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Rainwater Erosion and Abrasion Analysis of Soil Bricks Stabilised with Cow-dung in the Savannah Ecological Region

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ABSTRACT: *The continuous use of soil materials for housing in rural communities in Africa for purposes of cost affordability, sustainability and cultural reasons is important and requires soil modification through stabilisation in order to improve it properties needed for housing. It is on the premise of this need that this study investigated the effect of cow-dung powder on soil housing material rainwater and abrasion resistance. A total number of 40 bricks of size 215 x 105 x 80 mm were produced with 0%, 5%, 10%, 15%, and 20% cow-dung powder by weight of the soil, and compressed at 8 MN/m^2. The bricks were air-dried for 28 days and labelled as A_0 for the control bricks, B_5, B_{10}, B_{15} and B_{20} for the experimental bricks. The bricks were then tested for raindrop erosion and abrasion strength. The results showed a decrease in rain erosion from 3.12% for the control bricks to 2.32% for the 15% cow-dung content bricks, representing a 25.6% reduction. Abrasion coefficient also increased from 4.5 cm^2/g for the control bricks to 7.80 cm^2/g for the 15% cow-dung content bricks. Conclusively, cow-dung is a suitable soil stabiliser and can be added up to 15% by weight of soil to produce soil bricks and soil-plaster/screeding material with improved durability properties in soil-integrated buildings.*

KEYWORDS: *Cow-dung powder, soil bricks, rainwater erosion, abrasion strength*

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I. INTRODUCTION

Soil was the first and oldest building material used for the construction of housing shelter for human habitation [1]. Historical records indicate that the early use of soil materials as walling units or mortar to hold masonry stones and bricks together date back to the construction of the great pyramid in Egypt and great wall of China [2]. The continuous use of soil materials in Africa for housing provision up to this present time despite the advent of modern conventional materials had been assigned to cost affordability, sustainability, and cultural reasons. It has been reported that majority of housing shelters in rural and low-income communities in developing countries, particularly in Africa have been built with soil material due to availability and cost affordability [3]. Some scholars hold the view that soil material plays an important role in the provision of sustainable low-cost housing units for aesthetic, religion and cultural purposes [4]. Others also hold the view that traditional African soil architecture has been the vehicle that carried cultural expressions of shelter and spatial needs of African cultures [5]. Further to these assertions, findings from soil housing studies in Africa reported that completely soil-built housing structures portray cultural diversity and will continue to be an integral part of modern housing needs for both rich and poor [6]. Hence, the use of soil material for housing as a demonstration and portrayal of cultural heritage and diversity will continue to be an integral part in the housing architecture in Africa (Fig. 1), particularly in the savannah ecological zone.

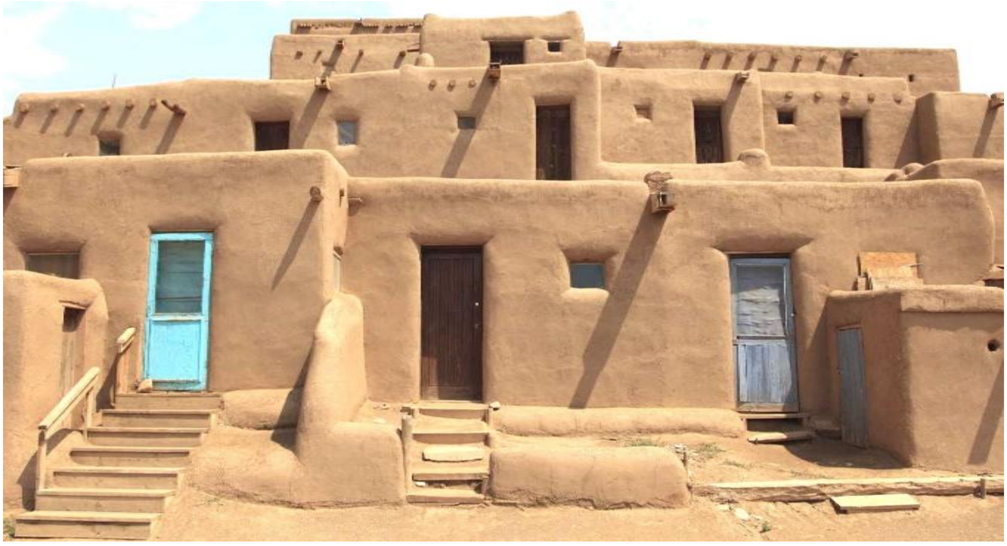

Fig. 1. Soil-integrated house in Africa (northern Ghana)

Despite the economic and cultural benefits of soil material for housing, soil generally has the tendency to absorb water readily with corresponding decrease in strength [1]. It is difficult in most times to get completely perfect soil materials for housing purposes because many of these soils are deficient either in terms of their particle size, compressive strength, rainwater erosion, abrasion, shrinkage cracks and water absorption capacity [7]. To enhance the performance of solid soil building units, two deductions on strength and durability improvements have been made through previous studies [8] as follows: First, increase in durability factor increases the compressive strength of soil materials and enhances their durability. Secondly, increase in compaction pressure reduces water absorption index and increases durability factor.

The above deductions highlight the need to investigate how soil materials can be stabilised or modified to improve and maintain the strength and durability requirements affirmed in standard practice [9]. Initially portland cement, lime and asphaltic emulsions were used as stabilisers to chemically modified soil to enable both compressed units such as blocks/bricks and soil mortar coatings on soil walls to attain the desirable strength and durability [1]. Studies have shown that cement, lime and asphaltic emulsions can improve soil strength and durability properties by as much as 500% in both wet and dry conditions [10]. However, the high cost of cement, lime and asphaltic emulsions and the associated environmental problems related to their production processes and usage make them less attractive for soil material stabilisation [11]. For instance, it has been found that the massive use of cement is responsible for the continuous increase of housing cost in developing countries [12], cement production processes account for 74 – 81% of the total carbon dioxide emissions [13], and cement/lime stabilised soil turns to have higher pH contents which have negative impact on the surrounding grounds due to alkaline migration [14].

To reduce traditional soil housing cost and minimise production related carbon emissions, soil stabilisation can be done by replacing the more expensive and pollutant conventional stabilisers (cement, lime, ashpaltic emulsions, etc.) with locally sourced agricultural-based waste materials that have less production cost and impact on the environment. It is in the light of these reasons that in recent times, various agricultural wastes and by-products which are found to contain pozzolanic properties due to the presence of silica, iron, aluminium and calcium oxides in large amounts are being studied for soil material stabilisation. For instance, shea butter residue [15], African locust bean waste water [16], cocoa bean shell ash [17] have been used to stabilised soil for blocks/bricks production. Again, proteinic casein formed by the souring of milk mixed with animal blood [18], cellulose properties in termite mound earth [18], yolk of eggs [14] were also used to stabilised soil mortar for rendering, plastering and screeding to produce marble finishes on soil-built walls in Africa and India.

To ensure that these cheaper and environmental friendly agricultural wastes used as alternative stabilisation materials meet up with the standard and demand of the building industry, it is required that the technology needed for their processing must be tested, proved and widely known at the local level [19]. It has been argued that if these technologies which have low import input and could be operated and maintained with available local skills are developed, then cost of housing provision in rural and low-income earning communities can be overcome over time [19].

Cow excreta commonly referred to as cow-dung is one agricultural-based waste natural plant fibre which has long been used locally in Africa and India as an additive to enhance soil materials strength and durability properties for construction purposes. Cow-dung possessed pozzolanic properties due to the presence of iron compounds, nitrogen, phosphorus, potassium and other organic materials when burnt to ash [20]. As such the effect of cow-dung as a soil stabiliser and supplementary cementitious material for concrete production have been conducted in previous studies. It improves coefficient of friction when used as soil stabiliser [21], increases workability, setting times and durability of concrete and mortar when used as partial replacement of cement [2][20][22]. Again, cow-dung improves the strength properties of adobe blocks/bricks [12], adobe walls and floor coatings when added to clay [23], and road soil stabilisation [4].

In all the studies using cow-dung for compressed soil material stabilisation, the focus was on compressive strength and water absorption characteristics. Results from literature showed that cow-dung slightly improved compressive strength development and significantly reduced water absorption. Driving rainwater erosion and abrasion strength are two key properties that influence the increase in compressed soil durability factor. However, the authors have not sighted any study conducted to determine the effect of cow-dung soil stabilisation on rainwater erosion and abrasion resistance of soil blocks/bricks and adobe structures. Thus this present work, studies the effect of cow-dung stabilised compressed soil bricks resistance to rainwater erosion and abrasion. Ghana is predominantly a farming economy with cattle being reared across all the sixteen regions. It has a total cattle population of 1.92 million with higher concentration in the northern savannah belt. With this high number of cattle being reared in the country, it is obvious that the excrete (cow-dung) will be in abundance, and as such cost savings in it use as soil stabiliser, will be achieved.

II. MATERIALS AND METHODS

2.1 Materials

The following materials were carefully selected and used to prepare the brick test samples for the study: cow-dung, lateritic soil and water.

2.1.1 Cow-dung

Cow-dung is the excreta or waste product of the bovine animal species such as cattle. It is the undigested residue of plant matter which has passed through the animal's gut. Fresh cow-dung was obtained from a large cowshed (kraal) located in Fielmuo, a fast growing farming community along the Ghana-Burkina Fasso border in the Sissala west district of the upper west region of Ghana. Cow-dung is abundant in and around the community due to the large numbers of cows owned and reared by almost every family.

2.1.2 Lateritic soil

Well and uniformly graded lateritic soil material was used for the study. An undisturbed soil sample was taken from a pit at a depth of 500 mm below the uppermost layer purposely to exclude organic soils from being part of the test samples. This type of soil was used because of it coarseness, as less than 31% of it particles is finer than 0.06 mm. The soil has liquid limit between 25% and 35% and plasticity index between 2.5% and 15% which makes it suitable to be stabilised with tar-like and herbivorous substances produced by plants and animals.

2.1.3 Water

Fresh, drinkable, colourless, odourless and tasteless tab water supplied by the Ghana Water Company Limited to the laboratory was used to prepare the test samples. The choice of water from this source was necessary to avoid chemicals and other reactive impurities that maybe found in unclean water that may have the potential to interfere with the stabilising properties of the cow-dung.

2.2 Methods and procedures

2.2.1 Cow-dung milling preparation

Fresh cow-dung was scooped in the cowshed with a hand trowel into a clean transparent plastic container with a lid. The green cow-dung sample was taken to the Building Technology and Civil Engineering laboratory of the Dr. Hilla Limann Technical University, Wa, Ghana, to be air-dried in a room temperature for a period of 14 days to constant weight. The weight was considered constant when the difference between the weightings in day thirteen and day fourteen was zero percent. The dried cake-like pieces of the cow-dung (Fig. 2) were first crushed to smaller pieces using a Thomas grinding machine. The pieces or particles were further milled to fine particle size using a cone crusher and sieved through a 0.4 mm sieve. The fine cow-dung particles or powder that passed through the sieve (Fig. 3) was used to stabilised the lateritic soil bricks for the experimental study.

Fig. 2. Dried cow-dung cakes

Fig. 3. Milled cow-dung powder

2.2.2 Soil classification

The soil sample was first passed through a 5 mm network of sieves to ensure that stones and other foreign matter were removed, before it was characterised to assess the index properties in line with BS 1377-2 [24]. The purpose of the soil test was to ascertain the suitability of the soil material used for preparing the samples for the tests. To determine the predominant size particles that form the soil and which is necessary to control the bulk density of the compressed soil body, the sieve analysis test was conducted. The assessment of the soil type from the silt, clay and sand/gravel fractions through sedimentation test was performed using the jar method. The Atterberg's limit test was also conducted to determine the strength and class of the soil. Other tests performed were linear shrinkage, specific gravity, organic content and natural moisture contents.

2.2.3 Mix design

The soil material was prepared with a constant soil-water mixture of 12% water and compaction pressure of 8 MN/m^2. The amount of water used was per the optimum moisture content (12%) by weight of the soil and the recommended optimum compaction pressure for soil block/brick production. In order to find out the effect of variation of cow-dung on rainwater erosion and abrasion strength, the soil mixtures had their cow-dung contents varied from 0%, 5%, 10%, 15% and 20% by weight of the soil. The soil and cow-dung powder were first mixed in a dry state manually to form a uniform mixture. Water was added in two phases and mixed to a semi-dry uniform colour and consistency. The soil was then moulded into bricks using the BREPAK brick press and labelled as A_0 for the control; B_5, B_{10}, B_{15} and B_{20} for bricks with 5%, 10%, 15% and 20% cow-dung contents respectively (expermental bricks). The bricks were stored and cured in a laboratory environment for 28 days. The bricks were initially covered with plastic sheets for the first seven days. This was to prevent shrinkage cracking due to speedy water evaporation which tends to promote undesirable loss of moisture in the bricks. The plastic sheets were then removed and the bricks air-dried at room temperature for the remaining twenty-one curing days (Fig. 4). A total of forty number bricks of size 215 x 105 x 80 mm were produced for the experimental tests.

Fig. 4. Bricks being cured

Fig. 5. Bricks further dried in electric oven

2.2.4 Test procedures

The bricks were further dried in an electric oven to constant weights (Fig. 5). Three number bricks from each stabilisation level that have no visible sign of cracks or any deformity were selected, thoroughly cleaned of any dirt or loose matter and tested for rainwater erosion and abrasion strength. The rainwater erosion test was performed using water spray in accordance with NZS 4298 [25] standard specifications. Again, the abrasion strenght test using wire brush was conducted in line with BS 3921 [26] standard specifications.

For the rainwater erosion resistance test, rainfall was simulated using a water hose connected to a tap and a water head of 20 mm diameter and a spraying pressure of 150 kN/m^2. The bricks were weighed using a weighing scale (M_1). The bricks were then placed slightly upright against a vertical background and held in position securely. Water was then sprayed from the water head against the face of each brick in turns for 5 minutes (Fig. 6). After the spraying was over, the bricks were all removed and oven-dried again to constant weights. Then, the loss in weight due to rain erosion was measured (M_2) and expressed as a percentage of the initial oven-dried weight as shown in equation 1.

Percentage weight loss = $(M_1\text{-}M_2/M_1) \times 100$ Eq. 1

Where M_1 is the weight before rainwater erosion and M_2 is the weight after rainwater erosion.

To determine the abrasion resistance, the bricks were first weighed (M_1) and then placed in a flat and wide metallic container on top of a table. A wire brush was used to rub the surface of each brick at one forward and backward movement for about a second for 60 cycles (Fig. 7). After the brushing (rubbing) was over, all loose material was removed from the bricks, using a very softer cleaning brush. Then the loss in weight due to particles detachment arising from the brushing was measured (M_2). The weight of the detached materials were measured and the abrasion coefficients computed using equation 2.

Abrasion coefficient = $A/(M_1 - M_2)$ Eq. 2

Where A is the brushed area, M_1 is the weight before brushing and M_2 is the weight after brushing.

Fig. 6. Rain erosion simulation

Fig. 7. Brick being brushed

III. RESULTS AND DISCUSSION

3.1 Soil properties

The geotechnical properties of the soil studied are listed in Table 1. The soil had a coefficient of uniformity (C_u) of 7.3 and coefficient of gradation (C_g) of 2.1. Any soil having coefficient of uniformity greater than 6 ($C_u > 6$) and coefficient of gradation greater than 1 and less than 3 ($1 < C_g < 3$) is a well graded clay soil of intermediate plasticity [27]. The soil recorded a silt content of 14%, clay content of 17% and a high sand/gravel content of 69%. This moderate clay content satisfied the requirement that suggests that an optimum fine content should be about 25%, of which more than 10% should be clay. The fines content per this results is 31%, of which the clay fraction is 17%. Again, the soil had a liquid limit of 34%, plastic limit of 20% and plasticity index of 14%. These values fall within the preferred range of between 30%-35% for liquid limit and 12%-22% for plastic limit as recommended in literature [28,29], According to the plasticity chart for soil classification, the soil used could be classified as moderately plastic clay. Furthermore, the soil recorded a percentage shrinkage value of 4.9%, less than the recommended 6%, and a specific gravity value of 2.69, which is between the lower and upper limits (2 and 2.8) recommended for soil material for housing in Ghana [1][30]. Thus, the values of all the soil properties studied satisfied the suitability limits and ranges reported in literature.

Table 1. Summary of soil properties

Constituent	Value
Soil colour	Brownish red
Sieve analysis	$C_u = 7.3$ and $C_g = 2.1$
Silt fraction	14%
Clay fraction	17%
Sand/grave/ fraction	69%
Liquid limit	34%
Plastic limit	20%
Plasticity index	14%
Shrinkage limit	4.9%
Specific gravity	2.69
Organic matter content	1.8%
Natural moisture content	6.7%
Optimum moisture content	12%

3.2 Rain erosion test

The effect of cow-dung on raindrop erosion resistance behaviour of soil bricks cured for 28 days is illustrated in Table 2 and Fig. 8. The amount of discarded soil particles from the bricks in percentage terms as a result of raindrop erosion was 3.12% for the control bricks. Discarded soil particles from the bricks steadily decreased to 2.32% for the 15% cow-dung stabilisation level, representing a 25.6% decrease. However, beyond the 15% cow-dung stabilisation level, discarded soil particles from raindrop erosion increased slightly to 2.46% for the 20% cow-dung stabilisation level.

Table 2. Rain erosion test results (%)

Cowdung (%)	Sample			Ave. (%)	SD
	1	2	3		
A_0	2.97	3.23	3.17	3.12	0.136
B_5	3.00	2.84	2.84	2.89	0.092
B_{10}	2.87	2.39	2.61	2.63	0.251

B_{15}	2.23	2.24	2.49	2.32	0.147
B_{20}	2.43	2.43	2.52	2.46	0.519

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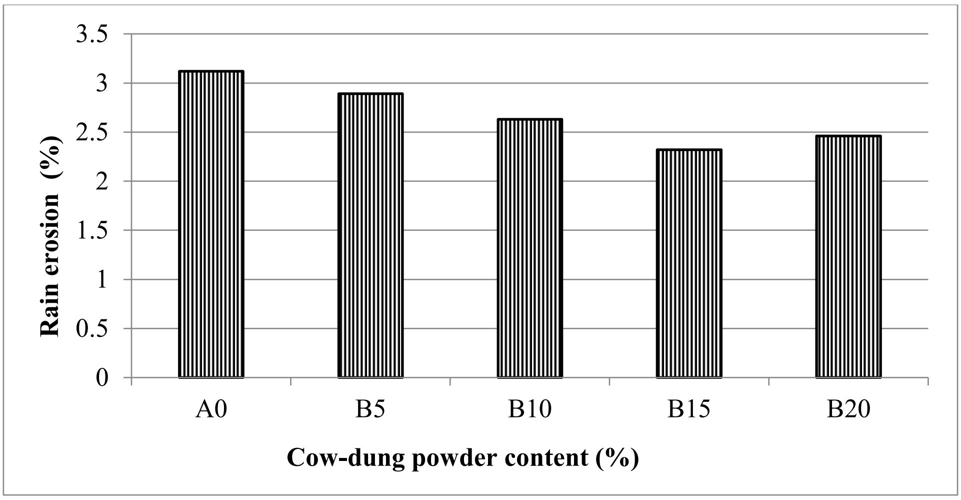

Fig. 8. Variation of erosion with cow-dung content

The steady decrease in the raindrop erosion and subsequent increase beyond the 15% cow-dung content was expected. A scanning electron microscope (SEM) analysis previously performed on cow-dung found that it possesses some amounts of insoluble silicate amine and oil [12]. The study indicated that the insoluble amine glues isolated soil particles together whiles the oil films coat pore linings within the soil after drying when the water has evaporated, making the soil material resistant to water penetration. Another study reported that cows are herbivores and as such their excreta contain large amounts of undigested plant residue in the form of fibres [31]. These undigested plant fibres serve as a sort of reinforcement in compressed soil materials. Thus, the combined effect of the insoluble silicate amine and oils helped glued the particles tightly, repelled and slowed down the penetration of water on the surfaces of the bricks from raindrop erosion. Again, the undigested fibres worked to provide some level of reinforcement in the compressed soil brick.

In addition to the descriptive statistics, the mean discarded particles percentage of the soil bricks were also compared using a One-way ANOVA test at a significant level of 0.05 as shown in Table 3. The results obtained indicate a high variability between the individual stabilization levels than within groups: $F(4,10)=13.863; P<0.05$. This shows that the differences found in the means were as a result of the effect of the cow-dung content.

Table 3 ANOVA analysis of rain erosion of bricks (%)

Source of variation	Sum of squares	df	Mean squares	F	P
Between groups	1.267	4	0.317	13.863	0.000
Within groups	0.229	10	0.023		
Total	1.496	14			

3.3 Abrasion strength test

The influence of cow-dung on abrasion strength, that is, wear resistance of the soil bricks cured for 28 days is summarised in Table 4 and plotted in Fig. 9. The results showed that soil bricks stabilised with cow-dung offered resistance to the abrasive forces up to the 15% stabilisation level. A high abrasion coefficient shows that a large brushing area of the brick is needed to produce a certain amount of discarded soil particles. The addition of cow-dung powder in the soil increased the abrasion coefficient from 4.50 cm^2/g for the control brick to 7.80 cm^2/g for the 15% stabilised soil bricks. Beyond the 15% cow-dung stabilisation level, abrasion coefficient declined slightly to 7.79 cm^2/g for the 20% cow-dung content brick samples since the bars for the 15% and 20% stabilisation levels almost levelled off (Fig. 9).

Table 4. Abrasion strength coefficients (cm^2/g)

Cowdung (%)	Sample			Average	SD
	1	2	3		
A_0	4.62	5.08	3.81	4.50	0.643
B_5	4.77	7.69	5.60	6.02	1.505
B_{10}	8.22	5.59	7.24	7.02	1.329

B_{15}	5.80	8.23	9.36	7.80	1.819
B_{20}	7.30	8.77	7.30	7.79	0.849

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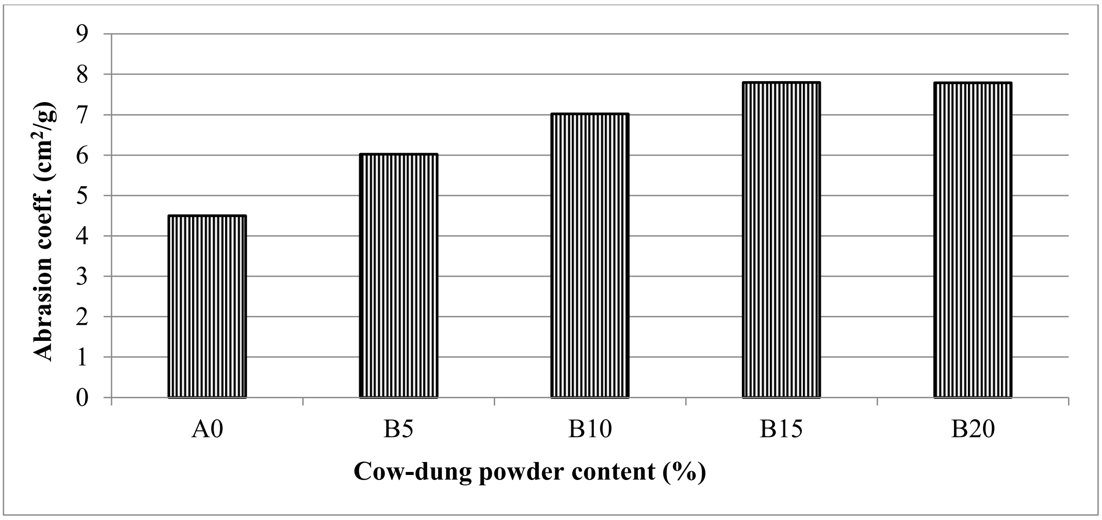

Fig. 9. Variation of abrasion with cow-dung content

The increased in the abrasion strength due to the presence of the cow-dung can be attributed to the large amount of coarse undigested fibres in the cow-dung as well as the insoluble silicate amine and oil contents. According to previous studies using cow-dung, it was reported that the undigested fibre content in it provided good adhesion to compressed soil material because of their rough surfaces [12]. These properties possessed by the cow-dung reduced the number and size of voids in the brick structure thereby increasing the wear resistance from any form of rubbing, brushing or friction against the bricks.

One-way ANOVA test to a significance level of 5% was conducted to test if a difference in groups means is attributed to chance or error. From the results presented in Table 5, the significant level is 0.050, that is, $F(4,10)= 3.430$; $P \leq .05$. This indicates that the difference in the mean abrasion coefficient values between the stabilisation levels of the soil bricks, given this small sample size, is so large that similar findings would be unlikely to recur by chance or error even if this study is replicated a number of times. This therefore is an indication that the cow-dung content has an influence on the abrasion resistance behaviour of the soil bricks.

Table 5. ANOVA analysis of abrasion of bricks (cm^2/g)

Source of variation	Sum of squares	df	Mean squares	F	P
Between groups	23.253	4	5.813	3.430	0.050
Within groups	16.947	10	1.695		
Total	40.200	14			

IV. CONCLUSION

In this experimental work, blended cow-dung and lateritic soil brick samples were prepared, cured for 28 days and tested for wear arising from rainwater erosion and abrasion due to rubbing or friction on the brick surfaces. These tests were carried out purposely to determine percentage erosion caused by rainwater and abrasion coefficient from the discarded soil particles of the test bricks.

- With the addition of up to 20% cow-dung to the lateritic soil material, the percentage of discarded soil particles decreased from 3.12% for the control brick to 2.32% for the 15% stabilised bricks.
- In a similar trend, the abrasion coefficient increased from 4.50 cm^2/g for the control brick samples to 7.80 cm^2/g for the 15% cow-dung content brick samples. The high abrasion coefficient value obtained at the 15% stabilisation level indicates that a large brushing area of the brick samples surface is required to yield a certain amount of discarded soil particles, that is, the higher the content of the cow-dung, the greater the resistance offered by the bricks against abrasive forces.
- However, beyond the 15% cow-dung content, wear of soil particles due to both rainwater erosion and abrasive forces were increased for the 20% stabilisation level.
- The authors are therefore of the opinion that with suitable lateritic soil materials properties, 15% addition of cow-dung by weight of the soil material as the optimum, will reduce wear cause by rainwater erosion and any form of abrasive forces. Hence, the use of 15% cow-dung by weight of soil as the optimun in soil

stabilisation for soil brick production, soil plaster and screeding mortar for traditional soil-built houses, particularly in the tropical savannah belt in Africa is recommended.

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