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Abstract: Little is known about the performance of unreinforced interlocking block masonry walls made using CINVA-Ram blocks subjected to static compression loads. In a laboratory study, Pozzolanic cement (C), hydrated lime (L) and rice husk ash (RHA) were used to stabilize laterite soil with sandy clay loam texture. The stabilized blocks were used to make three types of walls. The results indicated that block compression strength, water absorption and durability (1-minute abrasion test) were within the recommended levels at the optimum stabilizer percentages. The wall failure modes were characterized by either diagonal cracking of individual blocks or spalling of block debris. The performance of interlocking block walls in load capacity can be divided into three parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure. This paper has established that interlocking wall compression strength can be increased while the vertical load deflection reduced at the optimum stabilizer content.

Performance of interlocking laterite soil block walls under static loading

Sanewu Isaac Fundi¹, J.W. Kaluli¹, J. Kinuthia²

Cover letter

I wish to submit this research paper to Journal of Construction and Building Materials for publication. The research paper covers part of work on studying the performance of interlocking laterite soil blocks which are economically viable. However, the adoption rate of the blocks has been low due to lack of information on their performance in service.

Yours Sincerely

Isaac Fundi Sanewu.

Performance of interlocking laterite soil block walls under static loading

REVIEWER #1 COMMENTS

Comment Number	Action taken
1.	Statement changed to “ <i>the wall vertical displacement</i> ” throughout the manuscript
2.	Page 3 paragraph 2, the objective was to find the response when the wall is subjected to vertical (in-plane) and horizontal (out-of-plane) loading. These loads were applied simultaneously to simulate the case of a typical constructed wall.
3.	Clarity provided (page 5 paragraph 2 just before Figure 1)
4.	-Compressive strength test set up (described in section 2.2 paragraph 1) -Standard followed (Kenya Bureau of Standards (KS 02-1070: 1993), reference #15) -Number of specimens – 5 as suggested by KS 02-1070 (1993)
5.	-Corrected, page 12; last paragraph “0.9MPa was 26% that of the individual blocks (3MPa)” -Figure 2a, at 7-day, compressive strength for 4.8%C (0.76MPa), and 6%C (2.32MPa); percentage change will be 67%
6.	Correlation coefficients are unitless. They represent a relation between variables.
7.	The phrase is replaced
8.	The phrase is replaced
9.	Followed journal guidelines
10.	Mortar would aid filling up the voids caused by unevenness of the block surfaces, thereby <u>reducing the initial vertical deflection</u> . However, subsequent deflection will then depend on the mortar properties.

REVIEWER #2 COMMENTS

Comment Number	Action taken
1.	Load frame is provided
2.	Percentage changes represented as integers
3.	Units for stress (N/mm ²) changed to MPa
4.	Phrase changed (l/t is 4.09 and h/t is 5.45)
5.	Figure 5. Horizontal load was applied at the center and spread out by aid of steel sheet. The failure of the wall observed to occur in less constrained portions (at the sides of the wall)
6.	The failure behavior was governed by shear stresses and followed a diagonal tension. The block-load interface layers at the bottom corners regions were subjected to maximum stresses, this was reported in finite element modelling (discussion not in this manuscript).
7.	Steels’ stiffness is higher than that of concrete, it would be expected to provide a bigger deepening effect than concrete.
8.	-The percentage change is corrected. -The comparison of the percentage change is on the individual blocks that were used in making the masonry walls
9.	Correlation coefficients on p6, p12 and p13 are R ² values for linear regression for each multiple.
10.	Phrase corrected
11.	Grammatical errors corrected.

Highlights: Ref. No.: CONBUILDMAT-D-17-06316

- Failure modes of stabilized laterite soil block wall are characterized by diagonal cracking of individual blocks or spalling of block debris.
- Lime stabilized laterite blocks exhibit higher compressive strengths but become brittle, while rice husk ash stabilization makes the walls accommodate higher vertical deflections.
- Zero-mortar layer of interlocking block walls make them to have higher deflection when initially loaded before they can rapidly take up compressive load until failure is experienced.

Performance of interlocking laterite soil block walls under static loading

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Abstract

Little is known about the performance of unreinforced interlocking block masonry walls made using CINVA-Ram blocks subjected to static compression loads. In a laboratory study, Pozzolan cement (C), hydrated lime (L) and rice husk ash (RHA) were used to stabilize laterite soil with sandy clay loam texture. The stabilized blocks were used to make three types of walls. The results indicated that block compressive strength, water absorption and durability (1-minute abrasion test) were within the recommended levels at the optimum stabilizer percentages. The wall failure modes were characterised by either diagonal cracking of individual blocks or spalling of block debris. The performance of interlocking block walls in load capacity can be divided into three parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure. This paper has established that interlocking wall compressive strength can be increased while the vertical deflection reduced at the optimum stabiliser content.

Keywords: Durability, interlocking block wall, static loading, bricks

1. Introduction

The construction industry has over the years experienced introduction of different earth construction techniques geared towards improving the quality of earth construction. The interlocking stabilized soil block (ISSB) technology encourages sustainable construction. These blocks are manufactured by compressing stabilized soil in a mould with a manual or hydraulic press, and subsequent curing. The amount of stabilizer content mainly depends on soil characteristics and the desired strength. The interlocking mechanism enhances block stability and horizontal and vertical alignment of the constructed wall. The loads applied on an interlocking masonry wall are transmitted from one block directly to another and not through an intermediary mortar layer [1]. The absence of mortar in the bed and head joints of interlocking masonry wall may, however contribute to geometric imperfection. This

may lead to a different structural behaviour from that of conventional masonry wall when loaded under vertical (in-plane) or under horizontal (out-of-plane) loads.

Locally available laterite soils may not be suitable for block making due to weak or low bearing capacity. Therefore, different materials having cementitious properties and those that are pozzolanic in nature are added in order to stabilize the soils. In this study, pozzolanic cement, hydrated lime and rice husk ash (RHA) were used in laterite soil stabilization. Cement reacts with water in soil mixture to form an insoluble cementation colloidal gel. A study [2] on stabilization of laterite soil reported a 28-day block compressive strength of 2.5N/mm^2 with a cement content of 5%. Attempts to independently utilize lime in making stabilized earth blocks have been made out by several researchers [3,4]. An ultimate 28-day unconfined compressive strength of 2.4N/mm^2 for laterite soil with 4% RHA added to cement content of 8% has been recorded by [5].

Masonry walls are mostly utilised in supporting compressive and horizontal loads [6]. Therefore, the structural performance of the wall to these loading conditions is of critical concern. A study by [7] on limit analysis of shear wall under lateral loads found that masonry walls may fail by separation, sliding and crushing of the block interfaces.

In various studies, the performance of interlocking block masonry walls under compression loading and horizontal loading has been done. Full scale wall panels were tested [1] under axial compression, lateral tension and flexural bending loads and concluded that the compressive strength of the wall was directly proportional to the strength of the masonry units. The test also found that the wall panel under lateral loads tended to lift at the base and rotated about the middle section of the wall before failure of the wall. Increase of eccentricity from the centre has been found [8] to reduce the strength of interlocking masonry wall. A test by [9] on interlocking walls grouted and reinforced with steel bars found that a larger height-to-width aspect ratio causes strength reduction in a wall, however it tended to increase ductility of the system. They also found that the lateral load resistance of a flexure wall will be reduced due to presence of a window at its centre. A study on the effect of soil stabilization on the failure pattern of interlocking soil block walls [10] established that under compression loading,

un-stabilized soil block walls developed random vertical cracks while blocks stabilized with 2% municipal solid waste ash had cracks that propagated diagonally at an angle of 45 degree from the point of application. It was in [10] conclusion that the elimination of mortar in interlocking block walls made the failure not to depend on the weak bonds but on the characteristics of individual blocks.

In the previous studies, masonry walls have been tested with the vertical and horizontal loads being applied independently or with induced eccentricity on loading. A masonry wall in practice however, is subjected to vertical and horizontal loads simultaneously. The wall response to such loading is expected to be different. The aim of this paper therefore, is to evaluate the effect of pozzolanic cement, hydrated lime and RHA on the performance of unreinforced laterite soil block walls made using CINVA-Ram interlocking blocks subjected to vertical (in-plane) and horizontal (out-of-plane) compression loads simultaneously. The parameters measured included block compressive strength, masonry wall ultimate load capacity, vertical load displacement, stress-strain relationship and the failure mechanism.

2. Materials and methods

2.1. Test materials

The laterite soil used in this study was collected from Kiambu County, an area at the geographical coordinates of 1.1748°S and 36.8034°E. The laterite soil is commonly used for making stabilized blocks. The soil was obtained at a depth of 1 m below the earth surface in order to avoid the inclusion of humus materials. It consisted of about 25% fine gravel and 75% sand. The soil, classified according to the unified soil classification system as having a texture of sandy loam. The laterite soil plasticity index (12.1%) lies in the range (5 – 15%) proposed by [11] for soils which can be effectively stabilized using pozzolanic cement (Table 1). In this study, Portland pozzolanic cement 32.5N was used. The cement was sourced from a hardware in Kiambu County.

Lime has been found effective in stabilizing plastic clayey soils, ranging from clays to silty clays with plasticity indices greater than 10 leading to long term strength gain as reported by several researchers [12,13]. Commercial hydrated lime, Rhino lime, produced by Athi River Mining Company was used

in this study. The lime had 94% calcium hydroxide, 72% calcium oxide, and other elements like magnesium oxide and silica.

RHA has been found by [14] to freely react with extra lime present in cement thus encouraging pozzolanic reactions. The rice husk ash therefore was used in this study to replace commercial hydrated lime. The ash was sourced from un-controlled burning source at Mwea rice irrigation scheme, Kenya. The RHA was sieved through 150µm sieve before using as a stabilizer.

Table 1: Atterberg limits properties of laterite soil

Specimen	Type of test			
	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Linear shrinkage (%)
Laterite soil	29.0	16.9	12.1	7.5
Laterite soil + 6%C	39.1	31.3	7.8	5.5
Latetite soil + 6%C3%L	37.2	Non plastic	-	5.8

2.2. Material preparation and testing

The stabilizers (pozzolanic cement, hydrated lime and RHA) were replaced in percentage of dry weight of the soil. The interlocking blocks were moulded using CINVA-Ram press machine, producing units of dimensions 220 mm (length) x 220 mm (width) x 120 mm (height). The optimum stabilizer dosages were determined by testing the moulded blocks on curing for 7, 14 and 28 days. The physico-mechanical and durability properties of individual block units were established in accordance to [15]. The blocks that provided the highest compressive strength and had the best durability were used for construction of experimental walls.

The water uptake ability of the blocks was also determined in accordance with [15]. Two blocks that were cured for 28 days were randomly selected, weighed and submerged in a water bath for up to 24 hours. The blocks were then removed from water and re-weighed.

The abrasion test was carried out by use of a horizontal belt sander model HYS-900 having a frequency of 60 rpm. The sander utilised a sand paper belt of type GXK50-P60 with a width of 180mm. The blocks were subjected against the belt for a duration of one minute before determining their final weight.

Three types of wall panels, Laterite soil wall 1(LSW1), Laterite soil wall 2 (LSW2), and Laterite soil wall 3 (LSW3) of size 900 mm (length) x 1200 mm (height) were prepared in accordance to [16]. The length to thickness (l/t) and height to thickness (h/t) ratios were 4.09 and 5.45 respectively for all wall panels. The blocks were stacked utilising the interlocking system provided by the blocks. A grooved steel plate was placed at the top course of the wall to cover the projection and uniformly distribute the load. Horizontal loading was applied against a load cell placed on a steel plate (Figure 1). The vertical compressive strength was tested perpendicular to the bed joints without the effects of eccentricity. The wall vertical displacement was determined at mid length while lateral displacement was determined at three points equally spaced at 325 mm using linear variable displacement transducers (LVDT). The testing procedure was divided into two phases; first the vertical load was applied up to about 75% of the ultimate compressive load before the horizontal load was introduced. This was to represent pre-existing vertical compression in masonry walls before they are subjected to horizontal loading. The loads were then applied simultaneously until failure of the wall.

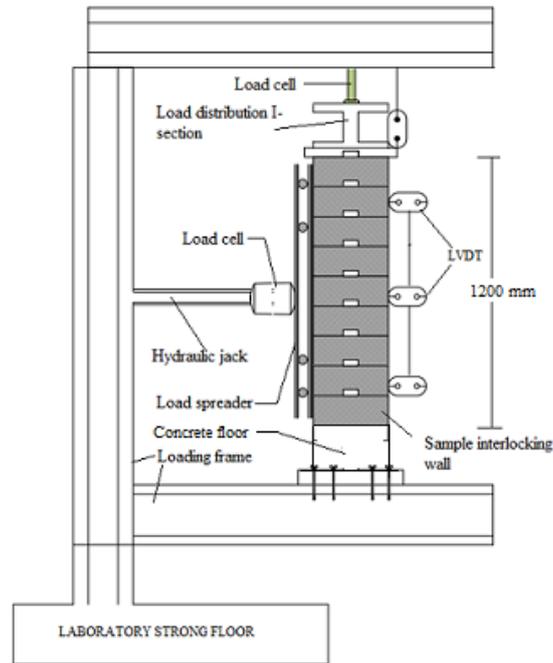


Figure 1: Experimental test set up for the wall

3. Results and discussion

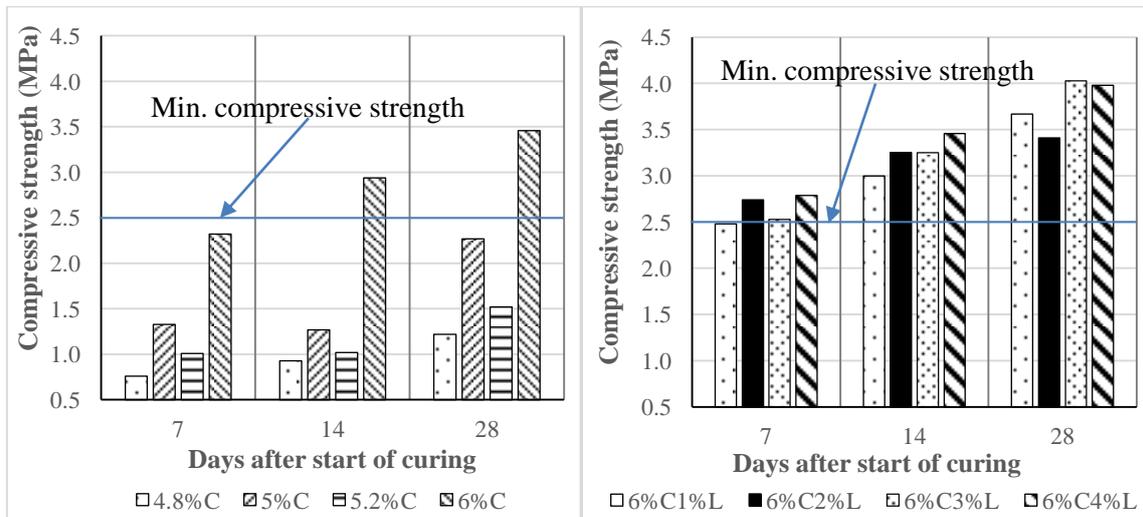
3.1 Effect of stabilizers on interlocking block properties

3.1.1. Compressive strength of stabilized blocks

Based on the test results, there was a consistent gain in compressive strength with curing days on adding pozzolanic cement, hydrated lime and RHA to laterite soil (Figure 2). The correlation coefficients obtained for percentage of cement stabilization only and the gain of strength of the blocks were 0.940, 0.952 and 0.891 on 7, 14 and 28 days respectively. A fairly strong correlation was established on 7 and 14 days with the lowest coefficient on 28-day. This indicates that pozzolanic cements' contribution to block compressive strength is higher on early days of curing and reduces with progression of days. These results were in agreement with the findings of [17]. It was observed that blocks stabilized with 6% cement only were 67% stronger than those stabilized with 4.8% cement on day 7 (Figure 2a). It has also been established [18] that with the presence of Portland cement in soil, calcium ions are easily provided that aid in improving the soil engineering properties. Therefore, the increase in compressive strength with cement dosage can be explained by the fact that the higher

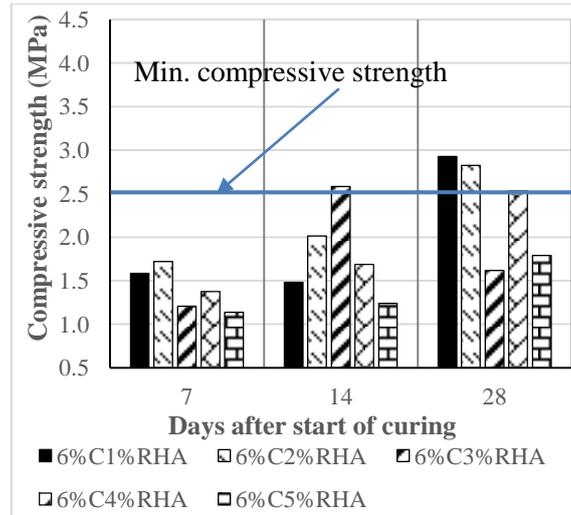
cement content greatly enhanced the hydration process due to high amounts of calcium ions introduced.

A highest 28-day compressive strength of 4.03MPa was reached on adding 3% of hydrated lime in presence of 6% pozzolanic cement. The addition of 3%lime caused a 42% increase on 28-day compressive strength as compared to a 33% increase in absence of lime. For blocks produced with hydrated lime quantities lower than 3% they had relatively low compressive strength. It is reported by [19] that when lime is added to clay soil it is first absorbed by the clay mineral until lime affinity for the soil is achieved. This amount of lime, [19] argues that is between 1% and 3% by weight of the soil. Therefore, lower dosages of lime may not be sufficient to increase the pH of the soil matrix to release silica and make it available for producing cementitious gel needed to stabilise the soil. This could probably be the reason for marginally lower compressive strength of blocks stabilized with 1% and 2% lime blended with 6% cement (Figure 2b).



(a) Laterite soil + cement

(b) Laterite soil + cement + lime



(c) Laterite sol + cement + RHA

Figure 2: Compressive strength of laterite soil stabilized blocks

Figure 2(c) shows that the addition of 1% RHA to a given 6% of cement, led to the highest 28-day compressive strength (2.93MPa). It was also observed that, in most cases, there is a decrease in compressive strength with increase in RHA. However, in comparison to the effect of adding 1% lime to 6% cement, the lime-cement blocks had a 28-day compressive strength 20% higher than adding 1% RHA. It can be inferred from the results that cement-lime-laterite soil mixture leads to blocks of higher compressive strength as compared to cement-RHA-laterite soil. The reason can be attributed to the insufficient availability of free lime for pozzolanic reaction in the cement-RHA-laterite mixture. Also, the presence of excess RHA cannot be easily mobilized for pozzolanic reaction which consequently occupies space within the soil thus reducing the strength. This was consistent with the findings of [20].

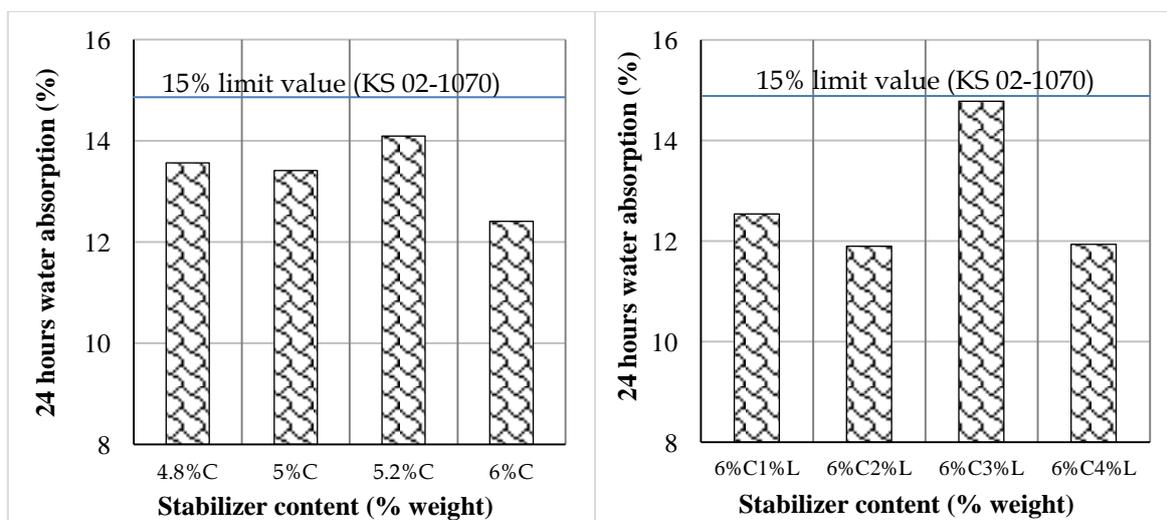
3.1.2. Water absorption by blocks

Generally, the total water absorption for laterite soil blocks indicated that increase of cement dosage led to reduction of water absorption (Figure 3a). Increasing pozzolanic cement content from 4.8% to 6% in laterite soil resulted in 9% reduction in water absorption by the blocks (Figure 3a). These results were expected because cement binds the laterite particles together thereby reducing the sizes of the pores through which water could flow into the blocks.

The increase in hydrated lime content in presence of 6% cement led to decrease in water absorption (Figure 3b). It has been found [21] that when hydrated lime is used in soil modification, the calcium ions from the hydrated lime migrate to the surface of the clay particles and displace water and other ions. This has an effect of drying the soil through flocculation of the particles. The results show that adding 2% lime in presence of 6% cement has a positive effect in increasing the water absorption resistance of the blocks.

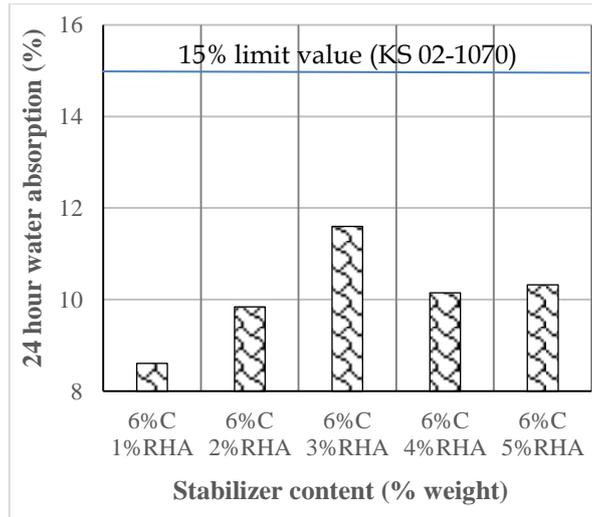
Contrary to water reduction in pozzolanic cement stabilization alone, there was an increase from 8.61 to 11.60% in water absorption on increasing RHA from 1% to 3% (Figure 3c). This phenomenon was found by [22] to be contributed by the weakening of the interparticle bonding that could have formed by the soil particles.

The results evidenced that blocks incorporating RHA have less absorptive capacity as compared to those with hydrated lime of the same content in presence of 6% cement. Therefore, replacing hydrated lime with RHA lowers the water absorption of laterite soil blocks. As noted by [23], hydrated lime combines with water more than RHA despite the RHA having a finer particle size. This agrees well with this research since blocks stabilized with hydrated lime had higher absorption than those of RHA (Figure 3b). However, the maximum water absorption of 15% recommended by [15] was satisfied by the stabilized blocks.



(a) Laterite soil + cement

(b) Laterite soil + cement + lime



(c) Laterite soil + cement + RHA

Figure 3: Water absorption by stabilized laterite soil blocks

3.1.3. Abrasion resistance of laterite soil blocks

The total loss of mass due to abrasion at the block surface decreased with increase in hydrated lime content (Figure 4a). The material erosion reduces from 0.58 to 0.27% when hydrated lime content increases from 0 to 4%. Thus, representing a 53% reduction of the abraded material. This indicated that abrasion resistance is enhanced with increase in hydrated lime content in laterite soil blocks.

The amount of abraded material decreased with increasing RHA content up to 2% and further addition of RHA caused an increase in the abraded material (Figure 4b). It has been reported by [24] that presence of calcium ions from cement react with silica from RHA to aid in strength development. However, increasing the quantity of RHA decreases the strength due to lack of adequate calcium ions for the continuation of reaction. This explains the observed behaviour of Figure 4(b) where the blocks durability was reduced beyond the optimum quantity of 2% RHA. Comparatively, the durability of both hydrated lime and RHA stabilized blocks is generally enhanced equally up to 2% replacement (Figure 4). However, beyond the 2% stabilizer content, durability is better achieved with hydrated lime than RHA stabilization.

Based on the test results of the individual interlocking blocks, the properties of the blocks used in making the experimental walls are summarised in Table 2.

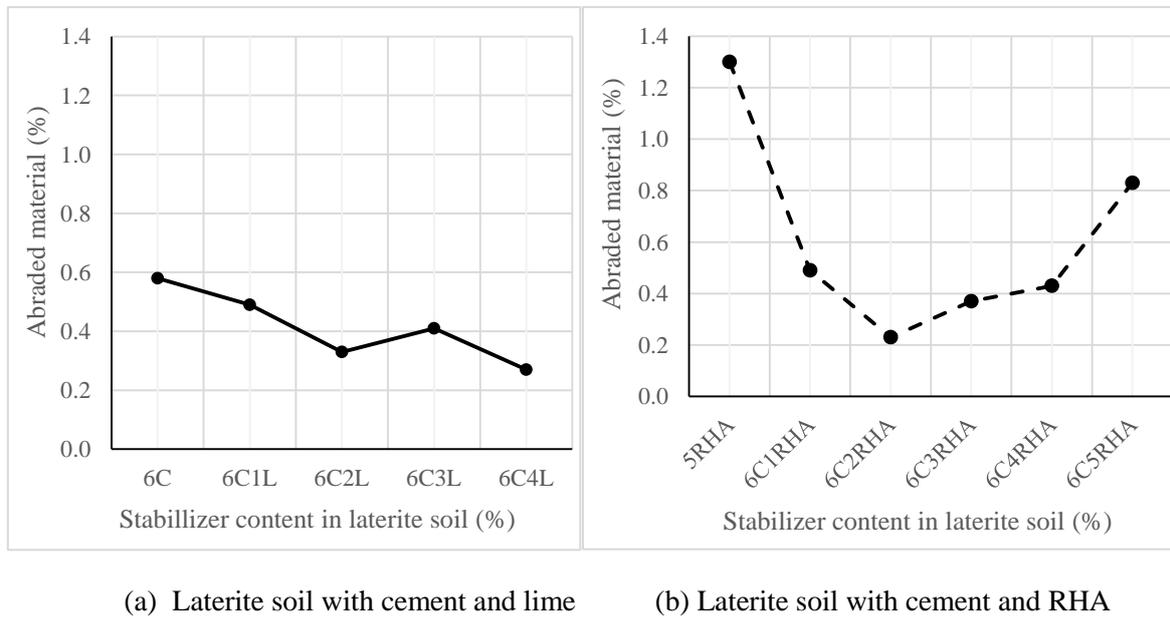


Figure 4: Abrasion resistance of stabilised Laterite soil blocks

Table 2: Physico-mechanical and durability properties of experimental soil blocks

Stabilizer percentage	Wall type	Soil type	28-day Compressive strength (MPa)	24 hour Water absorption (%)	Abrasion resistance (%)	Failure pattern
6%C	LSW1	Laterite	3.46	12.41	0.58	Pyramidal pattern
6%C3%L	LSW2	Laterite	4.03	14.78	0.41	Conical failure
6%C1%RHA	LSW3	Laterite	2.93	8.61	0.49	Conical failure

3.2 Interlocking block wall panel performance

LSW1 developed cracks mainly on the blocks at an inclined angle and not on the joints (Figure 5a). The cracks were mainly a combination of cone and split mode of failure as described in [25]. No cracks appeared on the side edges of the LSW1 panel. The wall failed through crushing by opening up

of fissures on individual blocks and finally propagation of cracks without opening up of joints. This could be attributed to the efficiency of the interlocking mechanism of the blocks. The horizontal load led to spalling of the blocks due to gradual opening of the cracks that were created by vertical loading. The wall then experienced gradual sway with increasing horizontal load; the bottom part of the wall having a lesser vertical sway due to additional self-weight of the wall (Figure 5a).



(a) LSW1

(b) LSW2



(c) LSW3

Figure 5: Crack propagation and wall failure modes for stabilized laterite soil

The failure of LSW2 was characterised by falling of block debris which spalled off due to the increase of horizontal loading. Cracks with wider widths mainly occurred at the middle height of the wall as compared to those at the top and bottom courses of the wall (Figure 5b). It was observed that increasing the lateral loading contributed to alignment of protruded blocks but ultimately pushed the

wall out of vertical plane. There was presence of side cracks on the wall once the ultimate load of LSW2 was reached.

The mode of failure in LSW3 panel was by cracks that developed first mainly at the bottom layers (Figure 5c). The cracks occurred through individual blocks just below the block header joint. There was gradual opening up of crack width with increase of vertical load but the wall did not experience spalling of materials. It was observed in all wall types, that the layer immediately below the spreader beam did not crack substantially to lead to collapse even when the other layers had failed. This phenomenon can be attributed to the deepening effect of the steel beam to the top layer in transferring the load to the entire wall.

The LSW1 ultimate compressive stress (0.9MPa) was 26% that of the individual interlocking blocks (3.46MPa). The correlation analysis between the compressive strength of LSW1 and that of the interlocking block was found to be 0.649 indicating a positive linear relation. The reason for a lower compressive strength has been found out to be contributed by the presence of a soft layer of mortar in the case of conventional masonry [26]. However, for interlocking masonry this can be caused by the blocks interface joints which leads to large displacements and structural instability.

The first crack on LSW1 occurred at a vertical load value of 15.96kN which was 15% of the ultimate strength of the wall. As the vertical load was increased, the wall bulged outwards as there was considerable expansion of the block interface joints. The wall attained a maximum vertical load of 106.49kN with a vertical deflection of 40mm (Figure 6a). The wall sustained a maximum horizontal load of 8.85kN which was 8% of the ultimate compression load.

The LSW2 sustained a maximum vertical load of 128.61kN with a vertical deflection of 36.16mm (Figure 6b). The results indicated that the ultimate compressive strength of LSW2 wall was 27% that of individual block. A regression analysis of the ultimate strengths of the wall and individual blocks indicated a positive correlation coefficient of 0.689. The addition of 3% lime to laterite soil caused 20% increment of strength capacity of the wall. This also led to a 9.6% reduction on the vertical

deflection at failure. These findings show that addition of lime to laterite soil makes the walls to have higher compressive strengths but they tend to be brittle.

A maximum vertical compression load of 135.09kN with a vertical deflection of 39.06mm was achieved by LSW3. The presence of 1%RHA in laterite soil stabilized with 6% cement resulted in increase of ultimate compressive strength capacity of the wall from 106.49kN to 135.09kN. This also led to 2% reduction of vertical deflection at failure. The LSW3 sustained a horizontal load of 19.75kN. The addition of 1%RHA to laterite soil stabilized with 6% cement resulted with walls of compressive capacity 7% higher than adding 3% lime.

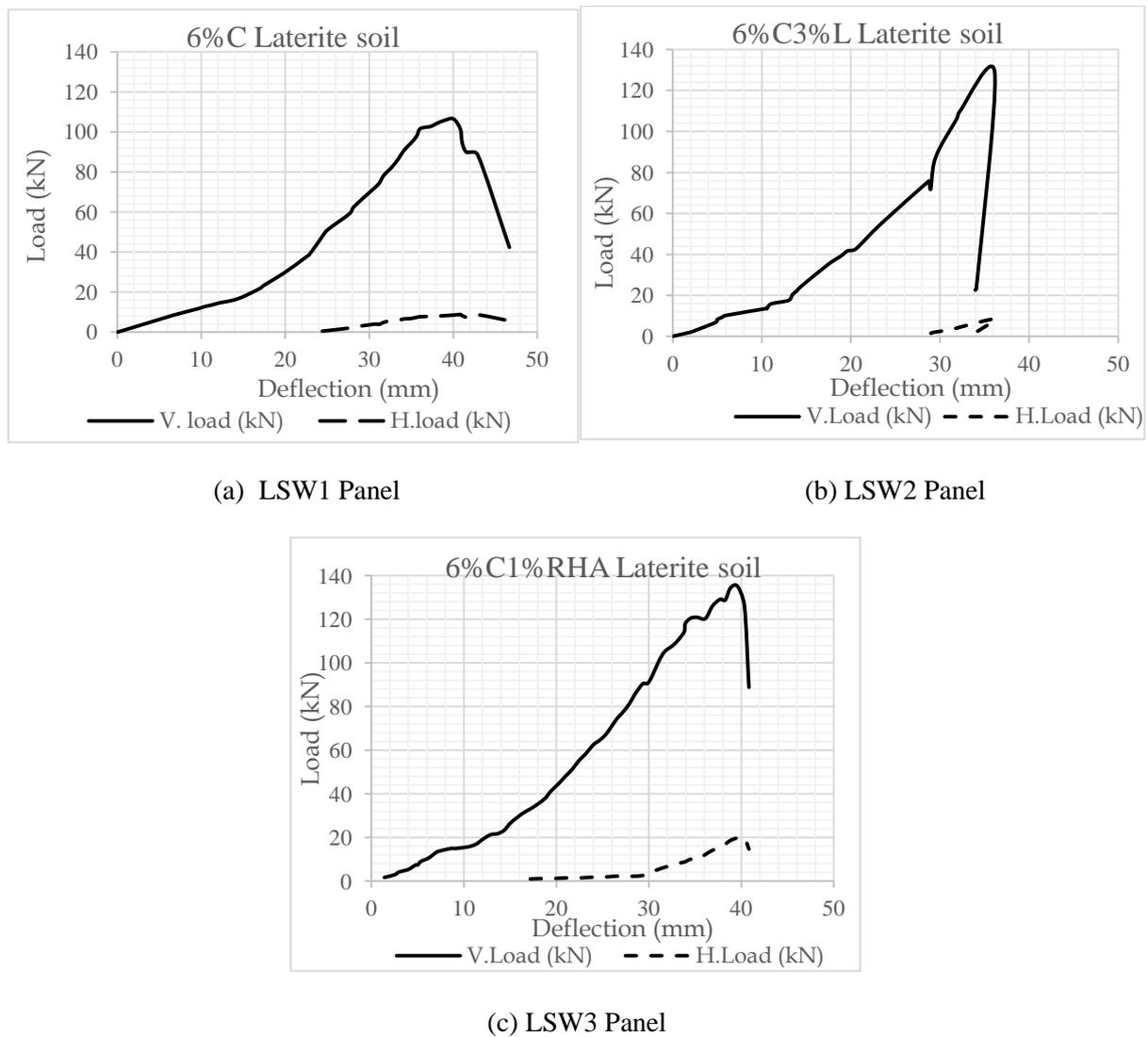


Figure 6: Load-deflection curve for experimental walls

The performance of interlocking soil blocks as presented in Figure 6(a), (b) and (c) can be divided into three parts: (1) slow closure of gaps, (2) rapid load uptake, and (3) wall failure. In the first part, there was rapid increase in deflection as the load was applied. This may be attributed to the closing of the interlocking gaps between the blocks. After the closure of the gaps the deformation evened out with increase of vertical load. In part two, the walls experienced a rapid increase of load capacity. The sharp compression capacity increase occurred at a higher compressive load in LSW3 than in both LSW2 and LSW1. This increase on the second part of the curves was sustained until the ultimate load was achieved. The cause of the second increase of load capacity can therefore be associated to the unit blocks bearing the load as the gaps had closed up making the load to be transferred from one-unit block to the other. In the third part, there was a drop of the load curve as the walls had failed. This occurred after the ultimate load capacity of the walls was achieved.

4. Conclusion

The improvement of the physico-mechanical properties of the interlocking blocks in terms of compressive strength, water absorption and durability is a positive aspect of the stabilizers. An optimum of 3% lime in laterite soil stabilized with 6% pozzolanic cement exhibited the highest 28-day compressive strength, with a highest reduction of 24-hour water absorption obtained through addition 1%RHA. The walls exhibited good mechanical strength, in spite of their ultimate compressive strength being lower compared to that of individual blocks. In relation to the wall performance under loading, the load-deflection curves can be divided into three distinct parts. This study concludes that;

- Compressive strength and increased resistance on abraded material of laterite soil blocks is optimally achieved with lime but water resistance is best achieved with RHA stabilization.
- Lime stabilised block wall exhibited higher compressive strengths but they tend to be brittle, while RHA stabilized block walls accommodate higher vertical load deflection.
- The wall failure modes were characterised by either diagonal cracking of individual blocks or spalling of block debris.

- The zero-mortar layer of interlocking block walls make them to have higher deflection when initially loaded before they can rapidly take up the compressive load until failure is experienced.

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