to prevent erosion [3]. The general belief is that rendering buildings with differing mixtures of sand, cement, bitumen and used engine oil keeps walls stronger and more resilient to damp conditions [9]. However, cementitious or bituminous renders bond poorly with earth, so new rendering must be applied annually. Furthermore, using an impermeable render prevents moisture loss from the walls, leading to rising dampness and a gradual weakening of the wall base. The loss of render also damages the underlying earthen material, increasing the likelihood of failure should flooding occur [8].

Improving construction materials' properties while reducing their environmental footprint is critical for developing regions [10]. Fieldwork carried out by the authors in northern Ghana [3] showed that the local communities traditionally mix solutions derived from the African locust bean (*Parkia biglobosa*, locally called *dawadawa*), and the roots of the *beini* plant (*Acroceras spp.* family), and waste from shea (*Vitellaria paradoxa*) butter processing with lateritic soil to create water-resistant mud plasters for cob or earth brick walls. *Dawadawa* and *beini* are sources of condensable and hydrolysable tannins biostabilisers [11]. 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, leading to the formation of tannin-iron complexes due to the iron content of the lateritic soil [12].

The traditional use of *dawadawa* or *beini* renders to protect earth walls has been demonstrated to be effective in the past [2,3,5]. However, it introduces an additional process to constructing a house, and if the render is not properly applied or maintained, its effectiveness is limited or negated. This paper explores extending the use of *dawadawa* and *beini* solutions in northern Ghana to stabilise and hydrophobise the mud bricks, to provide water resistance without the need to apply renders.

2 Methodology

Earth bricks were manufactured in the UK laboratories following local practices and tested for their mechanical properties and their resistance to water versus immersion, capillary absorption, and drip erosion.

2.1 Materials

Field studies were completed in Tamale and Wa in 2021. Housing topologies, construction materials, and procedures were analysed (amongst other aspects) and local soils sampled and characterised. These soils were reproduced in the UK laboratories to match (as closely as possible) the local soil particle size distributions and mineralogies (given the need to supply iron for the biostabilisation). The particle size distributions of brickmaking soils taken from superficial ("NRA 001", optimum water content 11.2%, maximum dry density 2.10 g/cm^3 (Standard Proctor compaction)) and deeper ("NRA 003", optimum water content 10.6%, maximum dry density 2.28 g/cm^3) deposits and that of the reproduced material are shown in Figure 1. It is notable that the gravel content (>2 mm) of these bricks is significant (>40%), which is contrary to adobe bricks, where it can be as low as 5% (e.g. [13]).

2.2 Biostabiliser solutions

The biostabiliser solutions were prepared following the traditional methods used in northern Ghana. Fresh *dawadawa* and *beini* samples were collected in Ghana and shipped to the UK laboratories for testing.

One kg of dry *dawadawa* husks was immersed in 10 kg of room-temperature water for 72 hours, whereafter the remains of the husks were removed (Figure 2). The *beini* roots were pulverised with a mallet to reveal the fibres (Figure 3). 1 kg of root fibres were soaked in 20 kg of room-temperature water for two hours to create the solution. The *dawadawa* solution had a viscosity like water. However, the solution derived from *beini* had a thick, gel-like consistency.

2.3 Specimen manufacture

Bricks are manufactured on-site by shovelling moist soil, close to the optimum water content, into an open-topped mould, as shown in Figure 4. The water content is not measured on-site; instead, the builder judges the consistency by eye and feel [3].

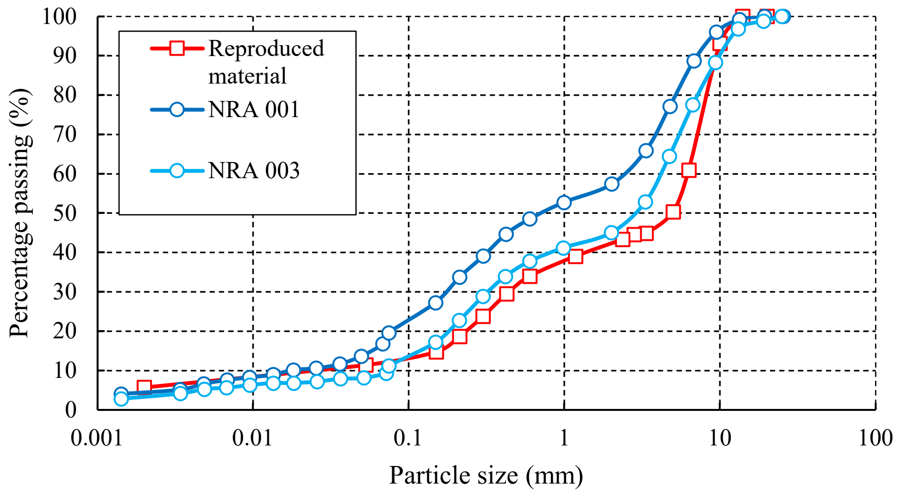

Fig. 1. Particle size distributions of the site soils (NRA 001 and NRA 003) and the reproduced material for testing in UK laboratories.

Fig. 2. Processing *dawadawa* husks. From left to right: the intact husks; the husks soaking in water; the husks after 72 hours (about three days); the extracted solution.

Fig. 3. Processing *beini* roots. From left to right: the intact root; the root after pulverizing; the roots soaking in water; extracting the roots to use the solution.

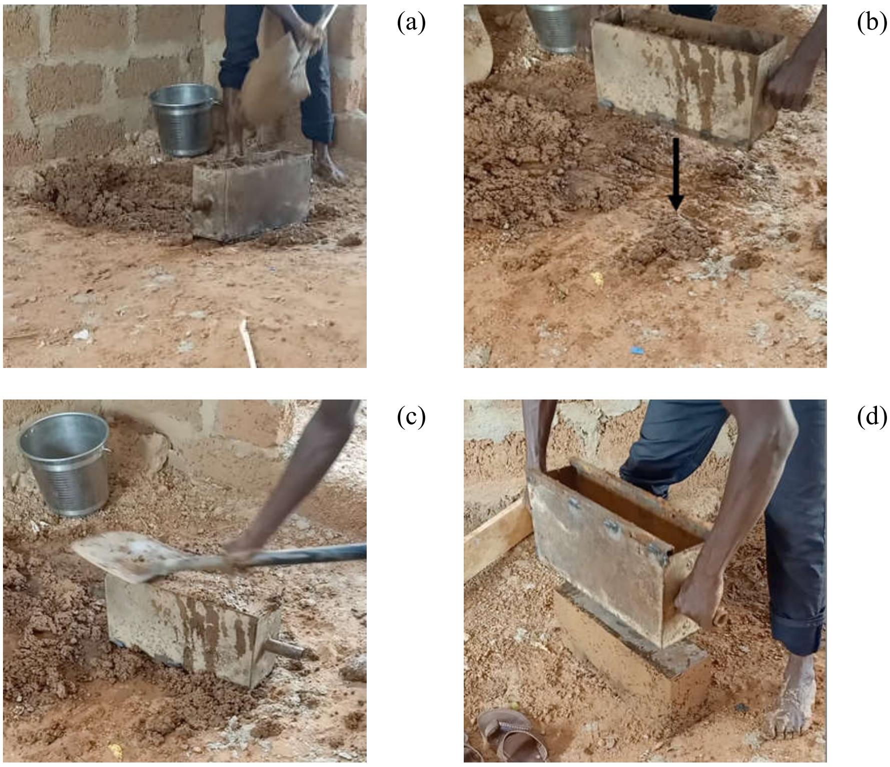

Fig. 4. Brick manufacturing process in Wa: a) filling the mould; b) tamping the mould to achieve the desired density; c) levelling the top of the mould; d) flipping the mould to remove the finished brick

However, matching the water content at manufacturing is critical to establish the correct material microstructure [14]. The manufacturing water content was determined by a visual similarity to the material consistency and flow obtained from site videos. Although it is unlikely to provide a perfect match, the consistency around the optimum water content is readily identifiable due to a change from a 'dry' to a 'wet' behaviour. The matching water content was 11%, notably identical to that found via Standard compaction.

The site bricks are manufactured using custom moulds owned by the individual builder. However, the size approximately matches standard cement blocks (440 mm x 220 mm x 100 mm). Bricks for this project were manufactured at half of this size (220 mm x 220 mm x 100 mm) to preserve material but to provide representative specimens. The moulds were oiled and comprised a false bottom to facilitate specimen removal. After manual tamping (until no further compaction occurred), the final dry density of the bricks was 1756 kg/m^3; although this is less than the maximum Standard Proctor dry density, it is expected given the lower (manual) compactive effort. Biostabilised specimens were manufactured by replacing the water with the same mass of the biostabiliser solution and tamping until no volume change occurred, to match the unstabilised specimen compaction conditions. The stabilised material was mixed until uniform in colour; the significance of biostabilisers on the mix workability and any variability in the mixing time are discussed in the following sections.

Given the high gravel content, it is impossible to core or lathe a cylindrical sample from a full brick for compressive strength testing. Therefore, 100 mm diameter, 200 mm high specimens were manufactured for compressive strength testing using the same procedure as for the bricks. All specimens were dried under conditions of c.18°C and c.40% relative humidity for 21 days, whereupon they had reached a constant mass. The average final water content (across all specimens) before testing was 1.3% (standard deviation = 0.4%).

2.4 Compressive strength testing

Specimens were tested at a displacement rate of 0.3 mm per minute. Loading cycles were performed at 40% of the compressive strength (determined *a priori*), also at 0.3 mm per minute, to assess the elastic stiffness.

2.5 Resistance to water

Absorption testing followed the procedure specified in [15] using the cuboidal specimens. Florist's foam was used as the capillary wick and the mass of water (room temperature) absorbed by the specimens was measured at 5, 10, 20, 30, 45, 60, 90, 120, 240, and 360 seconds.

The immersion test followed IS 3495-1992 [16]. However, the specimens were unable to resist immersion for 48 hours. Therefore, the test was modified to record the process of defect formation and was terminated when the specimen was no longer able to be removed from the water without collapsing.

Drip testing followed the Swinburne Accelerated Erosion test procedure [17]. A 400 mm high water tank terminating in a 5 mm diameter, 100 mm long outflow tube was suspended 1 m above the specimen (i.e. a total water head of 1.5 m). The specimen was inclined at a 2:1 slope ratio (27 degrees). The test ran for 10 minutes, and the subsequent depth of pitting was recorded using a 10 mm diameter flat-ended rod.

3 Results and Discussion

3.1 Compressive strength

Example compressive strength results for the *dawadawa* specimens are shown in Figure 5. Results for all specimens are given in Table 1, where the stiffness was determined from a linear fit to the reloading portion of the load cycle (R^2 quality of fit given). Strain was determined from the global change in length and may underestimate the strain in the unconfined region.

Except for one unstabilised specimen, the unstabilised and *dawadawa* specimens achieved similar compressive strengths at three weeks. Literature results for tannin-stabilised sandy gravel soils are not available, however these strengths are lower to results found for tannins-stabilised clayey soils found by [18] (1.77-3.32 MPa) but similar to results from [19] (c.0.6 MPa) for comparable water contents at testing. [18] also noted a marginal loss in compressive strength for clay mortars mixed with tannins derived from *P. biglobosa* (unfortunately for an unspecified curing time) and [19] noted a slight increase in compressive strength on oak-tannis addition after 60 days of curing, also for a clay mortar.

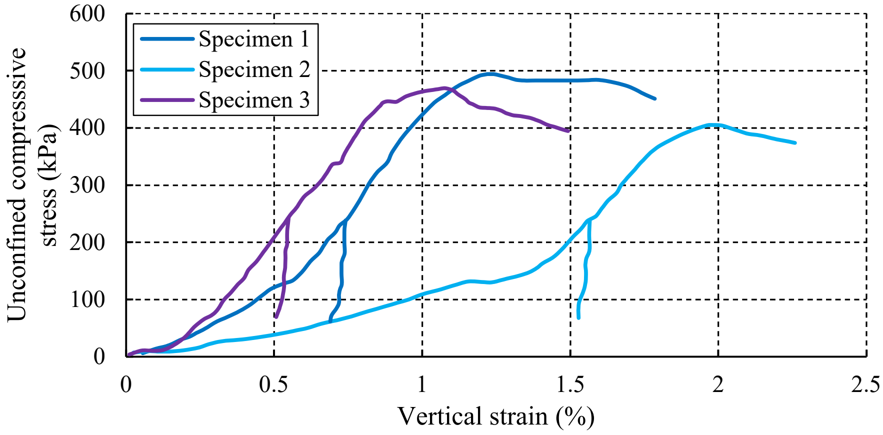

Fig. 5. Unconfined compressive strength test results for specimens stabilised with *dawadawa*

Table 1. Unconfined compressive strength and stiffness results for unstabilised and *dawadawa* and *beini* biostabilised specimens.

Specimen type	Water content (%)	Compressive strength (kPa)	Stiffness ($0.4\sigma_{fc}$) (MPa)	Stiffness R^2
Unstabilised	1.40	0.62	185.6	0.996
Unstabilised	1.03	0.40	250.9	0.977
Unstabilised	0.93	0.49	200.0	0.984
Beini	1.32	0.47	314.5	0.675
Beini	1.34	0.19	-	-
Beini	1.51	0.19	109.2	0.996
Dawadawa	1.19	0.49	328.5	0.812
Dawadawa	0.98	0.46	354.0	0.898
Dawadawa	0.94	0.41	445.2	0.875

Notably, the *dawadawa* specimens were significantly stiffer (single-factor ANOVA $p = 0.016$) than the unstabilised specimens. However, *dawadawa* did not affect the compressive strength. On mixing, it was seen that the *dawadawa* materials behaved as if wetter than the other mixes, indicating that the effect of the tannins complexes is to flocculate the soil and to transition the compaction curve to a lower optimum water content (an equivalent would be a plasticiser effect for concrete) [20].

An alternative investigation may, therefore, consider manufacturing stabilised specimens to the same consistency, and not solution content, as the unstabilised specimens; it might be that reducing the amount of *dawadawa* solution would achieve a higher dry density after tamping and, thereby, an increase in both strength and stiffness.

Unlike for *dawadawa*, the *beini* specimens displayed either similar or significantly lower compressive strengths and higher or lower stiffnesses than the unstabilised specimens; the causes of the poorer performance and the high variability of the *beini* specimens are discussed in the following section.

3.2 Immersion, absorption, and drip testing

Results for the resistance to water tests are given in Table 2. Note that the tests were performed on different specimens; the results do not reflect multiple tests performed on one given specimen. Insufficient *dawadawa* was available to manufacture three specimens per test. Only one specimen was tested per material for drip testing.

Table 2. Immersion, absorption, and drip test results

Specimen type	Immersion time to failure (seconds)	Absorption rate (kg/m^2min, 5 seconds)	Absorption rate (kg/m^2min, 300 seconds)	Pitting depth (mm)
Unstabilised	430	2.18	0.11	
Unstabilised	300	1.91	0.11	100
Unstabilised	420	1.91	0.20	
Beini	80	0.81 †	Failed	
Beini	1346	8.18	Failed	58
Beini	130	6.82	0.69	
Dawadawa	1740	3.54	0.24	33
Dawadawa	1710	1.09	0.14	

† c.10 g mass lost at the start of the test due to damage, which increases this value to 6.30 kg/m^2min. The remaining trend matched the other *beini* specimens.

Immersion test results showed a significant increase in durability with the addition of *dawadawa* (p-value unavailable due to the number of specimens). However, adding *beini* to the mix significantly reduced the durability. The absorption results showed a slight increase in the absorption rate between the unstabilised and *dawadawa* specimens but, again, a considerable degradation of the *beini* specimens; two of the *beini* specimens lost their integrity (preventing mass measurements) within the first minute of testing, and all specimens had significantly greater initial absorption rates (noting the mass error due to damage). The unstabilised specimens failed the drip test (100 mm of erosion is the full specimen thickness). However, the *beini* and *dawadawa* specimens showed improved performance.

Both the mechanical and durability testing revealed significant variability in the performance of the *beini* specimens. During manufacture, it was found that the mixing time for *beini* was crucial; shorter times produced weaker and less stiff specimens with a coarse surface texture. These specimens were also prone to slumping on removing from the mould (deformed specimens were not tested mechanically but were suitable for durability testing). Longer mixing times resulted in an improved surface texture, greater integrity on removal from the mould, and a greater colour change, indicating improved (early) formation of iron-tannin complexes [21].

4 Conclusions

This paper presented results for testing the ability of *dawadawa* and *beini* solutions to stabilise and protect earth bricks against water damage. Fieldwork examined methods used to produce the earth bricks, which were replicated in UK laboratories. The manufacturing process (material deposition, water content, and compacted density) were determined through a visual match to site examples and a match to expected soil mechanical behaviour (compaction water content for similar levels of compaction).

Compressive testing demonstrated that neither *dawadawa* nor *beini* were able to improve the compressive strength of the material. *Dawadawa* increased the material stiffness. *Beini* specimens were highly variable but displayed reduced strength. Similarly, *beini* specimens were unable to resist water damage via immersion or absorption. *Dawadawa* specimens displayed similar capillary absorption rates to unstabilised specimens but provided a four-fold improvement in resistance to immersion. Both the *beini* and *dawadawa* solutions resulted in an increase in pitting erosion resistance.

Throughout testing, *beini* specimens displayed highly variable behaviour due to difficulties encountered in the mixing process. Greater mixing times, perhaps extending to hours to match site practice, are required to ensure adequate material properties, suggestively through providing sufficient time for the formation of iron-tannin complexes. However, the most superior *beini* specimens were unable to surpass those stabilised with *dawadawa* for any of the completed tests. *Dawadawa* is therefore a suitable and reliable method to improve the water-resistance of earthen bricks in northern Ghana without compromising their mechanical characteristics.

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