

Communication

Durability of Compressed Earth Bricks: Assessing Erosion Resistance Using the Modified Spray Testing

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Abstract: The discussion in this paper is part of research directed at establishing optimal stabilization strategy for compressed bricks. The deployment context for the use of the compressed bricks was Dar es Salaam (Tanzania) where manually fabricated bricks are increasingly being used in low cost housing units. This discussion specifically focuses on strategies that can be used to counter deterioration due to wind-driven rain erosion. The impact of using cement, lime, fiber and a commercial stabilizing fluid was assessed. Factory-produced bricks were used for benchmarking. The durability of the bricks was assessed using the “modified” Bulletin 5 Spray Test. The different brick specimens were sprayed with water at 2.07 MPa and 4.14 MPa over one-hour time period while measuring the depth of erosion every 15 minutes. Factory-produced bricks hardly eroded at both 2.07 MPa and 4.14 MPa pressure levels. The maximum depth of erosion for Soil-Cement bricks ranged from a maximum of 0.5 mm at 2.07 MPa water pressure to 0.8 mm at 4.14 MPa. The maximum and minimum depths of erosion for Soil-Cement-Lime bricks were 25mm and 17 mm respectively. The inclusion of natural fiber in the bricks resulted in a sharp increase of the erosion depth to a maximum of 40 mm at 2.07 MPa and 55 mm at 4.14 Mpa. As the use of natural fibers and lime enhances some physio-mechanical properties, further research is necessary to determine ways of achieving this goal while maintaining acceptable levels of erosion resistance.

Keywords: durability; compressed earth brick; erosion testing

1. Introduction

The “green” movement has greatly influenced the design and construction of the built infrastructure across the globe. There is a growing interest in delivering “high performance building” systems. A “high-performance building” is as defined in the Energy Policy Act of 2005 [1]: “a building that integrates and optimizes all major high performance building attributes, including energy efficiency, durability, life cycle performance, and occupant productivity.” This view was echoed by the US building enclosure community in 2008 when they launched a formal initiative which underscored the linkages between energy efficiency, durability and the quality of the indoor environment [2]. The discussion in this paper focuses on the realization of high performance buildings through developing more ecological and durable walling elements based on the use of compressed earth bricks. Ecological goals are slightly less difficult to quantify compared to the durability issues that have now been formally linked to the quest for green materials. Material use greatly impacts on both the ecosystem in general and the delivery high performance building units. Building materials can account for as much 70–75% of the total cost of construction. The most commonly used construction materials include cement, steel, timber, plastics and glass. The manufacture of most conventional materials requires expenditure of non-renewable resources in various forms. Many of these manufacturing processes are detrimental to the environment. For example, steel and cement factories emit toxic gases leading to air pollution. Excessive quarrying of limestone for lime burning or cement manufacturing has disturbed the ecological balance. In addition, these conventional materials are usually transported over great distances thus contributing to the spending of fossil fuel energy.

Some of the ecological concerns can be addressed through adopting earth-based construction techniques. Documented ancient forms of earth construction suggest that this practice originated in the Middle Eastern region. Specific examples include the 7,000 BC Neolithic family villages in Mesopotamia. Similar examples from this era have been found in Crete, Egypt and India [3]. In some parts of the world, low income communities inhabit semi-permanent mud wall structures. This practice is generally limited to rural settings. Other common examples of earth wall construction based on the classification in the New Mexico Building Code have been summarized in the table below. Not all the examples in this table are ecological. The use of earth in the form of burnt bricks is harmful to the environment. The burning of bricks in the vicinity of fields damages plant life while the extraction of soil for brick making causes collection of water in pools creating unhygienic conditions and erosion of good agricultural soil.

The use of earth-based technologies has been greatly limited by concerns of their physio-mechanical properties [4,5]. Consequently, there are restrictions on their use. For example, in the New Mexico Building code Section 12.7.4.23 which governs the use of Compressed Earth Block Construction, a general clause “A” forbids their use in any building more than 2 stories in height. Compressed bricks are also less durable than conventional building materials [4-9]. In the recent years stabilizers, such as cement, are added to the soil to improve the physio-mechanical properties of the resulting wall. Despite these developments, the use of low cost, labor intensive and energy efficient traditional building materials and techniques such as compressed bricks remains problematic since they require frequent repairs [10]. This problem is more apparent in hot and humid conditions such as the deployment context for the study—Dar es Salaam Tanzania.

Table 1. New Mexico classification of earth wall construction.

Classification	Description
Stabilized Adobes	Water resistant adobes made of soils to which certain admixtures are added in the manufacturing process in order to limit the adobe's water absorption.
Untreated Adobes	Untreated adobes are adobes which do not meet the water absorption specifications.
Hydraulically Pressed Units/compressed earth bricks	Sample units must be prepared from the specific soil source to be used and may be cured for a period of twenty eight (28) days.
Fired bricks (Burnt adobe)	The term "burned adobe" shall refer to mud adobe bricks which have been cured by low temperatures kiln firing.
Rammed Earth	Based on tamping moist soil in a form.

The poor durability performance and associated short service life of earth-based bricks reduces the sustainable use of the material. The approach adopted in this paper is based on Healthcote's [11] definition of minimum service life as 50 years. There is therefore need for a more structurally enhanced, energy efficient, environmental friendly, economical approach to developing compressed, earth-based bricks. A review of existing work has revealed the lack of a systematic approach to fabricating compressed earth-based bricks that recognizes the inter-connection between the bricks structural performance over the service life of the resulting building system and sustainability.

A significant amount of effort has gone into identifying deterioration agents. Factors causing deterioration of building materials can be broadly classified into intrinsic and extrinsic factors [12]. Intrinsic factors are things such as anomalies in the production process that affect the quality of the resulting material. Examples of extrinsic factors include weather elements and any other destructive agents that a building material may be exposed to during service. Environmental factors include climatic and meteorological agents as well as biological and chemical processes that are often compounded by pollutants [12]. Specific examples of extrinsic factors include precipitation, moisture, temperature, solar radiation, chemical attack and intrusion by organisms.

Materials such as compressed bricks are known to be highly variable making it difficult to develop models that can predict their durability properties. This problem can be addressed through researchers in this area collectively contributing to the development of a material database capturing a diverse set of input materials from different parts of the world. The research discussed in this paper is directed at doing just that. For this research, wind-driven erosion has been identified as one of the main deterioration mechanisms. The durability of the bricks was therefore assessed on the basis of their resistance to wind-driven rain erosion.

2. Methodology

After analyzing both soil and bricks from the Dar es Salaam (Tanzania), the authors identified a local source of similar soil within the North Florida region that could be accessed readily. A sieve test and hydrometer analysis established that the soil sample consisted of: 11% clay, 2% silt and 87% sand.

The position of this paper is that where the existing soil is not ideal for use in the production of compressed bricks, it is possible to improve its workability through blending with soil known to be rich in the missing ingredient or through the use of carefully selected stabilizers. Some studies have already demonstrated that with the appropriate use of stabilizers, it is possible to produce compressed bricks whose mechanical properties compare well to those of concrete blocks [10]. There are generally two approaches to improving the quality of soil: one involves mechanical stabilization and the other the use of additives such as chemicals and pozzolans. Mechanical stabilization can be achieved through (1) compaction, (2) using soil reinforcement such as geotextiles that can control moisture conditions or soil permeability, and, (3) using larger aggregates to improve the load bearing capacity of the soil. Because of the great variability in soils, any given stabilization strategy can only be expected to yield the desired results in limited number of soil samples. This notwithstanding, there are some general guidelines that can be used when making a selection. The approach that was adopted for this research was based on the guidelines developed by Haro Streeter [13] summarized in Table 2. Haro Streetler guidelines provide flexibility in choosing stabilizers based on what they refer to as the “response spectrum” for the different types of soil. Based on these guidelines, the authors established identified cement, lime and natural fibers as potential stabilizers for the soil in the research. Compaction was achieved using a manually-operated device, mirroring the fabrication process in Tanzania.

Table 2. General guidelines for selecting stabilizers for different soils.

Type of Soil/ conditions	Stabilizer
For nearly all types of soil	Portland cement
Medium, moderately fine and fine-grained soils	Hydrated lime
Coarse-grained soil with little if any fine grains	Fly ash
Cold climate applications	Calcium chloride
For increasing resistance to water and frost	Bitumen

General guidelines for mixing fractions for the stabilizers that were adapted for the study are summarized in the table below. Through experimenting with different recipes, it was established that the most ideal mix design for the soil that was being used was as follows: (1) 45.35 kg of soil, 3.17 kg of cement, (2) 45.35 kg of soil, 2.27 kg of cement, 3.17 kg of lime, (3) 45.35 kg of soil, 2.27 kg of cement, 0.45 kg of fiber, (4) 45.35 kg of soil, 2.27 kg of cement, 2.27 kg of lime, 1.13 kg of Aeonian brick Stabilizer. The fifth brick in the study were the factory produced interlocking bricks that were used in the study for benchmarking purposes.

Table 3. Guidelines on using specific binders in bricks.

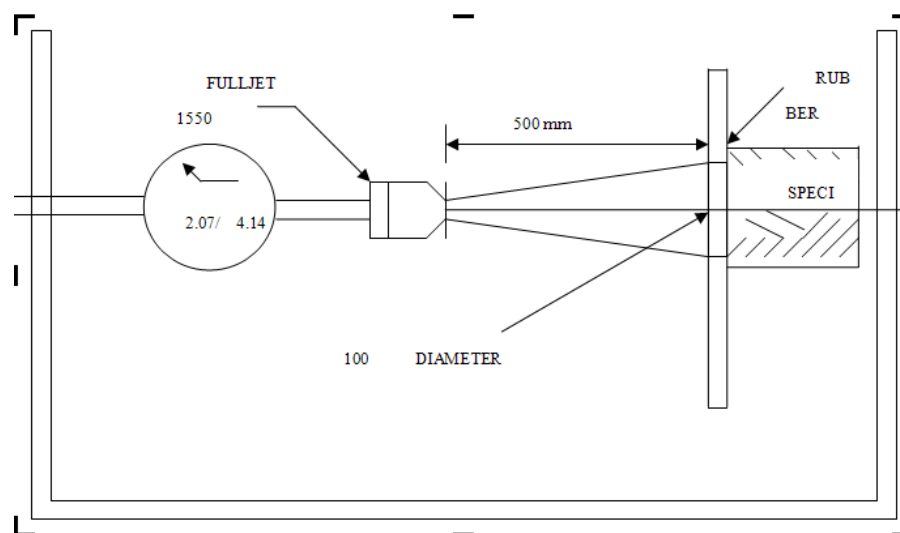
Stabilizer	Mixing Proportion
Portland Cement	Commonly used 6–10%, typically used 4–15%.
Lime	6–12%
Fly ash	Fly ash –30% and Soil –70% for making soil fly ash blocks
Bentonite	If the percentage of sand is greater than 50, add 4–6% of bentonite, less than 50, add 7–12% of bentonite.
Sodium Silicate	5%

The fabricated bricks cured through being exposed to sunlight for 2–3 weeks followed by air drying for a week. Water was sprinkled over the bricks to optimize the curing process. The cured bricks were stored under protective sheeting to minimize the risk of damage through, for example, rain-triggered erosion. After the fabricated bricks had cured (>28 days), their compressive strength was established.

The preceding section identified the main deterioration agents. Erosion, particularly the one triggered by wind-driven rain, was identified as a key deterioration mechanism. Consequently, the cured bricks were tested for their resistance to wind-driven rain erosion. This was used here as an indicator of the bricks durability. The authors acknowledge that rain is not the only factor that impacts on the durability of walls. However, it has been established that a wall's resistance to erosion, is indicative of its resistance to other degradation factors [11].

Ideally, to really understand the durability performance of a compressed bricks wall, one would have to track its performance over several years of exposure to climatic factors in the field. This not being a feasible option, some effort has gone into developing prediction models based on laboratory experimentation. The uniqueness of earth walls, using standard durability tests for conventional masonry walls would not result in meaningful data. Consequently, there are some tests that have been specifically developed for earth-based walls. The ASTM D559 Wire Brush Test is an example of a formally adopted procedure for testing the durability of earth bricks. It focuses on determining the minimum amount of cement requirement in Soil-Cement bricks. This test is not applicable for the research directed at characterizing durability problems that are largely attributable to wind-driven rain erosion. Bulletin 5 Spray Test was developed with wind-driven rain erosion in mind [11]. This method, along with its derivatives, has been used in Australia and New Zealand. Its use in predicting durability of earth-based bricks is in fact catalogued in the building codes for these countries. This suggests that there is a great potential for using this approach to develop durability prediction models for the case study context (Tanzania). It is important to note, that the existing models cannot be applied universally given the expected variability in performance based on the geographical context within which the application exists. Variation in performance can be attributed to factors such as soil property, intensity of rain, rain drop size and angle of incidence for the rain.

For this study, the authors modified Bulletin 5 Spray Erosion Test. It provides a logical basis for acceptance testing of earth building materials used in a particular climatic region. The test set up is as indicated in the schematic diagram in Figures 1 and 2. The specimens were placed with their external face surface exposed 0.1 m to a pressure washer spray. The nozzle was positioned 0.5 m from the face of the samples. Bulletin 5 Test involves spraying each specimen with water being emitted at a known pressure for one hour (or when failure occurs). Readings are taken every 15 minutes to establish the depth of erosion. By dividing the total depth of erosion by 60, one can establish the total depth of erosion in mm per minute, which must not exceed 1 mm/minute. In the ordinary Bulletin 5 Test, the bricks are subjected to water gushing out at 40 to 70 MPa. For this research, this pressure was deliberately compounded to 2.07 and 4.14 MPa to assess the resilience of the engineered brick. It is important to note that in this research, the authors were particularly interested in establishing whether or not it is possible to engineer compressed earth bricks that can withstand extreme weather conditions that are expected to become more common due to global warming.

Figure 1. Schematic view of the brick erosion test (Adapted from Heathcote [12]).**Figure 2.** Brick erosion test setup.

3. Results and Discussion

The compressive strength results have been summarized in Table 4. The factory produced bricks, which as indicated earlier, were used for benchmarking purposes, registered the highest value at 9,653 kPa. Of all the manually fabricated bricks, Soil-Cement-lime specimens emerged as superior registering compressive strength values of 8,274 kPa.

Table 4. Compressive strength.

Types of Brick	Compressive strength (kPa)
Soil-Cement	7,584
Soil-Cement-lime	8,274
Interlocking block	9,653
Soil-Cement-fiber	7,929
Soil-Cement-lime-fluid	6,895

The results for the bricks erosion tests have been summarized in Tables 5 and 6. This information can be used to develop prediction models for the durability of bricks. Based on the 1 mm/hour criterion for assessing the depth of erosion in Bulletin 5, all the different types of bricks have passed the durability test. As indicated in the preceding section, these bricks were exposed to compounded pressure values. Therefore these results suggest that they would withstand exposure to extreme weather conditions. From Tables 5 and 6, it is clearly that the factory-produced, interlocking bricks are totally erosion resistant. This notwithstanding, they do not constitute a feasible option for earth wall construction in developing economies in the short to medium term. The primary impediment will be resistance from the members of the local community—they work in the existing brick production processes as manual laborers. Secondly, based on the low per capita income of members of such communities, it will be difficult to secure the initial capital outlay required for mechanization at such a large scale. The authors are currently researching ways to improve the operations of the manual devices to result in bricks that have improved mechanical properties such as water resistance. This will be reported in subsequent publications.

Table 5. Brick erosion test result at 2.07 MPa.

Type of Brick	Time (minutes)	Depth of Erosion	Rate of Erosion (mm/minute)
Soil-Cement-Lime-Fluid	15	15	0.416
	30	17.5	
	45	25	
	60	25	
Interlocking bricks	15	<0.1	0
	30	<0.1	
	45	<0.1	
	60	<0.1	
Soil-Cement	15	0.1	0.008
	30	0.2	
	45	0.4	
	60	0.5	
Soil-Cement-Lime	15	17.5	0.375
	30	20	
	45	22.5	
	60	25	
Soil-Cement-Fiber	15	15	0.667
	30	25	
	45	35	
	60	40	

Table 6. Brick erosion test result at 4.13 MPa.

Type of Brick	Time (minutes)	Depth of Erosion	Rate of Erosion (mm/minute)
Soil-Cement-Lime-Fluid	15	17.5	0.50
	30	20	
	45	25	
	60	30	
Interlocking bricks	15	0.1	0.003
	30	0.2	
	45	0.2	
	60	0.2	
Soil-Cement	15	0.5	0.013
	30	0.6	
	45	0.7	
	60	0.8	
Soil-Cement-Lime	15	17.5	0.333
	30	18.5	
	45	19.5	
	60	20	
Soil-Cement-Fiber	15	25	0.917
	30	35	
	45	45	
	60	55	

All the bricks in the study had less than 1 mm/minute rates of erosion. Of all the manually fabricated bricks, the soil-cement ones registered negligible erosion rates. However, when compared against each other, it can be inferred that the use of lime and natural fibers such as coconut husks can be problematic as far as enhancing durability is concerned. This notwithstanding, it is impractical to eliminate them as stabilization options. As indicated in Section 2, soil types will have to be factored in when designing a stabilization strategy. For some soil types, lime/cement composites will be required. In addition, other stabilizers and additives may be necessary because of additional physio-mechanical properties required for the deployment context. If, for example, the wall element in question has to resist high tensile stresses, then locally available fiber strands such as coconut husks can be incorporated in the mix.

One may have to use some combination of stabilizers and/or additives to, for example act as binders, alter the effect of moisture or increase soil density. Given that placing the wrong type or wrong quantity of stabilizer or additive can be devastating to the overall project, it is therefore essential to start the design of any stabilization strategy with a good understanding of the soil type. From the erosion test, it is clear if that with an optimized stabilization strategy, stabilizers such as fiber or lime can be used without compromising the durability of bricks with respect to erosion resistance. It is important to note that the soil-cement-fiber bricks, having an erosion rate of 0.917 mm/minute, narrowly passed this test. This suggests that further work may need to be done to enhance their durability properties through experimenting with different proportions of cement and fiber. The

erosion test results can be used to identify a good compromise that would satisfy other design requirements while at the same time resulting in erosion rates that have a bigger safety margin.

4. Conclusions

Although the use of earth construction techniques in modern buildings has gained momentum in Sub Saharan African, the market share in countries such as Tanzania remains relatively small. Within this region, mud walls were used in traditional construction. During the colonial areas, the missionaries introduced the fired bricks, which are currently considered a less attractive option because of environmental concerns as the production process relies heavily on lumber. In the post-colonial area, compressed bricks have been introduced to different parts of Sub-Saharan Africa. Such usage is largely limited to small residential units; with many built environment professionals remain skeptical about their use largely because of their durability performance. During a three month field visit to Tanzania in 2008, the authors catalogued examples of degradation of earth walls that could be directly linked to the walls low resistance to water damage, particularly, the erosion of the walls due to the effect of wind driven rain. The erosion tests reported in the preceding section are consistent with the field observations.

The premise of this paper is that the use of the wrong stabilization strategy lies at the root of many of the durability challenges linked to the use of compressed bricks. A key objective in the research discussed in this paper was therefore designing a composite of stabilizers for the soil type identified in the project. There are many options for stabilization that can be explored. The decision should factor in the ease with each the stabilizer can be obtained without inflating costs through additional material transportation costs. In projects being executed in some parts of Tanzania, there has been an attempt to incorporate waste from the quarrying industry. From a material sustainability perspective, this is a desirable practice. Compressed bricks produced from crusher dust that has been stabilized with a combination of cement and another more eco-friendly additive (coconut fiber) off-sets the disadvantages of using cement would be ideal. In the absence of such industrial waste, then the fabrication will have to be done using locally available soil.

It is important to bear in mind the fabrication and testing of bricks was done in a controlled laboratory setting. In the field setting, it is more difficult to exert control over things which affect the quality of the bricks. It is therefore probable that some of the bricks, especially the ones incorporating lime in the mix may not withstand exposure to deteriorating agents. In addition, the depth of erosion needs to be put in perspective. In the case study context, load bearing walls are usually between 150 and 200 mm Thick. There are two levels of concern with the depth of erosion. The first one is structural—a 45 to 50 mm depth of erosion in a 100 mm Thick wall would trigger concerns over its structural integrity. The second level of concern, which is by no means less important, is the perception issue. In the case study context, there is a general perception among many professionals that compressed bricks are “cheap” (inferior quality) materials. To address both issues, researchers in this area would need to direct concerted efforts towards developing strategies that minimize the depth of erosion to values close to the ones attained for Soil-Cement bricks (0.5 to 0.8 mm).

Generally speaking, the use of compressed bricks can be embraced as a strategy for securing delivering high performance building system. However, as indicated in the introduction, durability has

in the recent years become a key metrics in the assessment of buildings from a holistic perspective. A high performance building is not only expected to perform well when assessed using ecological and life cycle costing tools; is also expected to perform satisfactorily throughout its required service life. This makes the use of compressed earth-based bricks problematic. Walls produced with such bricks have poor durability and associated short life service life. Should such elements fail prematurely, then the use of the earth-based bricks becomes a less desirable option.

There are some examples of earth buildings withstanding the test of time. However, such buildings are located in relatively drier regions. Outside of the drier climatic areas, earth walls are perceived as inferior materials. A key area of concern is their performance with respect to erosion resistance in areas that receive high annual rainfall amounts (averaging at least 800 mm). In addition, such buildings have also been well maintained. Following a comprehensive study of older earthen buildings, it also emerged that their durability is directly linked to significant investment in their maintenance and upkeep [5]. For many developers, such additional maintenance costs make earth wall construction a less attractive option. Compressed bricks have historically been used in low cost housing units within the Sub Saharan Africa, where the maintenance budget is generally non-existent. To build confidence in the material, there is a critical need for empirical data on the durability performance of compressed bricks. Data such as erosion test results presented in the preceding section can contribute to efforts directed at building confidence in the structural integrity of the material.

With a growing interest in performance-based specifications and the impracticality for generating empirical data from field-based studies, there is a need for several laboratory tests to be conducted to develop region specific models for predicting the durability performance of earth wall construction. The research discussed in this paper makes a valuable contribution to efforts direct towards just that. The combination of greener and structurally optimized stabilizers for earth-based bricks along with the extended life cycle of the resulting walling systems suggests that the sustainability of targeted buildings applications will surpass the current systems based on the use of earth-based bricks. The empirical data that has been generated in this research can be used in evolving specifications for compressed bricks to minimize their susceptibility to damage and deterioration due to the eroding effect of water. There are not silver bullet solutions; the realization of an optimized brick being an octopus of a problem requires making trade-offs. Efforts such as the ones reported in this paper are necessary if researchers in compressed earth bricks are to realize accurate models for optimizing the performance of earth-based bricks, especially within in hot and humid climatic conditions where the bricks remain very susceptible to moisture damage.

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