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Mechanical Characterization and Finite Element Simulation of Cement-Stabilized Earth Blocks in Humid Tropical Zones: Experimental Characterization and Monotonic Phase-Field Damage Modelling Using Comsol Multiphysics

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Abstract

The mechanical performance of cement-stabilized earth blocks (CSEBs) under humid tropical conditions remains insufficiently explored. This study investigates the static mechanical behaviour and structural durability of CSEBs produced from lateritic soils of Bamenda III, Cameroon, through combined experimental characterization and monotonic phase-field finite element damage modelling in COMSOL Multiphysics. All mechanical tests were performed under monotonic (non-cyclic) loading at ambient laboratory conditions; the results therefore characterize static strength and simulated damage response rather than measured fatigue behaviour, and humid-climate durability inferences are limited to the water absorption results obtained. Soil classified as A-2-7 exhibited a liquid limit of 65.9%, plasticity index of 23.7%, and maximum dry density of 1.614 g/cm^3 at 22.6% optimal moisture content. Blocks manufactured at cement stabilization levels of 0%, 4%, 6%, 8%, and 10% were tested for water absorption, bulk density, compressive strength, and flexural strength. Increasing cement content progressively reduced water absorption from 22.1% to 17.3%, while compressive strength increased from 4.5 MPa to 6.1 MPa and flexural strength from 0.7 MPa to 1.2 MPa. Three-dimensional FEM simulations demonstrated that stabilized walls exhibit superior stress distribution, reduced crack propagation, and enhanced load-carrying capacity, with the 10% stabilized wall achieving a load capacity of 599.38 kN against 485.53 kN for the unstabilized configuration. These findings provide design-oriented baseline data and modelling parameters for resilient earthen construction in humid tropical climates across sub-Saharan Africa.

Keywords

Mechanical Behaviour, Modelling, Humid Zone, Stabiliser

1. Introduction

Compressed earth blocks (CEBs) have attracted renewed global attention as an environmentally responsible alternative to conventional construction materials, offering low embodied energy, reduced greenhouse gas emissions, and the reuse of locally available soils [1]-[3]. Despite these advantages, their long-term mechanical performance remains uncertain, particularly regarding cyclic loading and fatigue-induced deterioration. Fatigue is defined as the progressive accumulation of microstructural damage under repeated stress cycles until failure [4]. Unlike conventional materials such as concrete or steel, the fatigue behavior of earthen construction materials is poorly understood, and experimental evidence remains limited to static performance indicators such as compressive or flexural strength.

Previous works have explored stabilization approaches to improve durability most commonly cement, lime, or natural pozzolans but these studies primarily examine short-term properties such as compressive strength, water absorption, or freeze-thaw resistance [1] [5] [6]. Moreover, many investigations are based on temperate climates or arid regions, overlooking the complex behavior of earth materials exposed to high humidity, intense rainfall, and cyclic wetting-drying conditions typical of sub-Saharan Africa. Humidity significantly alters microstructure, pore connectivity, and residual stresses in CEBs, accelerating fatigue failure and loss of stiffness [7] [8]. Thus, there is an urgent need to evaluate fatigue mechanisms in stabilized earth blocks exposed to humid tropical climates, where the interaction between water and repeated loading is likely to be a dominant deterioration parameter.

Cameroon is a representative case of these environmental challenges. The Bamenda region features prolonged wet seasons, high-temperature variability, and substantial moisture ingress, all of which may jeopardize the long-term integrity of earthen buildings [7]. Although cement stabilization is widely used in the country to increase mechanical performance, there remains little evidence quantifying its impact on fatigue behavior. Existing studies typically provide empirical compressive strength ranges, but rarely introduce predictive models capable of estimating fatigue life or residual stress accumulation over time, limiting their contributions to structural design or code development.

To address these gaps, this study investigates the mechanical response of cement-stabilized earth blocks produced from soils in the Bamenda III municipality, and proposes a finite-element model able to estimate stress concentration and damage evolution under monotonic loading, providing baseline data toward future fatigue characterization under cyclic loading. By analysing fundamental geotechnical characteristics, correlating them with mechanical performance, and implementing finite element simulations, we aim to: 1) evaluate how stabilization influences durability under humid conditions; 2) identify controlling parameters that govern damage resistance; and 3) provide design-oriented insights for sustainable construction in tropical regions. The results provide a critical contribution toward the development of performance-based guidelines for stabilized earthen architecture in humid climates.

2. Materials and Methods

2.1. Sampling

The soil samples were collected from Bamenda III our study area as shown in Figure 1. The site was selected based on its relevance to the study, ensuring it exhibited typical properties of soils found in tropical zones subjected to high humidity. That is, they are typically clay-rich with low fertility and high acidity, because heavy rainfall leaches nutrients such as magnesium and calcium and concentrating iron and aluminum oxides that give the soil a reddish or yellowish hues [9] [10]. These soils most at times have a compact structure, poor organic matter storage due to rapid decomposition, and are dominated by kaolinite and other secondary minerals [10] [11]. They have Nutrient limitations, particularly phosphorus, arise from strong binding with aluminum and iron oxides, while

Figure 1. Soil sampling.

high microbial activity supports rapid nutrient cycling [9] [10]. Eighty kilogram (80 kg) of distributed sample was collected and stored in a polystyrene bag so as to maintain the natural properties and later on was dried at room temperature for two weeks and the geological properties where determined. Soil and cement were proportioned to produce 100 blocks of 40 × 40 × 160 mm, that is 20 blocks each for 0%, 4%, 6%, 8% and 10% cement by weight of dry soil and Curing was carried out for 28 days, with the blocks being regularly sprinkled with water to ensure proper hydration and strength development as seen in **Figure 2**.

Figure 2. Curing of blocks samples.

2.2. Methods

2.2.1. Geotechnical Properties

The American Society for Testing and Materials standards was used to obtain the geotechnical parameters of the soil, that is (Particle size analysis, Atterberg Limits test, Moisture content test, Organic Content, Specific gravity and modified proctor test), physical properties of the compress earth block (water absorption and Volumic mass), mechanical properties of the compress earth block (flexural strength and compressive strength).

The grain size analysis was determined by dry sieving and sedimentation according to ASTM D 422. The Casagrande method was used to determine the and the roller method to determine the plastic limit. The difference between the liquid limit and plastic limit gives us the plasticity index (PI = WL-PL). These measurements were obtained according to ASTM D 4318.

2.2.2. Mechanical Properties

The modified Proctor test was carried out in accordance with ASTM D 1557 standards. The curve of modified Proctor permit to determine the optimum moisture content (OMC) and obtain the maximum dry density (MDD). The MDD is a good indicator of the compactness and bearing capacity of the soil after sufficient compaction.

Flexural strength test was performed based on ASTM C78/C78M, to determine the flexural strength of stabilized earth blocks, which is essential for understanding their resistance to bending forces in construction applications.

The compressive strength test followed the guidelines of ASTM D1633. The purpose of this test was to determine the compressive strength of stabilized earth blocks. Compressive strength is a critical parameter in evaluating the structural integrity and suitability of these blocks for construction purposes. The moisture or condition of the specimens at the time of each mechanical test was as-cured.

2.2.3. Modelling Using COMSOL Multiphysique

The simulation carried out was based on experimental data gotten from stabilizing earth bricks with cement and Additional parameter from [12] building Code as seen in Tables 1-6. In an attempt to understand the behavior of the new material as a wall filing, a wall of 1.14 m length, 1 m height, and 0.11 m thickness was simulated in the COMSOL software. two models exist:

- **Type A:** unstabilized earth brick wall with cement mortar joints;
- **Type B:** stabilized earth brick with cement mortar joints;
  . **type B1:** 4% stabilization
  . **type B2:** 6% stabilization
  . **type B3**: 8% stabilization
  . **type B4:** 10% stabilization

Table 1. Material properties for earth brick without stabilization (source: ACI Committee 530 (2013)). Building Code Requirements and Specification for Masonry Structures (ACI 530-13/ASCE 5-13/TMS 402-13).

Property	Variable	Value	Unit	Property group
Density	rho	1903.3	kg/m³	Basic
Young's modulus	E	2250e6	Pa	Young's modulus and P...
Poisson's ratio	nu	0.2	1	Young's modulus and P...
Critical energy release rate	Gc	50	J/m²	Phase field damage
Tensile strength	sigmat	0.61e6	Pa	Isotropic strength para...
Compressive strength	sigmac	4.5e6	Pa	Isotropic strength para...
Biaxial compressive strength	sigma...	4.5e6	Pa	Isotropic strength para...
Peak strength	sigmap	mat1.ls...	N/m²	Scalar damage
Fracture energy per area	Gf	100	J/m²	Scalar damage
Fracture energy per volume	gf	150	J/m³	Scalar damage
Critical fracture stress	sigmacr	0.45e6	N/m²	Phase field damage

Table 2. Material properties for earth brick of 4% fiber stabilization.

Property	Variable	Value	Unit	Property group
Young's modulus	E	10897.25e6	Pa	Young's modulus and Poisson's...
Poisson's ratio	nu	0.2	1	Young's modulus and Poisson's...

Continued

Critical energy release rate	Gc	50	J/m²	Phase field damage
Tensile strength	sigmat	0.62e6	Pa	Isotropic strength parameters
Compressive strength	sigmac	4.75e6	Pa	Isotropic strength parameters
Biaxial compressive strength	sigmabc	4.75e6	Pa	Isotropic strength parameters
Peak strength	sigmap	mat1.Isotro...	N/m²	Scalar damage
Fracture energy per area	Gf	100	J/m²	Scalar damage
Fracture energy per volume	gf	150	J/m³	Scalar damage
Critical fracture stress	sigmacr	0.3e6	N/m²	Phase field damage

Table 3. Material properties for earth brick of 6% fiber stabilization.

Property	Variable	Value	Unit	Property group
Density	rho	1959.47	kg/m³	Basic
Young's modulus	E	2630e6	Pa	Young's modulus and Poi...
Poisson's ratio	nu	0.14	1	Young's modulus and Poi...
Critical energy release rate	Gc	50	J/m²	Phase field damage
Tensile strength	sigmat	0.53e6	Pa	Isotropic strength param...
Compressive strength	sigmac	5.25e6	Pa	Isotropic strength param...
Biaxial compressive strength	sigmabc	5.25e6	Pa	Isotropic strength param...
Peak strength	sigmap	mat1.Isot...	N/m²	Scalar damage
Fracture energy per area	Gf	100	J/m²	Scalar damage
Fracture energy per volume	gf	150	J/m³	Scalar damage
Critical fracture stress	sigmacr	0.56e6	N/m²	Phase field damage

Table 4. Material properties for earth brick of 8% fiber stabilization.

Property	Variable	Value	Unit	Property group
Density	rho	1975.04	kg/m³	Basic
Young's modulus	E	2820e6	Pa	Young's modulus and Poisso...
Poisson's ratio	nu	0.11	1	Young's modulus and Poisso...
Critical energy release rate	Gc	50	J/m²	Phase field damage
Tensile strength	sigmat	0.48e6	Pa	Isotropic strength parameters
Compressive strength	sigmac	5.63e6	Pa	Isotropic strength parameters
Biaxial compressive strength	sigmabc	5.63e6	Pa	Isotropic strength parameters
Peak strength	sigmap	mat1.Isotr...	N/m²	Scalar damage
Fracture energy per area	Gf	100	J/m²	Scalar damage
Fracture energy per volume	gf	150	J/m³	Scalar damage
Critical fracture stress	sigmacr	0.56e6	N/m²	Phase field damage

Table 5. Material properties for earth brick of 10% fiber stabilization.

Property	Variable	Value	Unit	Property group
Density	rho	1999.4	kg/m³	Basic
Young's modulus	E	3040e6	Pa	Young's modulus and Poi...
Poisson's ratio	nu	0.08	1	Young's modulus and Poi...
Critical energy release rate	Gc	50	J/m²	Phase field damage
Tensile strength	sigmat	0.45e6	Pa	Isotropic strength param...
Compressive strength	sigmac	6.08e6	Pa	Isotropic strength param...
Biaxial compressive strength	sigmabc	6.08e6	Pa	Isotropic strength param...
Peak strength	sigmap	mat1.Isot...	N/m²	Scalar damage
Fracture energy per area	Gf	100	J/m²	Scalar damage
Fracture energy per volume	gf	150	J/m³	Scalar damage
Critical fracture stress	sigmacr	0.56e6	N/m²	Phase field damage

Table 6. Material properties for cement mortar (source: ACI Committee 530 (2013)). Building Code Requirements and Specification for Masonry Structures (ACI 530-13/ASCE 5-13/TMS 402-13).

Property	Variable	Value	Unit	Property group
Density	rho	2200	kg/m³	Basic
Young's modulus	E	22360.7e6	Pa	Young's modulus and Poisson'...
Poisson's ratio	nu	0.25	1	Young's modulus and Poisson'...
Critical energy release rate	Gc	100	J/m²	Phase field damage
Tensile strength	sigmat	3e6	Pa	Isotropic strength parameters
Compressive strength	sigmac	20e6	Pa	Isotropic strength parameters
Biaxial compressive strength	sigmabc	20e6	Pa	Isotropic strength parameters
Critical fracture stress	sigmacr	3e6	N/m²	Phase field damage

Geometry

The geometry for this model is a 3D wall as seen in **Figure 3**. In COMSOL, we used block tool an array tool to create the brick-and-mortar joints. The wall is 1.14 m long, 1 m high and 11 cm thick. Bricks are of sizes: 22 cm by 11 cm by 6 cm.

Model

Linear elastic damage Model (phase field damage model) was used based on the equation

$$\varepsilon(\phi,u)=\int_{\Omega}^{n}\left((1-\phi)^2\psi_0(\epsilon)+\frac{G_c}{c_\omega}\left(\frac{w(\phi)}{l}+l\|\nabla\phi\|^2\right)\right)\mathrm{d}\Omega \quad (1)$$

- $\psi_0(\epsilon)$ is the strain energy density.
- G_c is the critical energy release rate (fracture toughness).

- l is the length scale parameter controlling the width of the diffuse crack.
- $w(\phi)$ is a degradation function. This phase-field formulation captures monotonic (single-cycle) crack initiation and propagation under increasing load; it does not include a cycle-dependent damage-accumulation law, load waveform, stress ratio, or number-of-cycles-to-failure criterion, and therefore represents simulated static/monotonic damage rather than measured or predicted fatigue life.

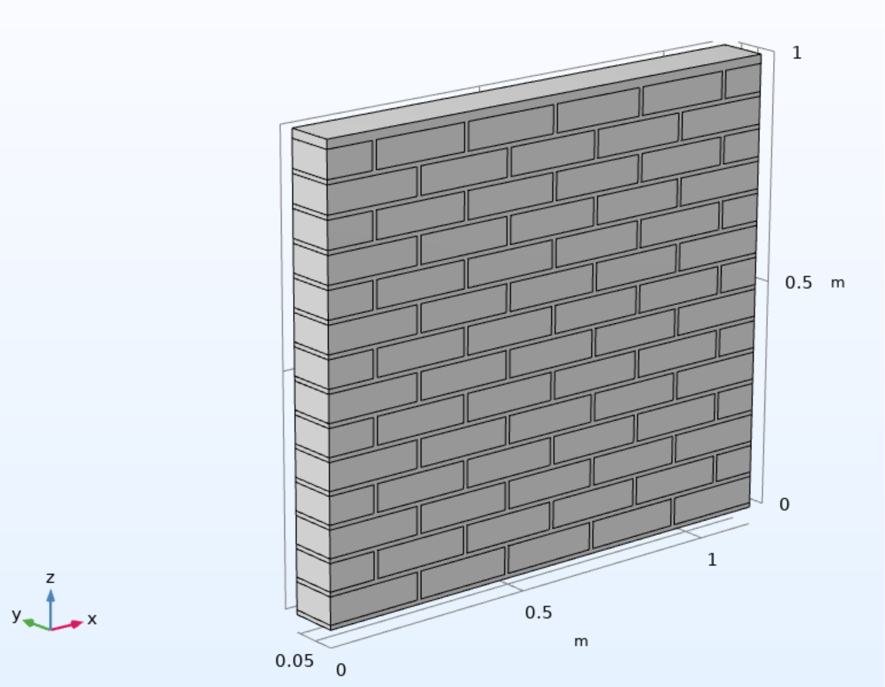

Figure 3. 3D wall model in COMSOL.

2.2.4. Loading

We applied the loads in COMSOL by using a parametric sweep whereby we loaded the wall at different intensities as seen in **Table 7**. This parametric sweep applies monotonically increasing static loads (6 - 12 kN, **Table 7**) along a single loading path to determine peak and ultimate capacity; it does not represent a cyclic load history, and no cycle count, loading frequency, stress ratio, or fatigue-failure criterion is defined.

Table 7. Vertical loads.

Load No.	Intensity (KN)
LV1	6
LV2	7.5
LV3	9
LV3	10.5
LV4	12

3. Results and Discussions

3.1. Geotechnical Characterization

3.1.1. Grain Size Analysis

Figure 4 and **Table 8** present the results of grain size distributions. The results show that it is composed of 48.7% gravel, 36.7% sand, 2.4% silt, and 12.2% clay. These results shows a coarse-grained soil with a significant proportion of gravel and sand, making it potentially suitable for use in construction, particularly in applications where high compaction and strength are required. In the AASHTO classification system, the soil is classified as "A-2-7," it aligns with studies from previous research [13], on the compaction effect on the compressive strength and durability of stabilized earth blocks since the high sand content in this laterite could contribute to improved compressive strength, as compaction is likely to be more effective with such a granular composition. On the other hand, Previous research [14] in their study on the fatigue behavior of shot-earth emphasized the role of finer particles like silt and clay in enhancing cohesion and fatigue resistance. However, the relatively low percentage of fines in this soil suggests that it may require stabilization or additional fines to enhance its durability and resistance to fatigue under cyclic loading conditions.

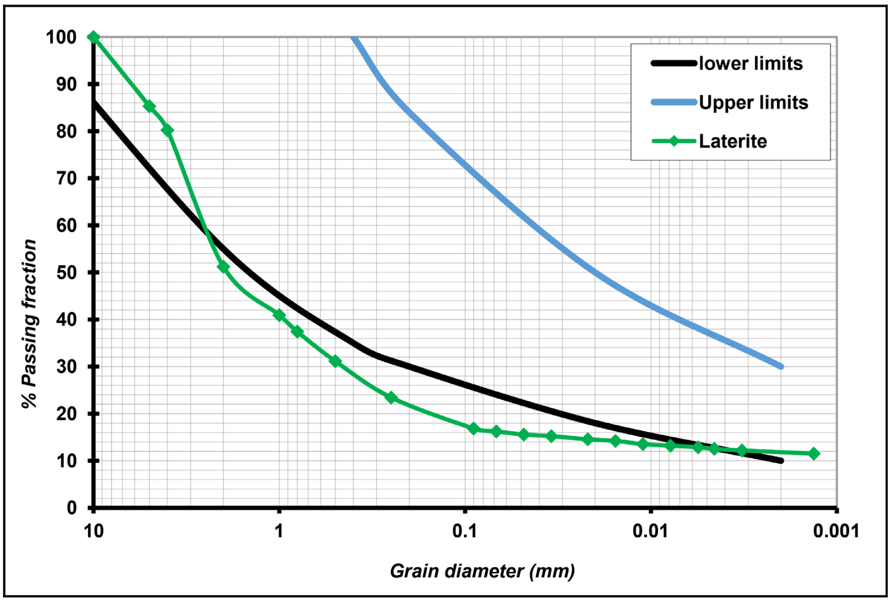

Figure 4. Particle size analyses curves for samples.

Table 8. Particle size distribution.

Sample	% Gravel Φ > 2 mm	% Sand 2 > Φ > 0.02 mm	% Silt 0.02 > Φ > 0.002 mm	% Clay Φ < 0.002 mm
Laterite	48.7	36.7	2.4	12.2

3.1.2. Atterberg Limits

The Atterberg limit results is shown in **Table 9**. The results show a liquid limit

(LL) of 65.9%, a plastic limit (PL) of 42.2%, and a plasticity index (PI) of 23.7%. These values tell us that the soil has a high plasticity, which indicates a significant amount of clay content. Such a high PI indicates the soil's potential for considerable volume change with moisture fluctuations, which is crucial in construction applications. The findings align with previous studies [13], who noted that soils with higher plasticity indices tend to exhibit better compaction behavior but require careful moisture management to avoid excessive shrinkage or swelling. Similarly, Previous research [15] emphasized that soils with a high liquid limit and plasticity index often require stabilization techniques, such as the addition of cement or lime, to enhance their suitability for construction, particularly in earth block manufacturing. These results highlight the need for proper treatment or stabilization to manage the high plasticity and ensure the soil's structural integrity, particularly in applications where dimensional stability is critical, such as in road construction or the production of stabilized earth blocks.

Table 9. Atterberg limits results.

	Laterite						
	Liquid limit				**Plastic limit**		
Mt (g)	0.21	0.21	0.2	0.22	0.26	0.25	0.26
Mth (g)	6.44	6.23	4.91	4.89	2.63	1.63	1.74
Mts (g)	3.96	3.84	3.02	3.01	1.93	1.22	1.3
Ms (g)	3.75	3.63	2.82	2.79	1.67	0.97	1.04
Mh (g)	6.23	6.02	4.71	4.67	2.37	1.38	1.48
W(g)	2.48	2.39	1.89	1.88	0.7	0.41	0.44
TE%	66.13	65.84	67.02	67.38	41.92	42.27	42.31
MTE%	65.99		67.20			42.16	
Nc	25		21				
Ll	65.99		65.80				
LI				**65.9**			
Lp				**42.2**			
PI				**23.7**			

3.1.3. Discussion of Proctor

The Proctor test results as shown in **Figure 5**, indicate that the soil achieves its maximum dry density (MDD) of 1.586 g/cm^3 at an optimal moisture content (OMC) of 23.7%, meaning this moisture level allows for the tightest packing of soil particles during compaction. After making corrections, the maximum dry density slightly increases to 1.614 g/cm^3 with a corresponding optimal moisture content of 22.6% with a degree of saturation (S'r) slightly above 100%, are indicative of a well-compacted soil mix. These findings aligns with the research by

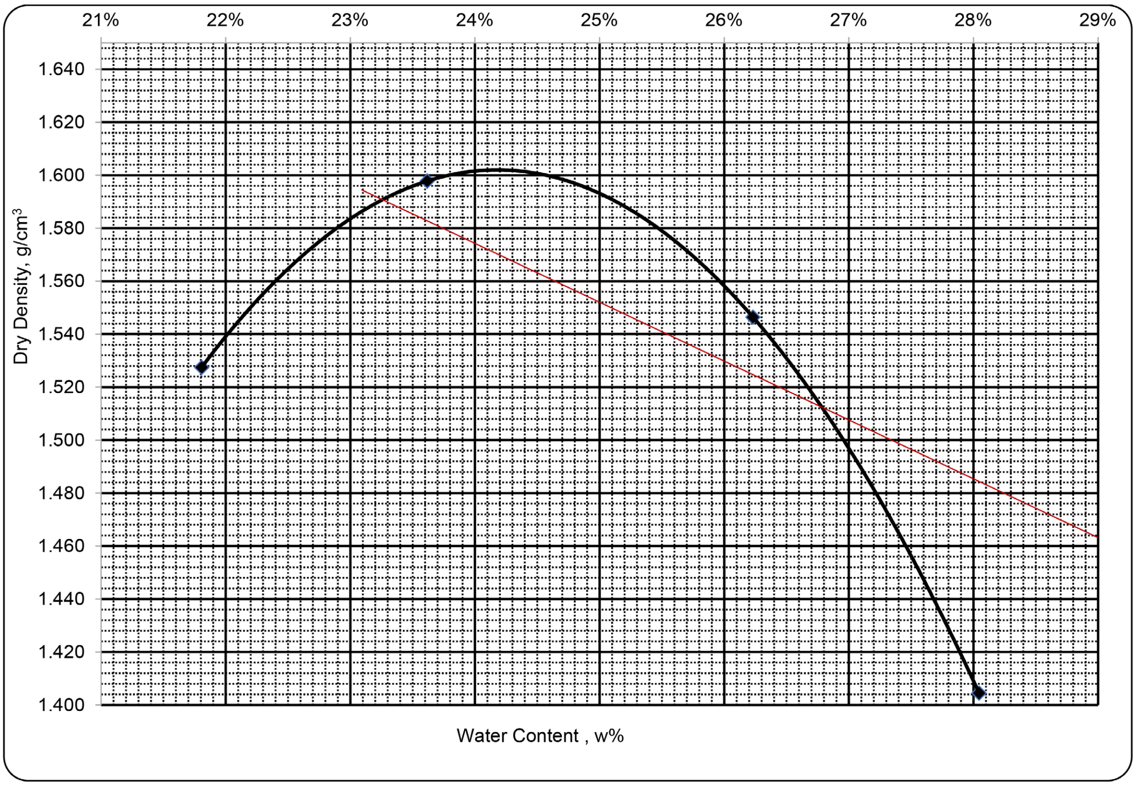

Figure 5. Soil proctor curve.

[8], who studied the mechanical behaviour of compressed earth blocks (CEBs) enhanced with cement stabilization. They found that achieving an optimal dry density and moisture content is crucial for improving the mechanical performance of CEBs. The slight increase in dry density and the fine-tuning of moisture content in the present study are consistent with [8] observations, where cement stabilization combined with optimal compaction significantly enhanced the compressive strength and durability of the blocks. The comparison underscores the importance of precise compaction and moisture control, particularly in cement-stabilized earth, to maximize the mechanical benefits in construction materials like CEBs.

3.1.4. Methylene Blue Test, Organic Content Test and Specific Gravity Test

Table 10 gives us the results of Methylene blue test, A Methylene Blue Value (MBV) of 2.53 indicates the presence of a moderate amount of clay minerals, which influences the soil's reactivity and plasticity. The organic matter content (OM) averages around 21.60% as indicated in Table 11, suggesting a high level of organic material, which can affect soil structure, compressibility, and stability. The specific gravity (Gs) presented in Table 12 averages at approximately 2.395, which is typical for soils with a mix of mineral components, suggesting a balanced mineral composition with a potential influence from organic matter. Comparing these results with other studies, the MBV value aligns with findings of previous work [16], who observed that soils with MBV values around this range typically exhibit moderate plasticity and are suitable for stabilization efforts in earth construction. The high organic matter content, as shown in previous research [17], can be a double-edged sword; while it can improve soil fertility and water retention, it also introduces challenges in compaction and structural stability, necessitating careful management, especially in engineering applications. The specific gravity results are consistent with previous work [18], who found that soils with similar Gs values tend to have balanced mechanical properties, though the presence of high organic content requires additional stabilization for construction purposes.

Table 10. Methylene blue test.

M(g)	V (mL)	MBV
30	76	2.53

Table 11. Organic content results.

Mt (g)	Mts (g)	Mtf (g)	OM (%)	Average
34.66	56.35	51.71	21.39	
38.45	48.22	46.09	21.80	21.60

Table 12. Specific gravity results.

No	M1	M2	M3	M4	Gs	Average
1	91.97	111.97	351.88	340.22	2.398	**2.39**
2	91.97	111.97	351.87	340.22	2.395	
3	91.97	111.97	351.81	340.22	2.378	

3.2. Physical Properties of Blocks Sample

3.2.1. Blocks Water Absorption Results

The results indicated in **Figure 6**, shows a decreasing trend in water absorption as the percentage of stabilization increases, with water absorption starting at 22.1% for 4% stabilization and reducing to 17.3% at 10% stabilization. This trend tells us that higher stabilization percentages improve the blocks' resistance to water absorption, this can be explained by a denser and more compacted matrix that reduces porosity and improves water resistance. These results align with previous research [19], who demonstrated that increasing the cement content in stabilized earth blocks leads to a significant reduction in water absorption, which aligns with the current findings. Additionally, as shown in research [20], stabilizing agents like cement or lime significantly improve the durability of earth blocks by reducing their water absorption capacity. These suggest that the stabilized earth blocks become increasingly resistant to moisture as the percentage of stabilization increases. This improved water resistance is particularly important in humid zones, where exposure to high levels of moisture can lead to deterioration of construction materials. In humid zones, high moisture content can compromise the structural integrity of earth blocks if they are not sufficiently resistant to water absorption. The results indicate that with a higher level of stabilization (8% to 10%), the earth blocks achieve better durability by limiting water ingress, thereby reducing the risks of swelling, shrinkage, and weakening of the blocks.

3.2.2. Blocks Bulk Density

Figure 7 shows the results of bulk density. The bulk density of stabilized earth blocks (SEBs) increases with higher percentages of stabilization, starting from 1.9 g/cm^3 at 0% stabilization to 2.0 g/cm^3 at 10% stabilization. This trend indicates that the stabilization process enhances the compaction and reduces the porosity of the blocks, thereby increasing their density. These results align with studies by

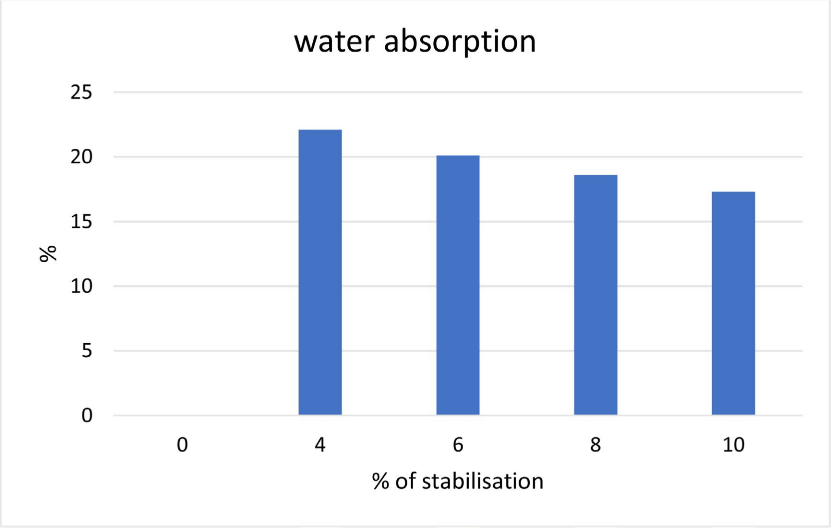

Figure 6. Stabilized blocks water absorption graph.

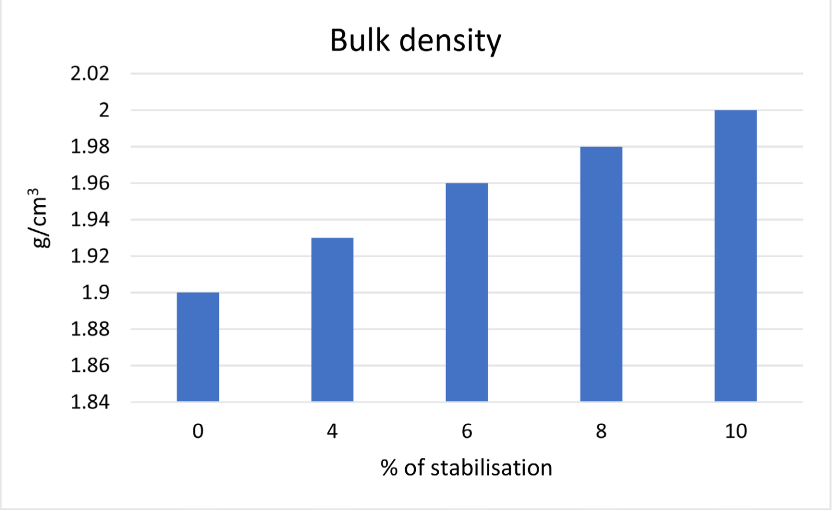

Figure 7. Blocks bulk density graph.

[13], who found that higher density in stabilized earth blocks contributes to improved compressive strength and durability, particularly important in humid zones where moisture resistance is crucial. The increased bulk density in SEBs makes them more suitable for construction in humid environments, as the denser material is less likely to absorb water, reducing the risk of degradation over time.

3.3. Mechanical Properties of Blocks Sample

3.3.1. Compressive Strength of Blocks Sample

From our results shown in **Figure 8**, the compressive strength increases progressively with the percentage of stabilization, rising from 4.5 MPa at 0% stabilization to 6.1 MPa at 10% stabilization. This indicates that the addition of cement enhances the structural integrity of the blocks, making them more resistant to compressive forces. These findings are consistent with studies by [13], who demonstrated that stabilized earth blocks exhibit improved compressive strength, which is crucial for their durability and load-bearing capacity. In humid zones, where materials are subjected to frequent moisture exposure, higher compressive strength is vital as it reduces the risk of block deformation and erosion. Therefore, the increased compressive strength achieved through stabilization makes SEBs more suitable for construction in humid environments, as it ensures greater resilience against the mechanical stresses and environmental challenges prevalent in such areas.

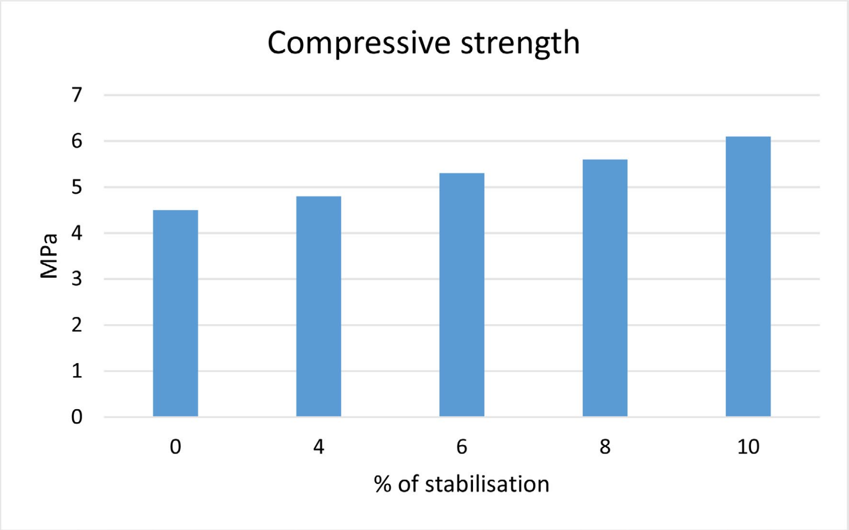

Figure 8. Blocks compressive strength graph.

3.3.2. Blocks Flexural Strength

From the results presented in **Figure 9**, the flexural strength increases with the percentage of stabilization, starting from 0.7 MPa at 0% stabilization and reaching 1.2 MPa at 10% stabilization. This upward trend indicates that the addition of cement improves the blocks' resistance to bending forces, which is crucial for their structural performance, especially in applications where the blocks may be subject to lateral loads or bending stresses. These results are in line with studies like those by [13], which highlight the role of stabilization in enhancing the mechanical properties of SEBs, including their flexural strength. In humid zones, where buildings are exposed to varying moisture levels, increased flexural strength is particularly important as it helps prevent cracking and structural failure due to swelling and shrinkage caused by moisture absorption. Thus, the improved flexural strength with higher stabilization levels makes SEBs more reliable for construction in humid environments, ensuring better durability and longevity.

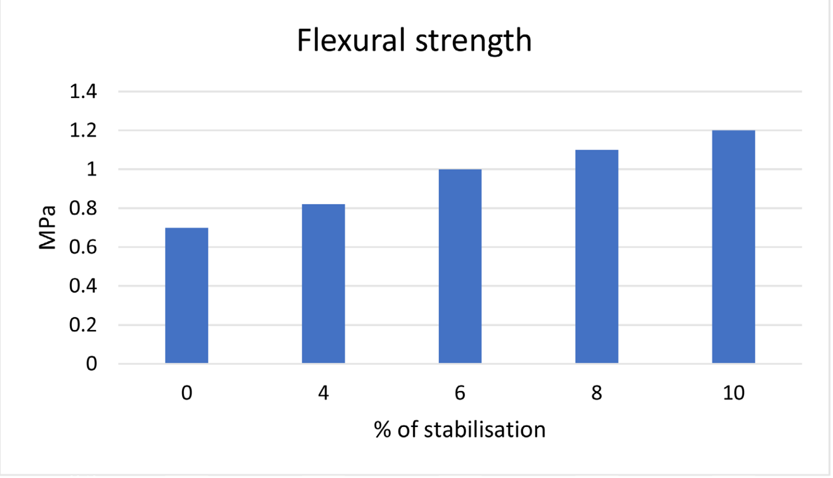

Figure 9. Blocks flexural strength graph.

3.4. Numerical Modelling Using COMSOL Multiphysics

3.4.1. Displacement and Stability

Figures 10-14 shows the horizontal displacement map on the wall TYPE A, TYPE B1, TYPE B2, TYPE B3 and TYPE B4 respectively. The values are very small in the order of 10^{-4} mm reason why Eurocode 6 norms neglect the tensile strength of the brick and joints in the design of load bearing walls. The code rather focusses on exploiting the Compressive strength of the material. The minimal displacement observed in both the stabilized and unstabilized walls is advantageous, as it suggests that these walls can maintain structural stability under environmental stresses. However, the moisture absorption rate of the materials needs careful consideration. For unstabilized earth brick walls (Type A), which show higher displacement and stress, water infiltration could weaken the structure over time due to swelling and shrinkage of the bricks, leading to cracks. Stabilized bricks (Type B) provide better protection against such moisture-induced expansion and contraction. By increasing stabilization (from 4% to 10%), the bricks show reduced stress and displacement, suggesting enhanced resistance to moisture. This is essential in humid zones where water ingress can lead to structural degradation. Stabilization helps in reducing the pore size in the bricks, thereby limiting water absorption and enhancing the durability of the wall, as supported by research on stabilized earth materials [21].

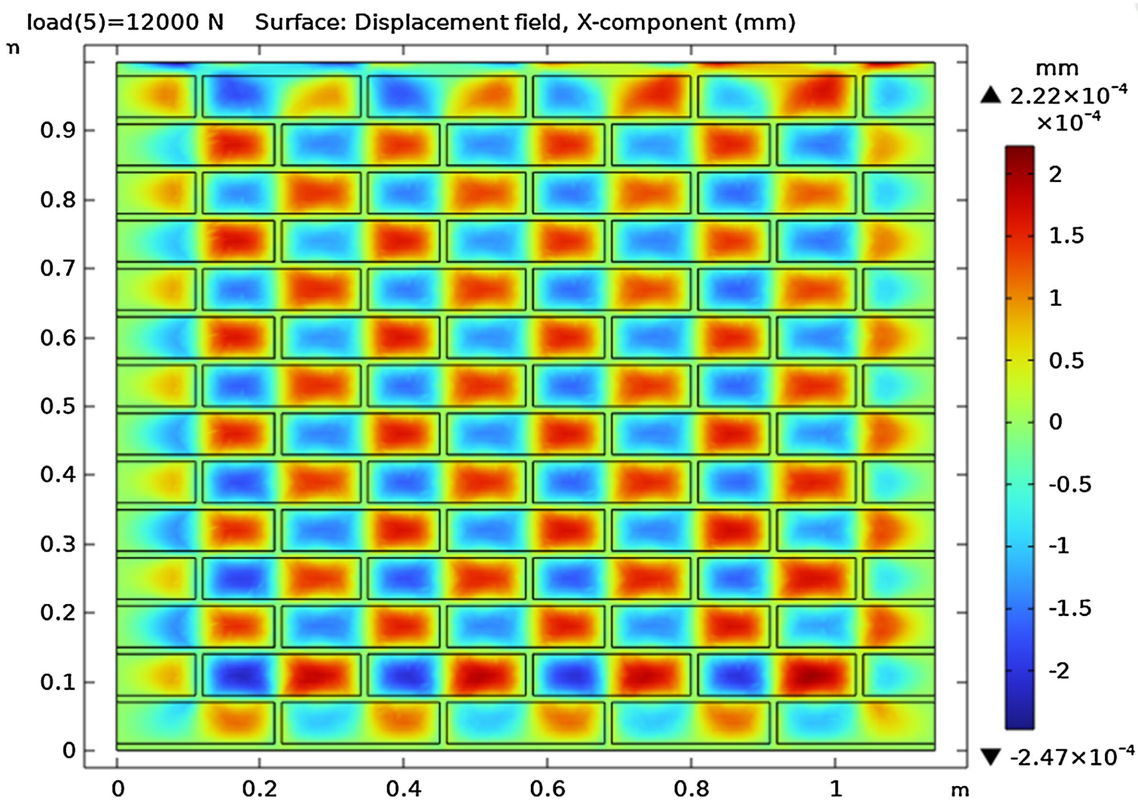

Figure 10. Horizontal displacement in wall TYPE A.

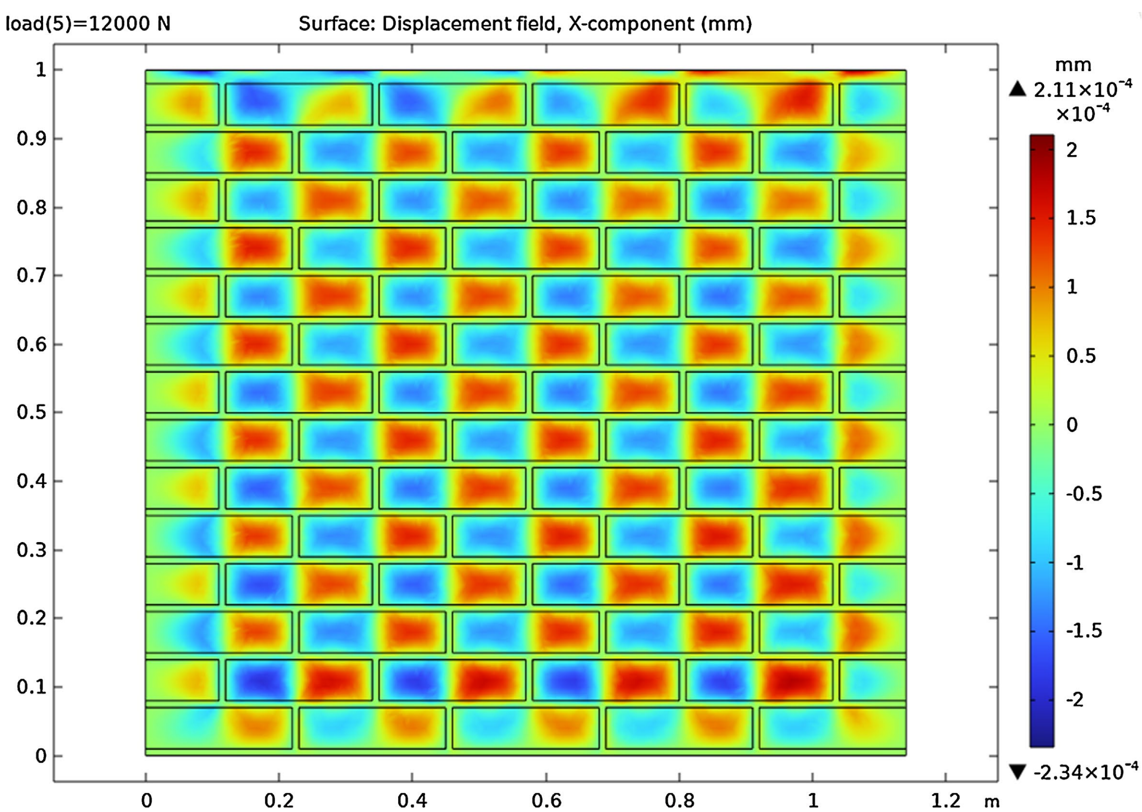

Figure 11. Horizontal displacement in wall TYPE B1.

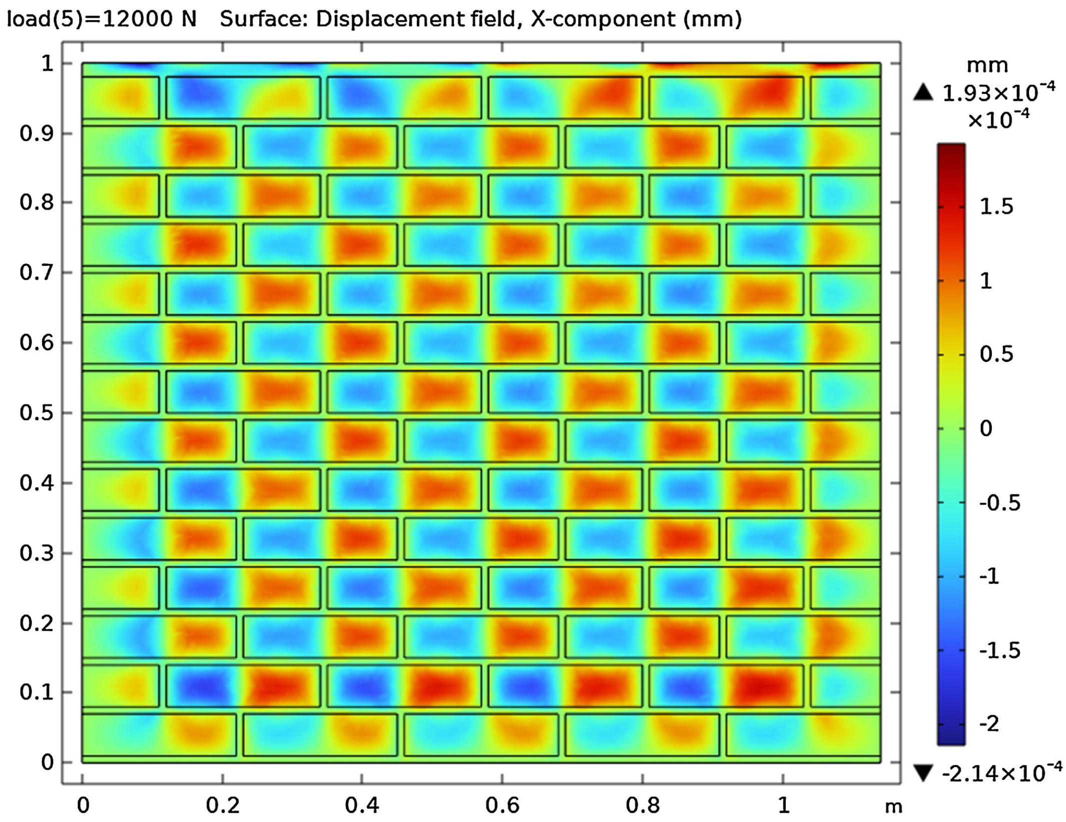

Figure 12. Horizontal displacement in wall TYPE B2.

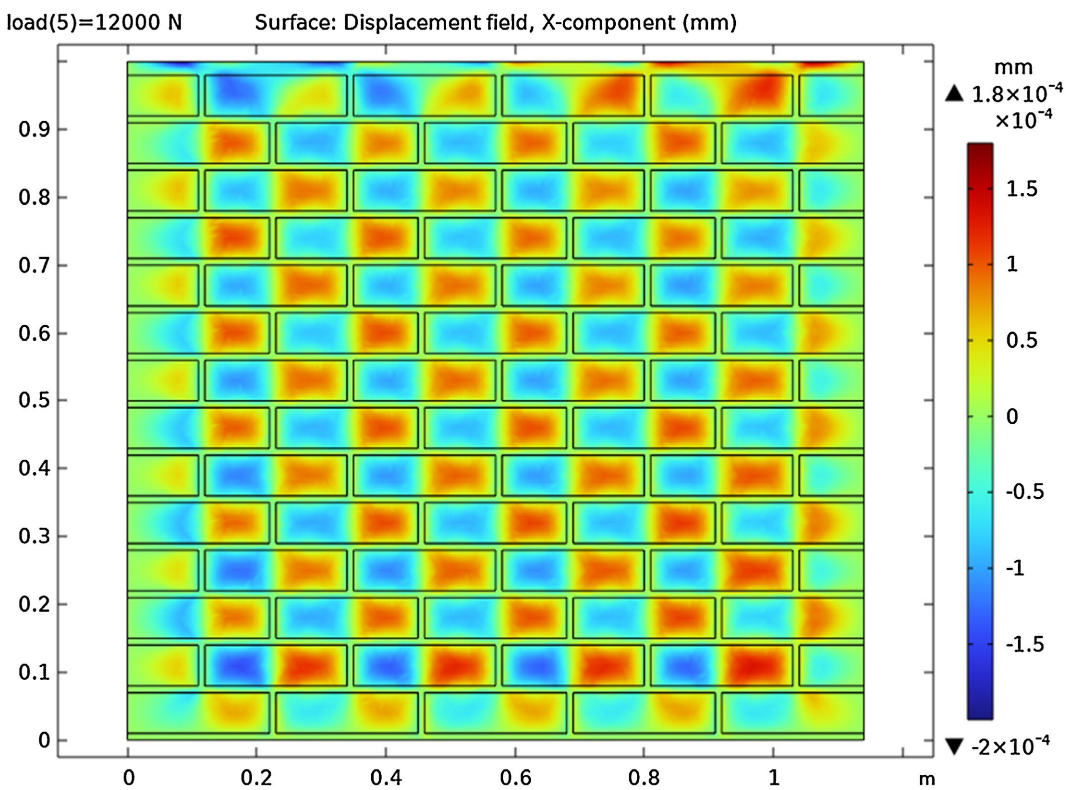

Figure 13. Horizontal displacement in wall TYPE B3.

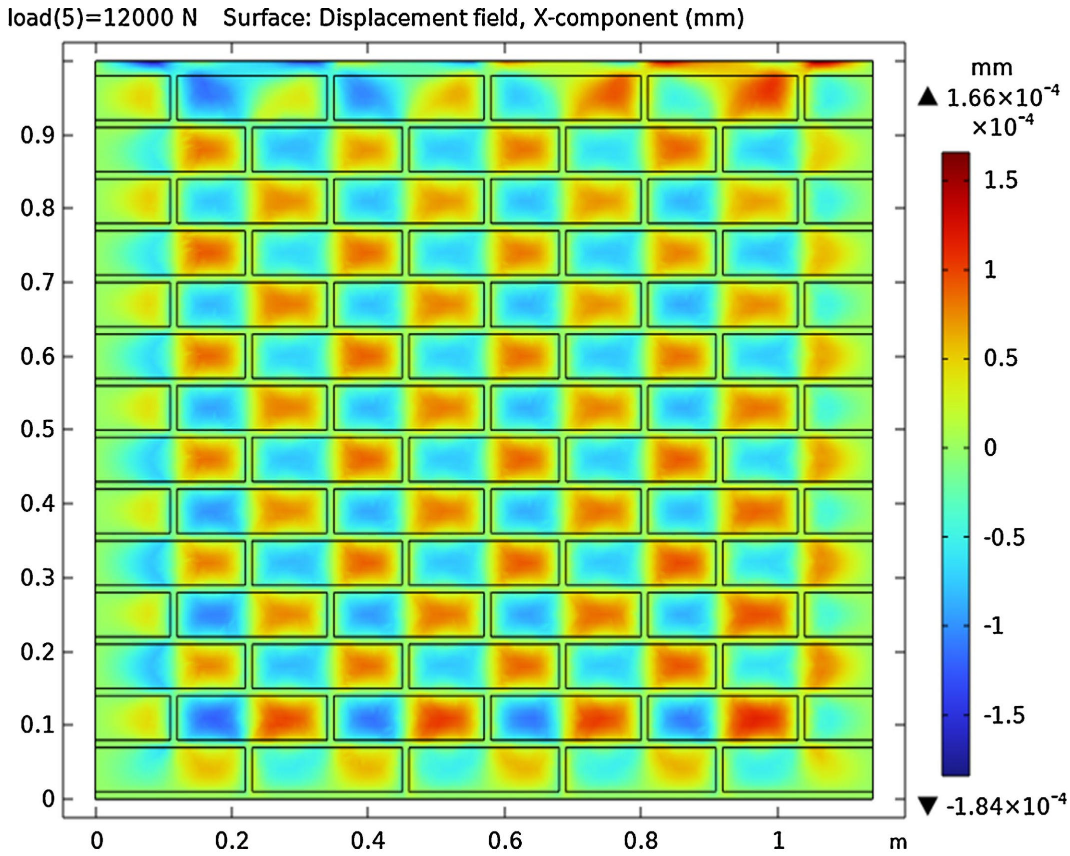

Figure 14. Horizontal displacement in wall TYPE B4.

3.4.2. Stress Distribution and Water Resistance

The von Mises stress distribution in the walls at peak load shown in Figures 15-19 and at ultimate load shown in Figures 20-24 for walls TYPE A, TYPE B1, TYPE B2, TYPE B3 and TYPE B4 shows that the mortar joints, especially the vertical ones, experience higher stress concentrations. In humid zones, the joints are particularly vulnerable to water infiltration, which can weaken the mortar and lead to joint failure. Unstabilized walls (Type A) are more susceptible to this issue as seen in Figure 25, as they exhibit higher stresses in both the bricks and the joints. Over time, water accumulation in the joints can cause erosion and loss of bonding strength, leading to structural instability. On the other hand, the stabilized walls (Type B) display improved stress distribution as in Figure 26, with the stress levels decreasing as the percentage of stabilization increases. The 10% stabilized bricks, for example, show significantly lower stress levels. This suggests that stabilized bricks are more suitable for humid environments, where higher resistance to stress and moisture is crucial to prevent long-term structural damage. This behavior has been documented in studies such as [22], who noted that the mismatch in mechanical properties between bricks and mortar leads to stress redistribution, causing higher stress in the mortar under increased loading. Similarly, [23] observed that in load-bearing masonry walls, stress concentrations tend to be higher in the mortar joints due to their lower stiffness, which aligns with the

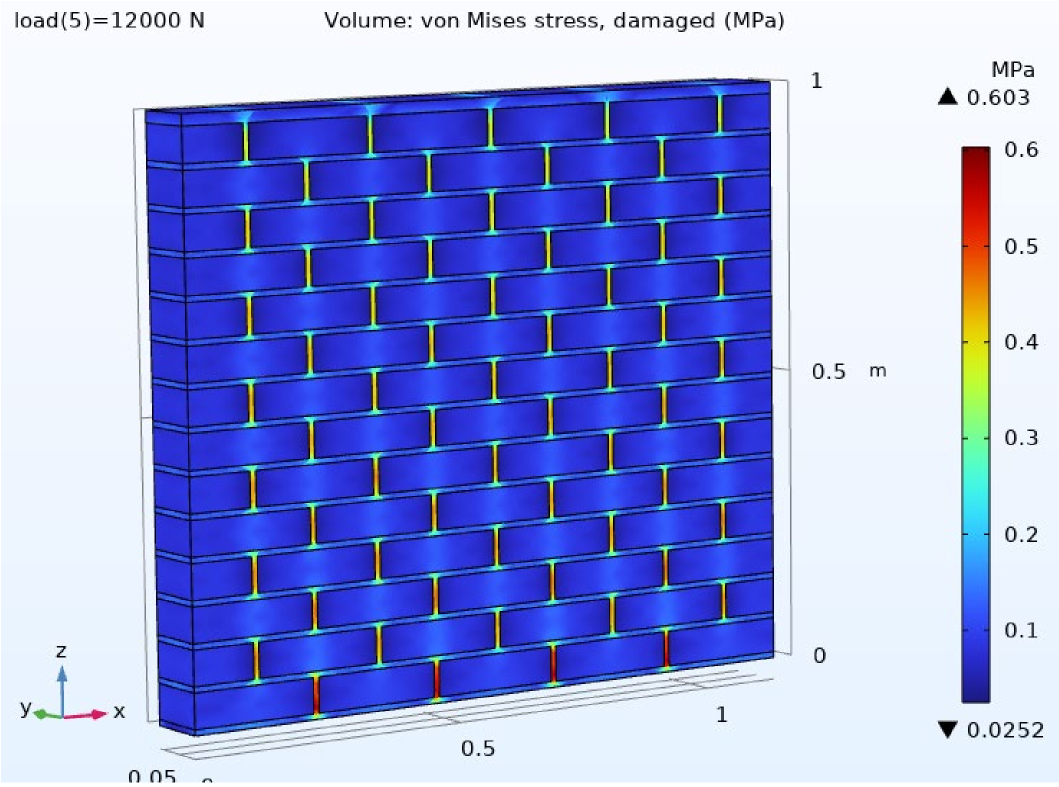

Figure 15. Von Mises stress, damage cartography in bricks for TYPE A model at peak load.

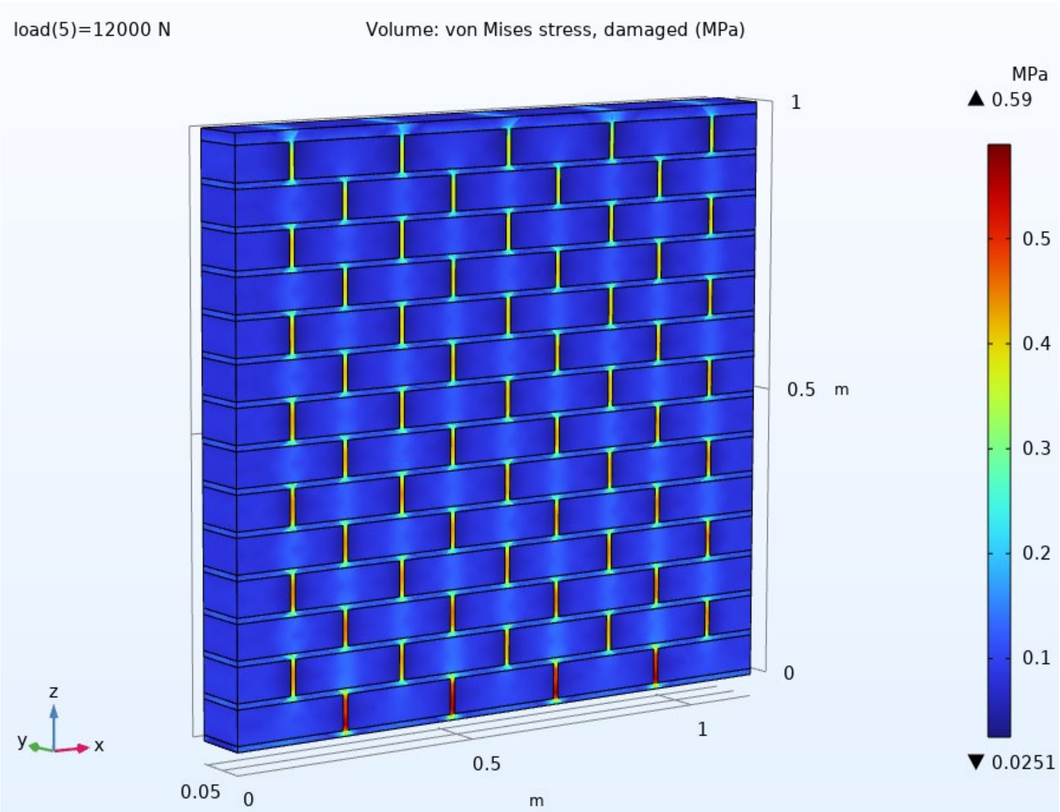

Figure 16. Von Mises stress, damage cartography in bricks for TYPE B1 model at peak load.

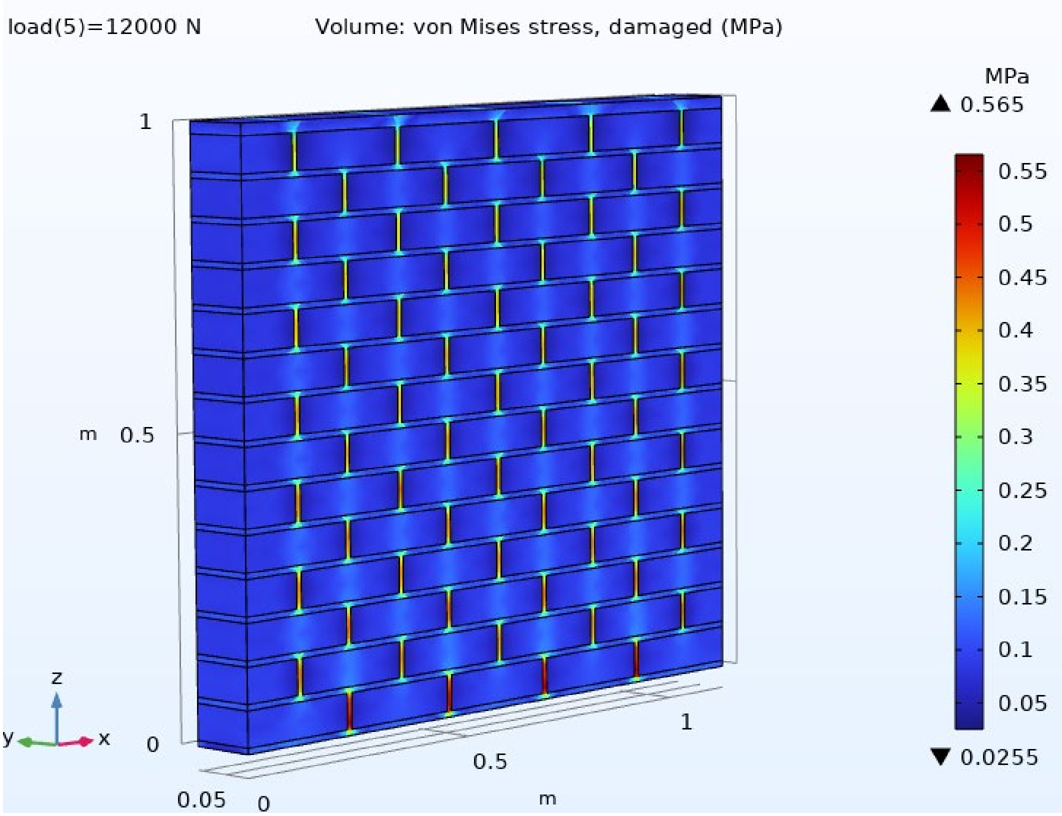

Figure 17. Von Mises stress, damage cartography in bricks for TYPE B2 model at peak load.

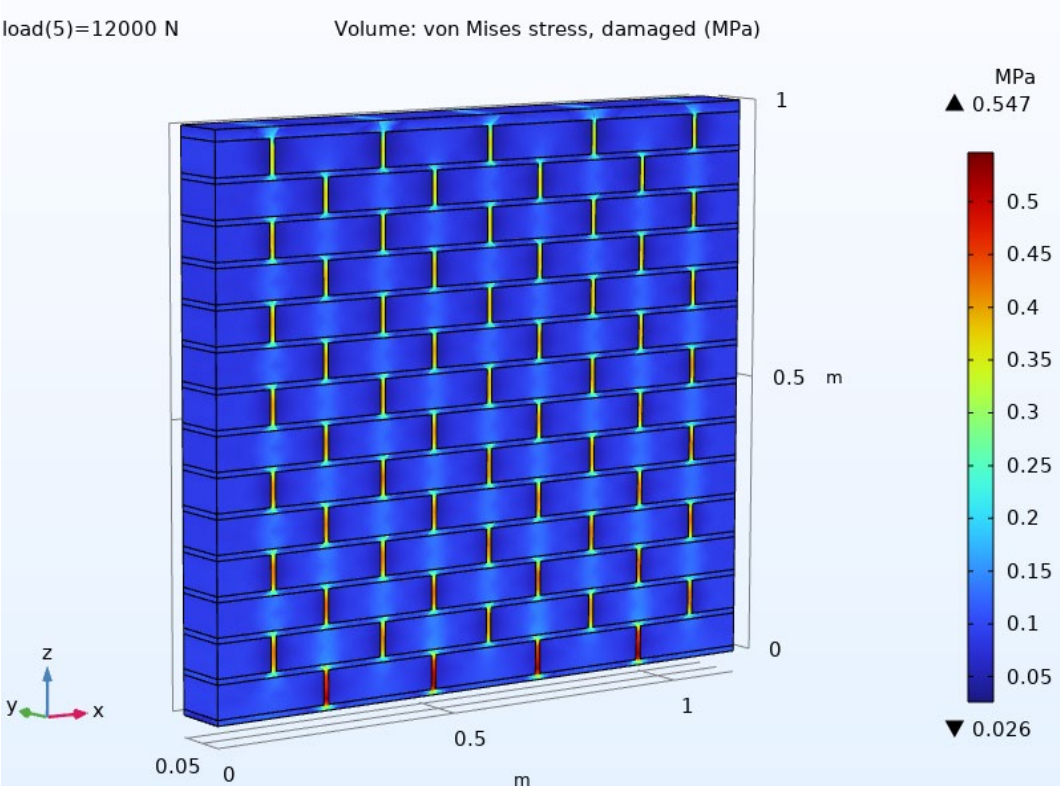

Figure 18. Von Mises stress, damage cartography in bricks for TYPE B3 model at peak load.

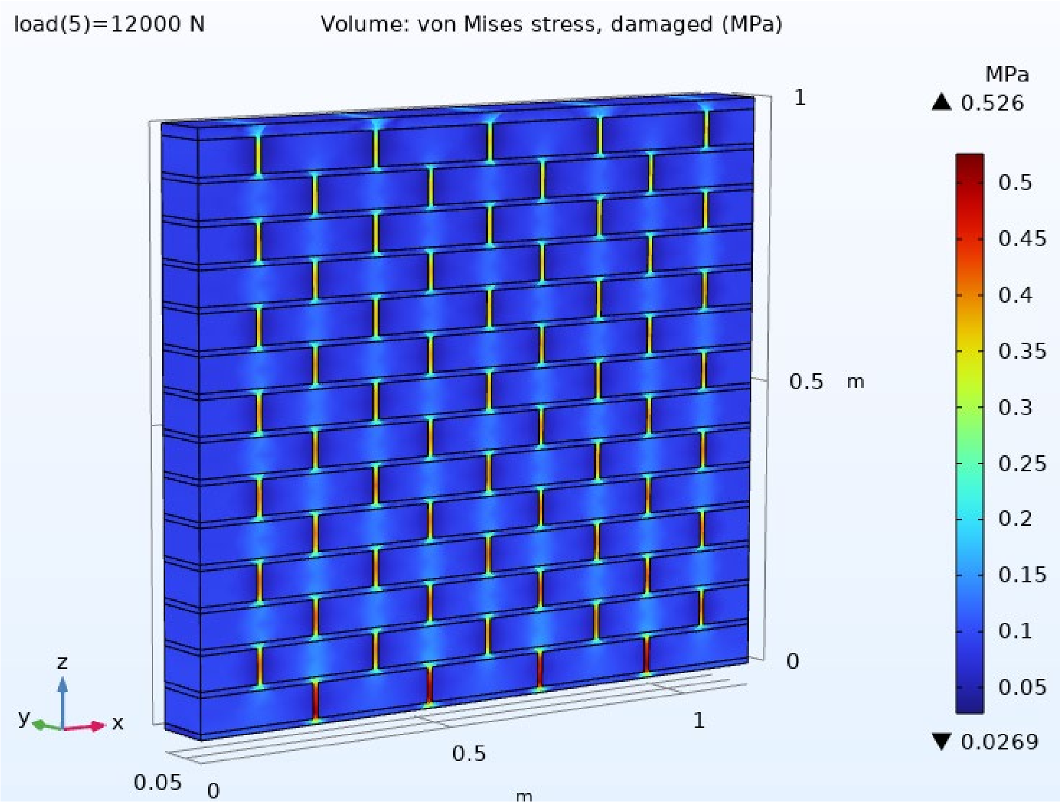

Figure 19. Von Mises stress, damage cartography in bricks for TYPE B4 model at peak load.

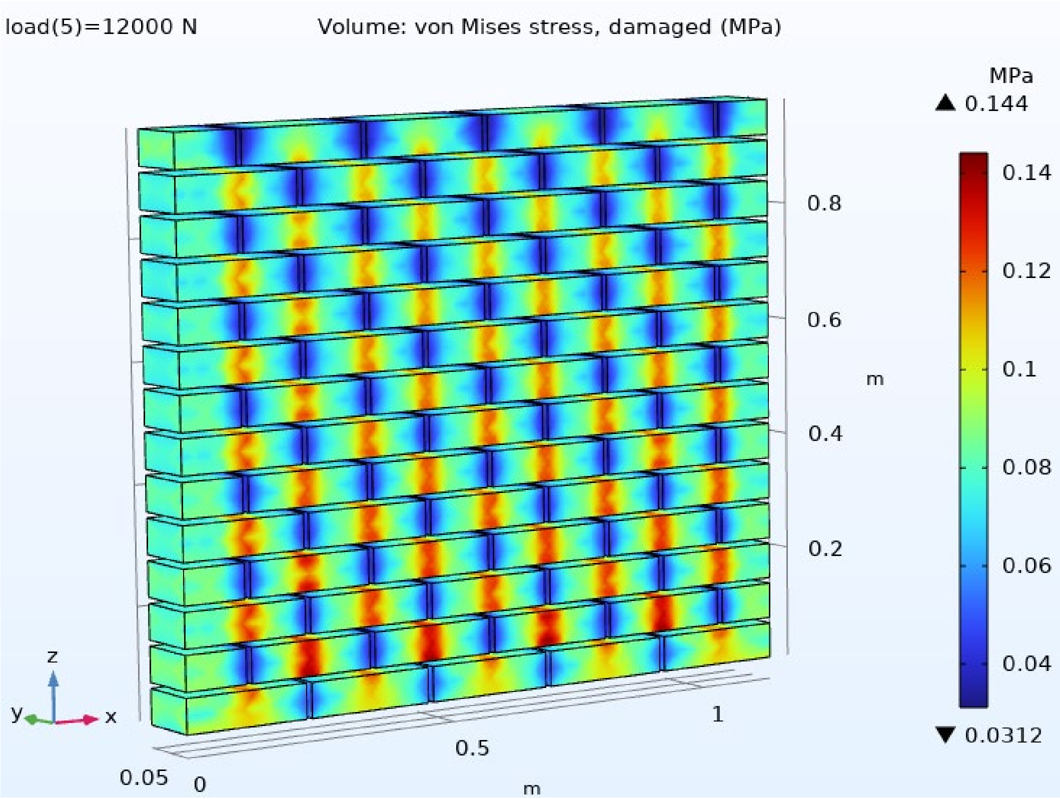

Figure 20. Von Mises stress, damage in brick at ultimate load for Model TYPE A.

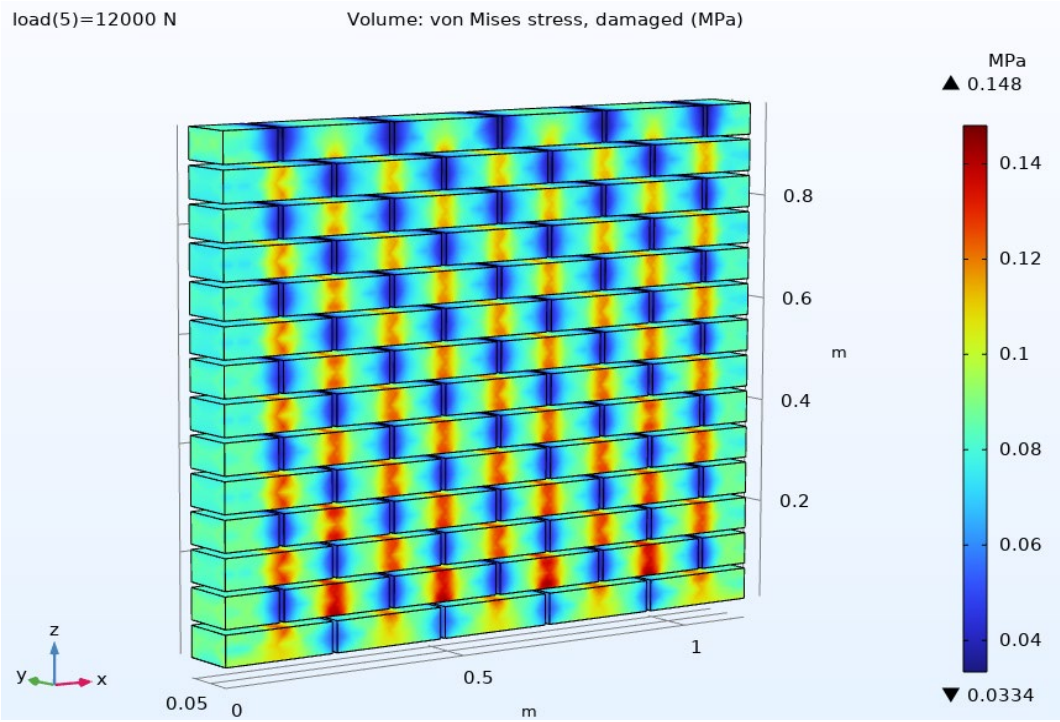

Figure 21. Von Mises stress, damage in brick at ultimate load for model TYPE B1.

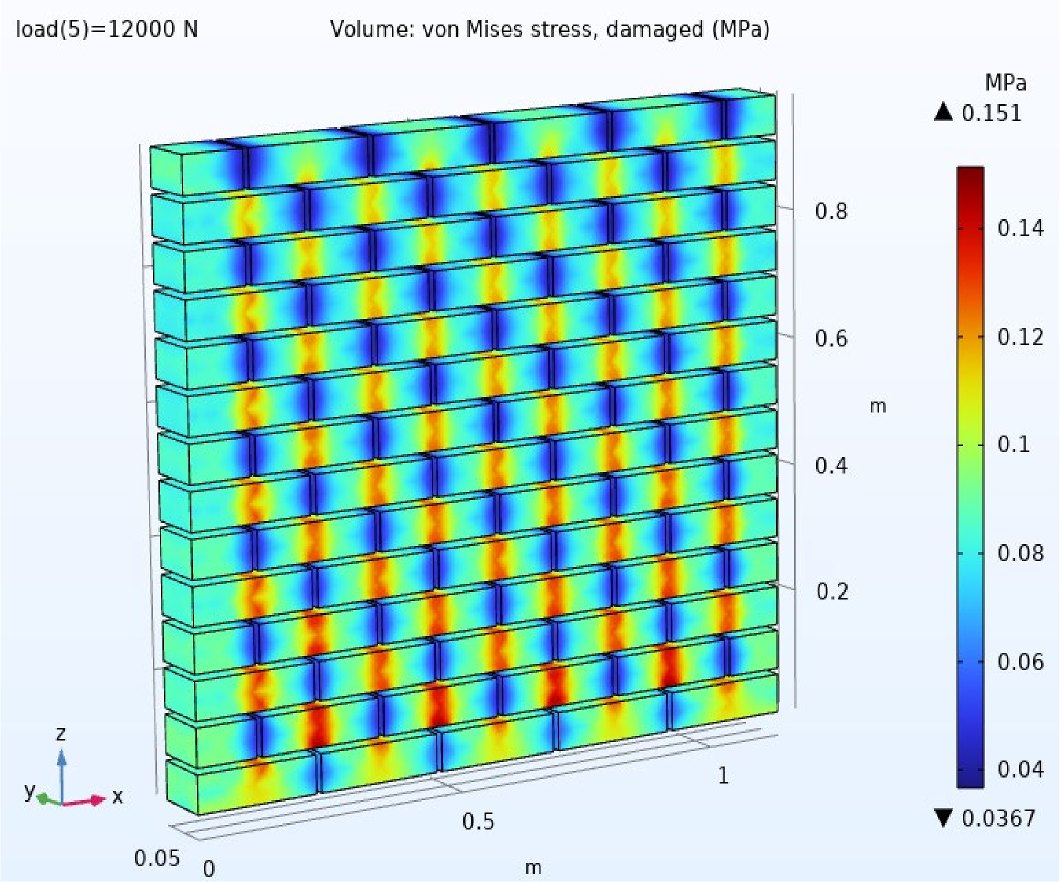

Figure 22. Von Mises stress, damage in brick at ultimate load for model TYPE B2.

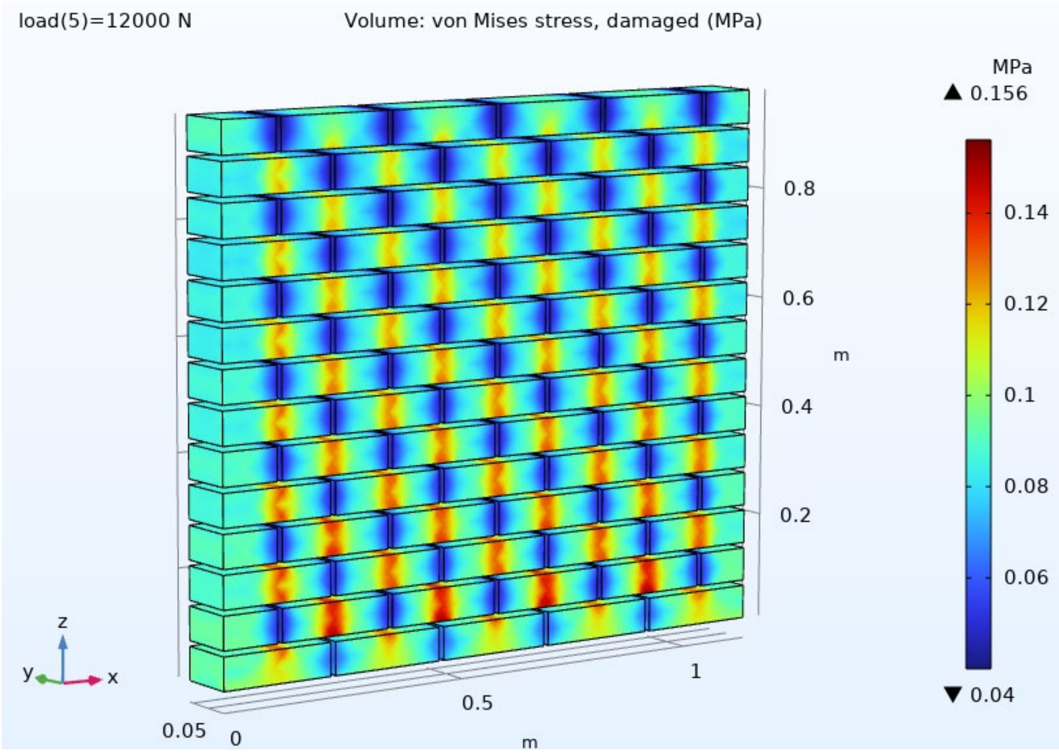

Figure 23. Von Mises stress, damage in brick at ultimate load for model TYPE B3.

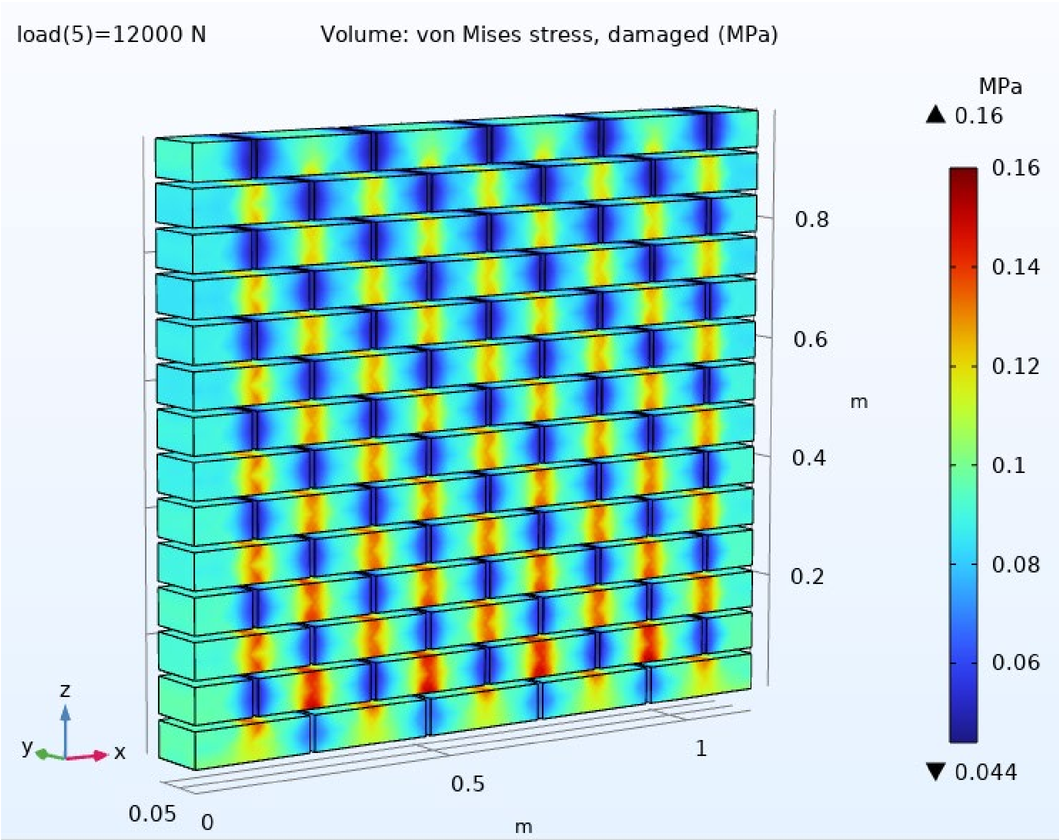

Figure 24. Von Mises stress, damage in brick at ultimate load for model TYPE B4.

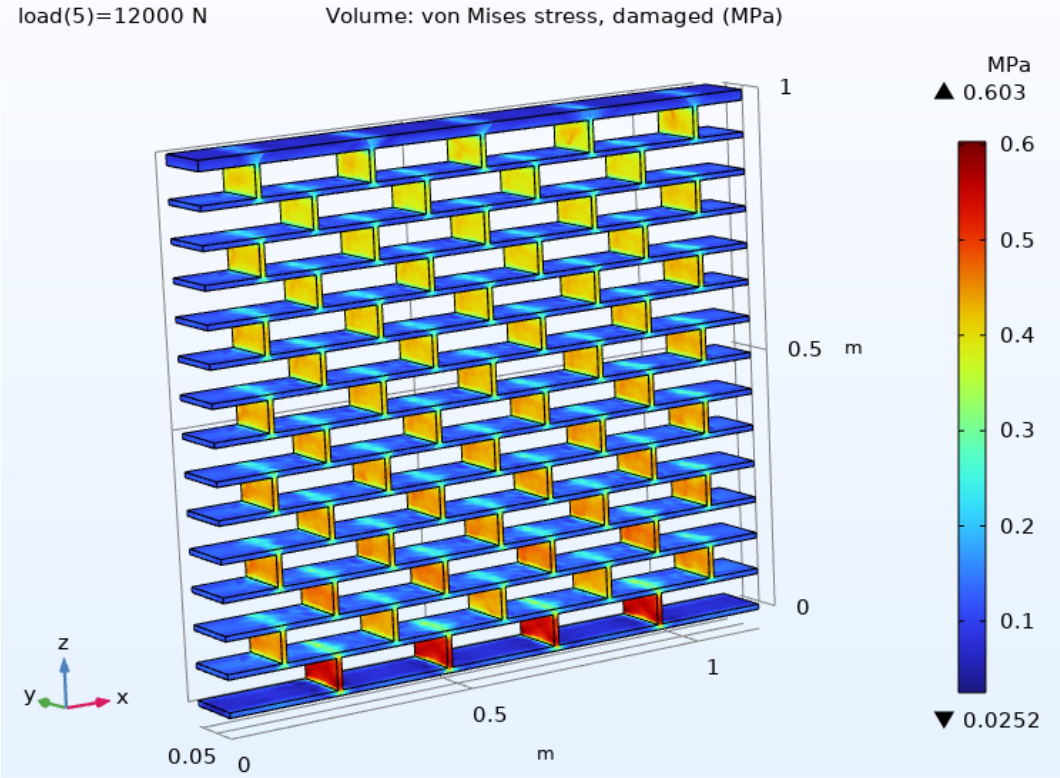

Figure 25. Von Mises stress in mortar joint, damage at initial and final load for model type A.

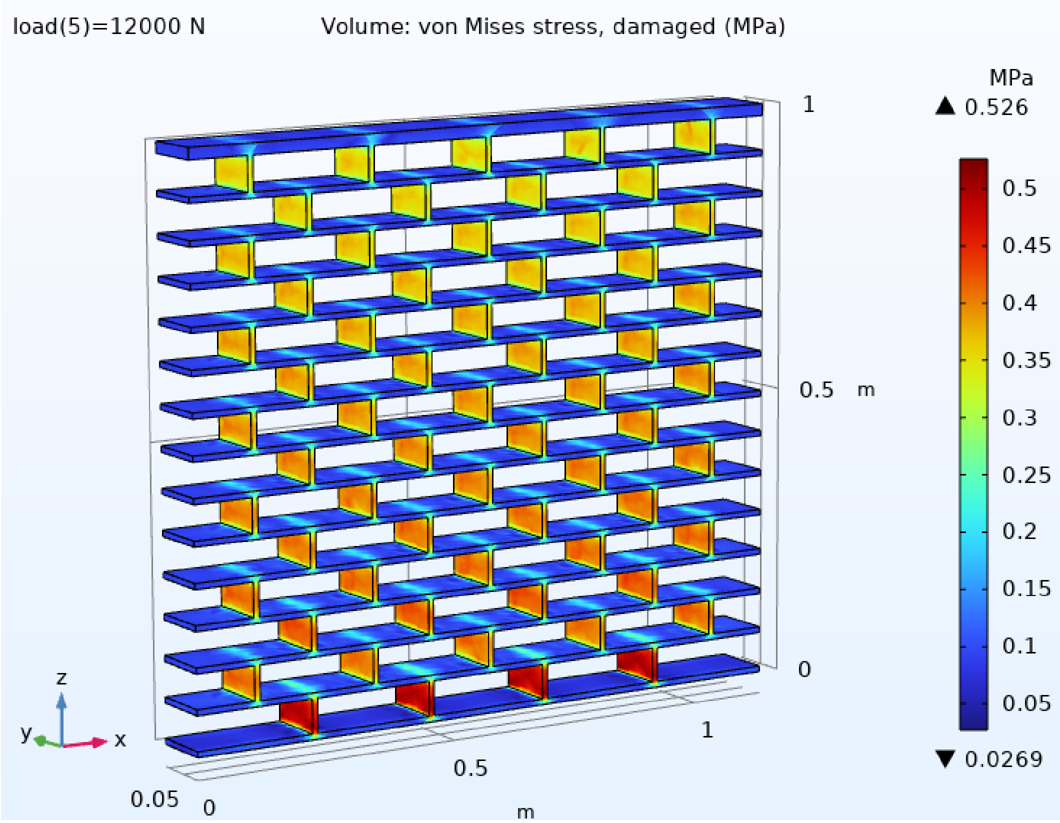

Figure 26. Von Mises stress in mortar joint, damage at initial and final load for model type B4.

stress patterns seen in your results.

We equally observe that the vertical joints bear more stress than the horizontal joints. Vertical joints at the base of the wall are subject to higher stresses than vertical joints at the top face of the wall.

3.4.3. Load Capacity in Humid Zones

The load capacity results in the analysis show that the stabilized walls have significantly higher load-bearing capacities than the unstabilized ones. For instance, the 10% stabilized wall (Type B) has a load capacity of 599.38 kN, compared to 485.53 kN for the unstabilized wall. This higher load capacity is critical in humid zones where buildings are often exposed to heavy rains and potential flooding, which can weaken the materials over time. Stabilization improves the compressive strength of the bricks, making them more resistant to environmental degradation. This is crucial for the longevity of structures in humid areas, where the high moisture content in the atmosphere can lead to rapid deterioration of construction materials if they are not adequately protected. Research by [24] supports the notion that stabilized masonry performs better in challenging environmental conditions, particularly in terms of resisting the effects of moisture.

3.4.4. Durability and Crack Propagation

One of the key concerns in humid zones is the formation and propagation of cracks due to continuous moisture fluctuations and drying-wetting cycles. The analysis reveals that cracks are more likely to propagate in un stabilized walls due to higher stress levels in the mortar joints. In contrast, the stabilized walls, especially with higher percentages of stabilization, show reduced crack propagation tendencies. The use of stabilized bricks minimizes the effects of moisture on the wall, reducing the likelihood of crack formation and ensuring a longer-lasting structure. According to [22], masonry structures in humid environments need to account for the differences in stiffness between bricks and mortar to avoid stress concentrations that can lead to cracking. The use of stabilized bricks helps to create a more uniform distribution of stress, thus enhancing the durability of the structure.

4. Conclusion

The main aim of this research was to stabilize earth bricks with cement for construction in humid zones and characterize their static mechanical behaviour and simulate monotonic damage response using COMSOL MULTIPHYSIC software. The laboratory test results on the geotechnical parameters of soil classified the soil as A-2-7 based in grain size analysis with a liquid limit (LL) of 65.9%, a plastic limit (PL) of 42.2%, and a plasticity index (PI) of 23.7%. The Proctor test results, showed a corrected dry density (g'd_OPM) of 1.614 g/cm^3 and a moisture content (W'OPM) of 22.6% with a degree of saturation (S'r) slightly above 100% indicating of a well-compacted soil mix. Methylene Blue Value (MBV) gave 2.53, indicating the presence of a moderate amount of clay minerals, which influences the soil's reactivity and plasticity, the organic matter content (OM) averaged around 21.60%, suggesting a high level of organic material, which can affect soil structure, compressibility, and stability and the specific gravity (Gs) was approximately 2.395, which is typical for soils with a mix of mineral components, suggesting a balanced mineral composition with a potential influence from organic matter. The physical and mechanical properties of the blocks sample improved as the percentage stabilization with cement increased from 0%, 4%, 6%, 8% and 10%, compressive strength increased from 4.5 MPa at 0% stabilization to 6.1 MPa at 10% stabilization, flexural strength increased from 0.7 MPa at 0% stabilization and reaching 1.2 MPa at 10% stabilization, water reduced from 22.1% for 4% stabilization to 17.3% at 10% stabilization and the bulk increased from 1.9 g/cm^3 at 0% stabilization to 2.0 g/cm^3 at 10% stabilization. All these shows that stabilisation with cement is good and effective for humid zones and modelling with COMSOL showed that stabilized walls exhibited better stress distribution and higher load-bearing capacity, with a load capacity of 599.38 kN compared to 485.53 kN for un-stabilized walls. The model outputs can assist policy makers, construction engineers, and local material producers in selecting optimal stabilization ratios to enhance long-term durability of earthen structures. By aligning material performance with tropical environmental challenges, the findings support the implementation of sustainable, low-carbon building technologies across sub-Saharan Africa.

Availability of Data and Materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Author Contributions

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Contributions: Conceptualization, data curation, formal analysis, methodology, writing review and editing, original draft.

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Contributions: Conceptualization, data curation, formal Analysis, funding acquisition investigation, methodology, project administration, resources, software, supervision validation, visualization, writing original draft, writing review and editing.

Author 3: Mbuh Moses Kuma

Contributions: Methodology, software, validation, writing review.

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Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

During the preparation of this work the author(s) used ChatGPT in order to correct the English and better organize the results and discussions. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Turco, C., Paula Junior, A.C., Teixeira, E.R. and Mateus, R. (2021) Optimisation of Compressed Earth Blocks (CEBs) Using Natural Origin Materials: A Systematic Literature Review. *Construction and Building Materials*, **309**, Article ID: 125140. https://doi.org/10.1016/j.conbuildmat.2021.125140

[2] Newman, J.C. (1998) The Merging of Fatigue and Fracture Mechanics Concepts: A Historical Perspective. *Progress in Aerospace Sciences*, **34**, 347-390. https://doi.org/10.1016/s0376-0421(98)00006-2

[3] Ugwu, O.O. and Haupt, T.C. (2007) Key Performance Indicators and Assessment Methods for Infrastructure Sustainability—A South African Construction Industry Perspective. *Building and Environment*, **42**, 665-680. https://doi.org/10.1016/j.buildenv.2005.10.018

[4] Coffel, E.D., Horton, R.M. and de Sherbinin, A. (2017) Temperature and Humidity Based Projections of a Rapid Rise in Global Heat Stress Exposure during the 21st Century. *Environmental Research Letters*, **13**, Article ID: 014001. https://doi.org/10.1088/1748-9326/aaa00e

[5] Bui, Q., El-Nabouch, R., Miccoli, L., Morel, J., Oliveira, D.V., Silva, R.A., *et al.* (2021) Seismic Assessment of Earthen Structures. In: Fabbri, A., Morel, J.C., Aubert, J.E., Bui, Q.B., Gallipoli, D. and Reddy, B.V., Eds., *Testing and Characterisation of Earth-Based Building Materials and Elements*, Springer, 181-210. https://doi.org/10.1007/978-3-030-83297-1_5

[6] Magalhães, L., Gavilán, A., Ferreira, D. and Merelles, S. (2024) Diatomaceous Earth as a Partial Replacement for Portland Cement in Mortars—A Review. https://bibliotecadigital.ipb.pt/entities/publication/ab8aaaf3-a73c-4b9f-a5c2-3a04dea19b6c

[7] Laibi, A.B., Poullain, P., Leklou, N. and Gomina, M. (2025) Experimental Assessment of the Dynamic Hygrothermal and Mechanical Behavior of Compressed Earth Block Walls in a Tropical Humid Climate. *Buildings*, **15**, Article 3484. https://doi.org/10.3390/buildings15193484

[8] Goutsaya, J., Ntamack, G.E. and d'Ouazzane, S.C. (2022) Damage Modelling of Compressed Earth Blocks Stabilised with Cement. *Advances in Civil Engineering*, **2022**, Article ID: 3342661. https://doi.org/10.1155/2022/3342661

[9] Buckman, H.O. and Brady, N.C. (1960) The Nature and Properties of Soils. *Soil Science*, **90**, 212. https://doi.org/10.1097/00010694-196009000-00018

[10] Sanchez, P.A. (2019) Properties and Management of Soils in the Tropics. Cambridge University Press. https://books.google.com/books?hl=en&lr=&id=YKh7DwAAQBAJ&oi=fnd&pg=PR13&ots=2MHxrd5GYk&sig=YEEWgBuBV-ZZn3-m8U1a_6aXLpM

[11] Buol, S.W., Southard, R.J., Graham, R.C. and McDaniel, P.A. (2003) Soil Genesis and Classification. https://www.researchgate.net/profile/Stanley-Buol/publication/48377211_Soil_Gen-

esis_and_Classification/links/55140ee50cf23203199cd5f5/Soil-Genesis-and-Classification.pdf

[12] Schroeder, H. (2016) Standards and Regulations in Earth Block Masonry—The Current Situation in Germany. *International Journal of Masonry Research and Innovation*, **1**, 241-252. https://doi.org/10.1504/ijmri.2016.080432

[13] Elahi, T.E., Shahriar, A.R. and Islam, M.S. (2021) Engineering Characteristics of Compressed Earth Blocks Stabilized with Cement and Fly Ash. *Construction and Building Materials*, **277**, Article ID: 122367. https://doi.org/10.1016/j.conbuildmat.2021.122367

[14] Pucillo, G.P., Carpinteri, A., Ronchei, C., Scorza, D., Zanichelli, A. and Vantadori, S. (2023) Experimental and Numerical Study on the Fatigue Behaviour of the Shot-Earth 772. *International Journal of Fatigue*, **177**, Article ID: 107922. https://doi.org/10.1016/j.ijfatigue.2023.107922

[15] Jalal, F.E., Xu, Y., Jamhiri, B. and Memon, S.A. (2020) On the Recent Trends in Expansive Soil Stabilization Using Calcium-Based Stabilizer Materials (CSMs): A Comprehensive Review. *Advances in Materials Science and Engineering*, **2020**, Article ID: 1510969. https://doi.org/10.1155/2020/1510969

[16] Suhendra Nugraha, A., Rahardjo, P.P., Hutapea, B.M. and Sadisun, I.A. (2020) Correlation between Plasticity Index and Methylene Blue Value to Determining Soil Classification. *IOP Conference Series: Materials Science and Engineering*, **852**, Article ID: 012012. https://doi.org/10.1088/1757-899x/852/1/012012

[17] Shepherd, M.A., Harrison, R. and Webb, J. (2002) Managing Soil Organic Matter—Implications for Soil Structure on Organic Farms. *Soil Use and Management*, **18**, 284-292. https://doi.org/10.1111/j.1475-2743.2002.tb00270.x

[18] Zhao, Y., Gao, Y., Zhang, Y. and Wang, Y. (2016) Effect of Fines on the Mechanical Properties of Composite Soil Stabilizer-Stabilized Gravel Soil. *Construction and Building Materials*, **126**, 701-710. https://doi.org/10.1016/j.conbuildmat.2016.09.082

[19] Walker, P.J. (1995) Strength, Durability and Shrinkage Characteristics of Cement Stabilised Soil Blocks. *Cement and Concrete Composites*, **17**, 301-310. https://doi.org/10.1016/0958-9465(95)00019-9

[20] Arshad, A., Shaffie, E., Ismail, F., Hashim, W., Abd Rahman, Z. and Ismail, Y. (2018) Cement Stabilized Soil Subgrade: Design and Construction. *International Journal of Civil Engineering and Technology*, **9**, 1192-1200. https://www.researchgate.net/profile/Ahmad-Kamil-Arshad/publication/326817140_Cement_Stabilised_Soil_Subgrade_Design_and_Construction/links/5b64e45ea6fdcc94a70c1455/Cement-Stabilised-Soil-Subgrade-Design-and-Construction.pdf

[21] Deboucha, S. and Hashim, R. (2011) A Review on Bricks and Stabilized Compressed Earth Blocks. *Scientific Research and Essays*, **6**, 499-506. https://www.academia.edu/download/78177710/093C6D821208.pdf

[22] Lourenço, P.B., Rots, J.G. and Blaauwendraad, J. (1997) Continuum Model for Masonry: Parameter Estimation and Validation. *Journal of Structural Engineering*, **123**, 660-668. https://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9445(1998)124:6(642)

[23] Capozucca, R. (2011) Experimental Analysis of Historic Masonry Walls Reinforced by CFRP under In-Plane Cyclic Loading. *Composite Structures*, **94**, 277-289. https://doi.org/10.1016/j.compstruct.2011.06.007

[24] Sathiparan, N. and Rumeshkumar, U. (2018) Effect of Moisture Condition on Mechanical Behavior of Low Strength Brick Masonry. *Journal of Building Engineering*, **17**, 23-31. https://doi.org/10.1016/j.jobe.2018.01.015

Abbreviations

$\psi_0(\epsilon)$	is the strain energy density.
G_c	is the critical energy release rate (fracture toughness).
l	is the length scale parameter controlling the width of the diffuse crack.
$w(\phi)$	is a degradation function,
PL	Plastic Limit
LL	Liquide Limit
PI	Plastic Index
CSEBs	Compress Stabilized Earth Bricks
CEBs	Compressed Earth Blocks
MBV	Methylene Blue Value
OM	Organic Matter Content
Gs	Specific Gravity