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Development and Performance Evaluation of Sustainable Earth Blocks Incorporating Incinerated Sanitary Sludge Ash

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Abstract

Urbanisation-driven housing demand and the environmental burden of sewage sludge disposal highlight the need for low-carbon, circular construction materials. This study evaluates incinerated sanitary sludge ash (ISSA) as a supplementary cementitious material in stabilised earth blocks, aiming to reduce the use of cement and lime while valorising waste sludge. Lateritic soil blocks were produced with a binder-to-soil ratio of 1:7 by mass, in which ISSA partially replaced the primary stabilising binder (cement or lime) at a replacement level of 10–40% within the binder fraction. ISSA's mineralogical characteristics were analysed using XRD and XRF. The compressive strength and density of earth blocks were measured at 7 and 28 days under curing conditions (29–36 °C; 60–75% humidity). Cement-stabilised blocks were water-cured to support cement hydration, whereas lime-stabilised blocks were air-cured to promote carbonation and pozzolanic reactions. The results, therefore, compared practical binder-specific curing regimes rather than strictly identical curing environments. ISSA exhibited moderate pozzolanic potential, and its incorporation enabled substantial partial replacement of both binders. Cement-stabilised blocks achieved higher strengths, up to 7.7 MPa, after 28 days of curing, whereas lime-stabilised blocks developed strength more gradually, reaching 4.8 MPa. Optimal mixtures were identified at 40% cement + 60% ISSA and 30% lime + 70% ISSA, balancing mechanical performance and binder reduction. A positive density–strength relationship was observed, but chemical bonding predominated over densification effects. ISSA-based stabilised earth blocks show promising structural performance and reduced binder use, but durability and life-cycle assessment need further evaluation before large-scale implementation.

Keywords: stabilised earth blocks; sanitary sludge ash; supplementary cementitious materials; lime and cement stabilisation; pozzolanic reactivity; circular economy; low-carbon construction

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1. Introduction

The global construction industry is facing many challenges due to increasing urbanisation and population growth, which have intensified the demand for affordable housing and sustainable building materials [1]. Simultaneously, waste management, particularly the disposal of sewage sludge, has become a pressing issue in developing countries like Tanzania [2,3]. Traditional methods of handling sewage sludge, such as landfilling, open dumping, incineration, or direct agricultural application, pose serious environmental and health risks [4]. Considering these challenges, there is a growing need to explore innovative approaches to address both waste management and sustainable construction practices.

The construction industry is a major contributor to global carbon emissions, with Ordinary Portland Cement (OPC) production alone responsible for approximately 7–8% of total CO_2 emissions [5]. The substantial environmental footprint is primarily attributed to the energy-intensive clinker production process and the release of carbon dioxide during limestone calcination [6]. It is acknowledged that every 1 kg (kg) of cement production releases approximately 1 kg of CO_2 emissions [7,8]. In addition, the production process of lime and cement depletes non-renewable natural resources such as limestone and fossil fuels [9]. These concerns have driven extensive research into developing alternative materials that can partially replace conventional binders while maintaining the required strength. In this context, incorporating supplementary cementitious materials (SCMs) derived from industrial and agricultural wastes has become a promising strategy for reducing clinker demand and supporting the circular economy in the construction industry [10]. Conventional SCMs such as fly ash, rice husk ash, and sugarcane bagasse ash provide useful reference materials because they demonstrate how reactive siliceous or aluminosilicate wastes can contribute to cementitious bonding [11]. However, their direct comparability with ISSA is limited because ISSA has a more variable mineralogy, higher impurity content, and a stronger dependence on sludge source and thermal treatment. Therefore, the present study uses conventional SCMs only as contextual benchmarks, while focusing on the specific behaviour of ISSA in stabilised earth blocks production.

The rapid expansion of wastewater treatment infrastructure has led to a continuous increase in sewage sludge generation worldwide [12]. Traditional disposal approaches are becoming less viable due to land scarcity, stricter environmental regulations, and concerns over soil and groundwater contamination. As a result, thermal treatment methods such as incineration are increasingly adopted to reduce sludge volume, eliminate pathogens, and stabilise hazardous components [13]. Sewage sludge incineration yields a solid by-product known as incinerated sewage sludge ash (ISSA), the sustainable management of which remains a challenge.

Incinerated sewage sludge ash (ISSA) contains a significant amount of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) [14,15]. These oxides can engage in pozzolanic reactions, where amorphous siliceous and aluminous phases react with calcium hydroxide in water to produce calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which are vital for strength and durability in cementitious materials [16,17].

Recent studies have investigated ISSA in concrete, mortar, bricks, lightweight aggregates, and road construction materials, including its use as a partial replacement for natural aggregate or cementitious components [18–20]. For example, Zhou et al. [21] demonstrated the potential of sewage sludge ash in solid-waste-based lightweight concrete systems. Despite these promising applications, ISSA generally exhibits lower and more variable reactivity than conventional SCMs because of its source-dependent chemistry and crystalline phases formed during thermal treatment [22]. This limitation often requires activation with traditional binders such as cement or lime to enhance its engineering performance. These physicochemical characteristics underpin its potential application as a supplementary cementitious material in construction.

While the application of ISSA in conventional cement-based materials has been widely explored, its use in earth-based construction materials remains relatively limited. Stabilised earth blocks represent a sustainable alternative to fired bricks, as they require significantly less energy to produce and can be manufactured using locally available resources [23]. The incorporation of ISSA into such systems offers dual benefits, such as waste valorisation and reduced use of conventional stabilisers. However, the mechanical performance and long-term behaviour of ISSA-stabilised earth blocks are not yet fully understood.

Despite these advancements, few studies have systematically investigated ISSA in earthen systems under non-controlled curing conditions, particularly with a comparative evaluation of lime and cement stabilisation at varying replacement levels and the influence of low incineration temperature, whose unique physicochemical properties may enhance reactivity.

Therefore, this study aims to address these research gaps by examining the development and performance of ISSA-stabilised earth blocks. The study evaluates the compressive strength of ISSA-stabilised earth blocks, compares the effectiveness of lime and cement stabilisation at different replacement levels, and determines the optimal lime and cement content that balances mechanical performance and sustainability. Furthermore, the study examines the pozzolanic behaviour of ISSA by analysing strength development trends over curing time. This approach aligns with sustainable development goals by promoting resource efficiency, reducing waste disposal burdens, and lowering the carbon footprint of construction materials.

The novelty of this study lies in its comprehensive assessment of ISSA within earthen construction systems using a comparative binder approach, providing new insights into its potential as a sustainable construction material and supporting reduced environmental impacts from both sewage sludge disposal and cement production. This study provides one of the first experimental comparisons of ISSA performance in stabilised earth blocks under uncontrolled curing conditions, while systematically evaluating cement and lime activation mechanisms at varying replacement levels.

2. Materials and Methods

This section presents the collection of materials, mix designs, production procedures, curing conditions, and testing methods.

2.1. Materials

2.1.1. Laterite Soil

Laterite soil was obtained from the Kimbiji borrow pit in Kigamboni, Tanzania, a deposit known for its high iron and aluminium oxide content and suitability for earth construction as illustrated in Figure 1. The soil was excavated at a depth of approximately 7 m below ground level to obtain representative samples of the in situ soil profile. The material was air-dried under ambient laboratory conditions, sieved through a 425 μm–10 mm sieve to remove coarse particles larger than 10 mm, and homogenised to ensure uniformity.

Figure 1. Source of laterite soil at the Kimbiji Borrow Pit.

Geotechnical characterisation was conducted to determine particle size distribution, Atterberg limits, and compaction properties in accordance with ASTM standards.

2.1.2. Incinerated Sanitary Sludge Ash (ISSA)

Sanitary sludge was sourced from the Mburahati wastewater treatment plant. The sludge was sun-dried to remove free moisture, then carbonised in a closed drum with a limited air supply to reduce the organic matter content. The temperature for carbonisation was recorded every 15 min at the lower, middle and upper parts of the drum. The carbonised material was subsequently incinerated at 600 °C in a laboratory muffle furnace for two hours to produce ISSA, which was used as a supplementary stabiliser (Figure 2). The selected temperature and residence time were intended to ensure sufficient burnout of organics while limiting excessive sintering of the ash particles, in line with the use of thermally treated sewage sludge for construction materials [24].

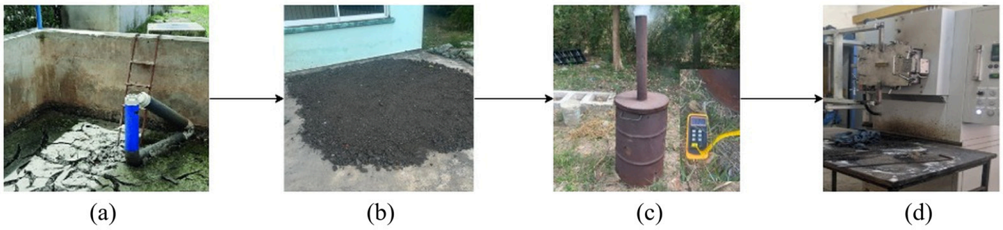


Figure 2. Preparation process of incinerated sanitary sludge ash for use in construction materials. (**a**) Collection of sanitary sludge from the drying bed at the treatment plant; (**b**) sun drying of sanitary sludge to reduce moisture content; (**c**) carbonisation of sanitary sludge to remove organic matter while monitoring temperature; and (**d**) incineration of sanitary sludge at 600 °C for 2 h to produce sanitary sludge ash.

The resulting ash was ground and sieved before use. ISSA was used as a supplementary cementitious material (SCM) rather than a primary binder.

2.1.3. Stabilising Binders

Ordinary Portland cement (OPC) and hydrated lime were used as stabilisers. Each stabiliser was used both on its own and in combination with ISSA to assess the synergistic effects on mechanical performance and the potential for lime replacement in stabilised earth blocks, which is relevant to reducing the embodied carbon of masonry products.

2.2. Mix Design and Block Production

Predetermined proportions of laterite soil, ISSA, and stabiliser were dry-mixed until a visually uniform blend was obtained. Wet mixing then continued until no visible agglomerates remained. The overall mix design followed a 1:7 binder-to-soil ratio by mass. In this ratio, the binder fraction consisted of cement, lime, ISSA or their combinations, while the soil fraction remained constant. A water-to-binder ratio (w/b) of 1.0 was adopted to compensate for the high absorption capacity of ISSA, ensure adequate workability and maintain consistency across all mixes.

The primary stabilising binder in this study was either cement or lime, while ISSA was used as a supplementary binder within the binder fraction. Mixing proportions were prepared following series such as ISSA + soil (Series B), ISSA + cement + soil (C1–C4), cement + soil (C5), ISSA + lime + soil (L1–L4), and lime + soil (L5). For the cement-stabilised series, cement content varied from 10% to 100% of the total binder with a corresponding ISSA replacement from 90% to 0%. Similarly, for the lime-stabilised series, lime content ranged from 10% to 100% of the total binder, with a corresponding ISSA replacement from 90% to 0%, as shown in Table 1. For each sample ID, three specimens (replicates) were prepared (3 specimens for 7 days and 3 specimens for 28 days) and the average of the three specimens were reported. Series B (100% ISSA within the binder fraction plus soil at 1:7) was included as a reference mixture to assess the standalone stabilising capacity of ISSA and to demonstrate whether ISSA alone could act as an effective binder. It was not treated as a primary binder because ISSA has limited hydraulic activity without cement or lime activation [25].

Table 1. Mixing proportions of laterite soil and binder used for earth block production.

Sample ID	Series Type	Laterite Soil (%) (LS)	% of Primary Binder and SCM	Mixing Ratio (Binder:LS)
B	ISSA	100	100% ISSA	1:7
C1	Cement	100	90% ISSA + 10% cement	1:7
C2	Cement	100	80% ISSA + 20% cement	1:7
C3	Cement	100	70% ISSA + 30% cement	1:7
C4	Cement	100	60% ISSA + 40% cement	1:7
C5	Cement	100	100% cement	1:7
L1	Lime	100	90% ISSA + 10% lime	1:7
L2	Lime	100	80% ISSA + 20% lime	1:7
L3	Lime	100	70% ISSA + 30% lime	1:7
L4	Lime	100	60% ISSA + 40% lime	1:7
L5	Lime	100	100% lime	1:7

The fresh mixtures were compacted in a manual compression mould to produce rectangular blocks with nominal dimensions of 200 × 100 × 70 [mm]. The production procedure comprised batching, mixing, moulding, compaction using a mechanical press, demoulding, and curing as illustrated in Figure 3.

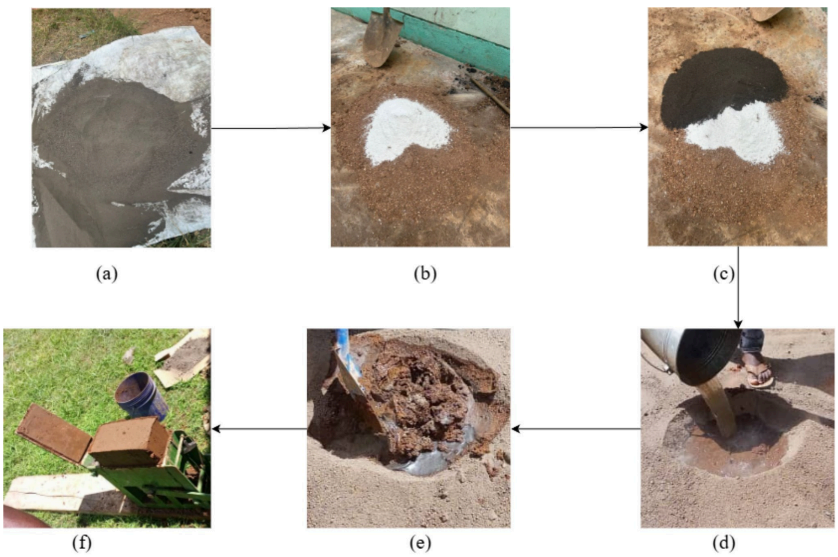


Figure 3. Production process of stabilised earth blocks incorporating sanitary sludge ash and lime. (**a**) Sanitary sludge ash after incineration at 600 °C; (**b**) laterite soil mixed with lime; (**c**) laterite soil blended with sanitary sludge ash and lime; (**d**) addition of water to the mixture; (**e**) material mixing to achieve uniform consistency; (**f**) block production using a manual compression machine.

2.3. Curing Regime and Environmental Monitoring

Blocks stabilised with hydrated lime were air-cured for 28 days under indoor ambient conditions, while cement-stabilised blocks were water-cured for 28 days. These curing regimes were selected because cement hydration requires sustained moisture availability, whereas lime stabilisation relies strongly on carbonation and slower pozzolanic reactions under air exposure. Consequently, the results should not be interpreted as a direct comparison under identical curing conditions. Instead, they represent practical binder-specific curing regimes that are commonly adopted to promote the dominant reaction mechanisms of each stabiliser. To characterise the curing environment and support the interpretation of strength development, temperature and humidity were monitored during curing using four sets of HOBO® UX100 series data loggers (Onset Computer Corporation, Bourne, MA, USA) installed at different locations within the building to capture spatial variability in the indoor microclimate. These compact indoor devices feature built-in sensors that measure air temperature and relative humidity, and the data were recorded continuously from 18 January 2026 to 14 February 2026. Measurement parameters include a temperature range of 29 °C to 36 °C and a relative humidity (RH) range of 60% to 75% (non-condensing), as shown in Figure 4.

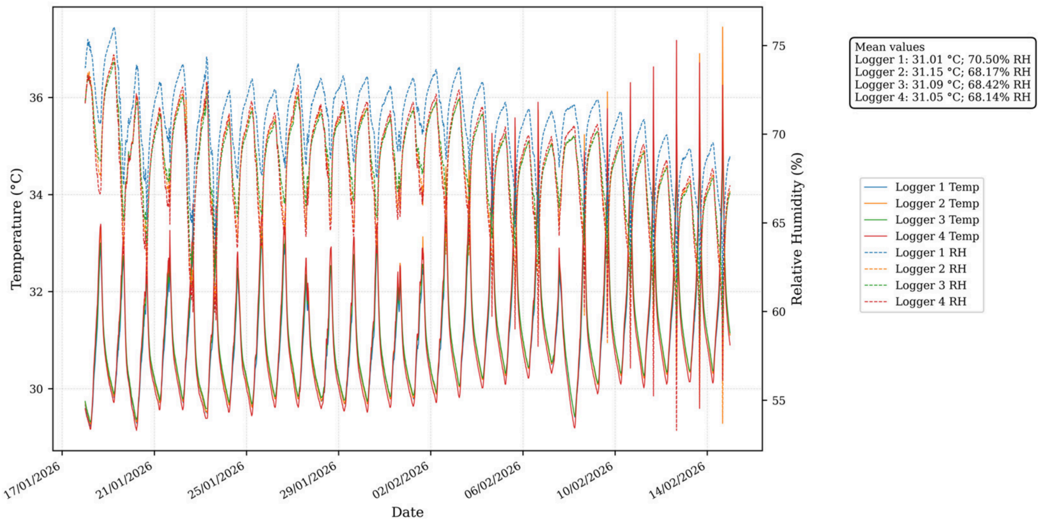


Figure 4. Comparison of curing temperature and relative Humidity across loggers (1–4).

These conditions represent real-world construction settings in tropical areas. However, because the cement and lime systems were cured differently, comparisons between them are interpreted qualitatively and in relation to their respective curing requirements rather than as strictly equivalent controlled-environment comparisons.

2.4. Soil and ISSA Characterisation

The laterite soil was characterised using standard geotechnical tests, including sieve analysis (Figure 5), Atterberg limits (Figure 6), and Standard Proctor compaction tests (Figure 7). Sieve analysis was performed in accordance with ASTM D6913 [26].

Standard Proctor compaction tests were performed in line with ASTM D698 [27] to obtain the maximum dry density and optimum moisture content of the soil, as illustrated in Figure 7.

The ISSA was also characterised using X-ray fluorescence (XRF) to determine its elemental oxide composition. The ISSA samples were ground with a laboratory milling machine (HERZOG disc mill, HERZOG Maschinenfabrik GmbH & Co. KG, Osnabrück, Germany) capable of producing particles smaller than 75 µm. The prepared powder was compressed into pellets using a hydraulic press with a load capacity of 20–40 tons, applying 20–30 MPa pressure through a standard 32 mm die as shown in Figure 8. The chemical composition was then determined using an XRF spectrometer (Bruker AXS GmbH, Karlsruhe, Germany) calibrated against certified reference materials.

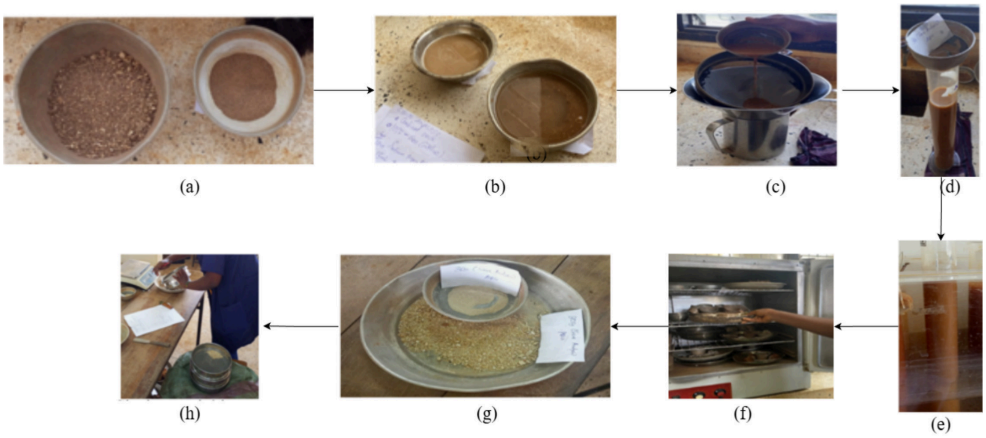
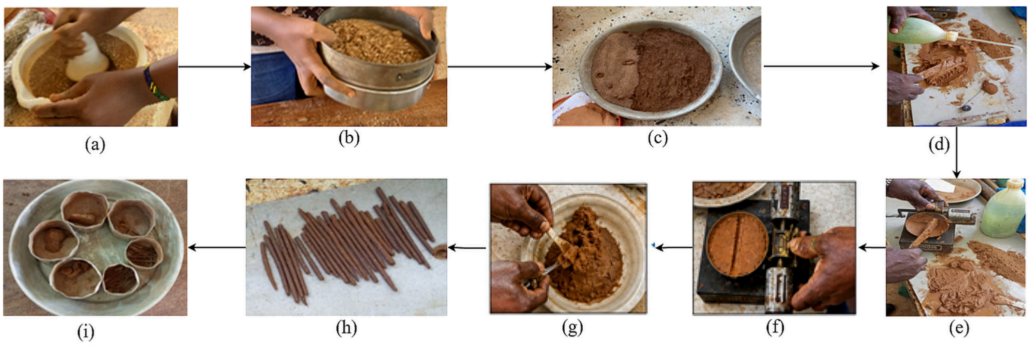


Figure 5. Step-by-step procedure for hydrometer analysis of fine-grained soil. (**a**) Air-dried soil sample prepared through quartering and pulverisation; (**b**) soil sample mixed with distilled water and dispersing agent to form a uniform suspension; (**c**) suspension poured through a 75 µm sieve to remove coarse particles; (**d**) filtered suspension transferred into a graduated cylinder and diluted to the required volume; (**e**) hydrometer readings taken at specified time intervals during sedimentation; (**f**) suspension transferred to trays and oven-dried at 105–110 °C; (**g**) dried soil sieved to separate sand-sized fractions; (**h**) weighing of retained fractions for particle size distribution analysis.



Note: Liquid limit (LL) is determined from the flow curve (number of blow)
Plastic limit (PL) is determined from the thread rolling test

Figure 6. Procedure for determination of Atterberg limits of soil (liquid limit and plastic limit). (**a**) Mixing soil with water to obtain a uniform paste; (**b**) sieving the soil to remove coarse particles; (**c**) preparing soil paste for Atterberg limits testing; (**d**) addition of water and further mixing to achieve required consistency for liquid limit test; (**e**) placement of soil paste in the Casagrande cup; (**f**) operation of the Casagrande device and counting the number of blows for groove closure; (**g**) collection of soil paste for plastic limit test; (**h**) rolling the soil into threads of approximately 3 mm diameter; (**i**) soil threads at the point of crumbling, indicating the plastic limit.

Mineralogical characterisation (XRD) of ISSA was performed using a Bruker D2 PHASER X-ray diffractometer (Bruker AXS GmbH, Karlsruhe, Germany), as shown in Figure 9. The analysis employed Cu Kα radiation (λ = 1.5406 Å) at 30 kV and 10 mA. Diffraction patterns were recorded within a 2θ range of 5° to 70°, using a step size of 0.02° and an appropriate scanning rate.

These diffractograms helped identify crystalline phases, including quartz, calcite, and other minerals present in the ash. Additionally, the XRD results were used to assess the amorphous content and support the interpretation of ISSA's pozzolanic reactivity based on its chemical composition.

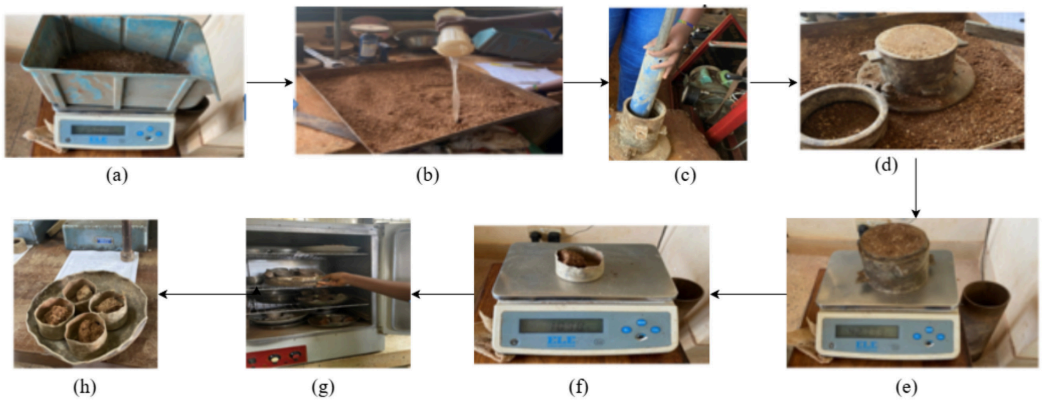


Figure 7. Standard Proctor test process. (**a**) Weighing the soil sample; (**b**) mixing soil with water; (**c**) free drop of rammer for compaction in 3 layers, 27 blows per layer; (**d**) full compacted soil in a mould; (**e**) weighing of compacted soil; (**f**) weighing of representative portion of soil for determination of moisture content; (**g**) oven drying of soil; (**h**) dried sample from oven, weighed and recording OMC and MDD determinations.

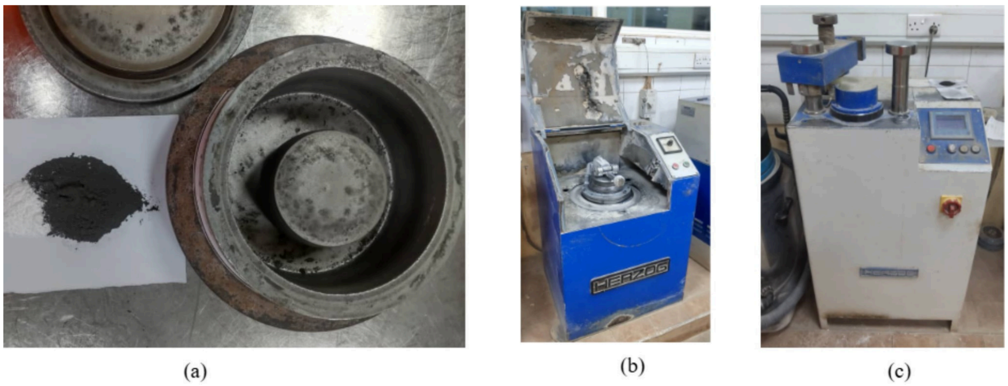


Figure 8. (**a**) Sample preparation; (**b**) grinding/milling; (**c**) pressing equipment for XRF.

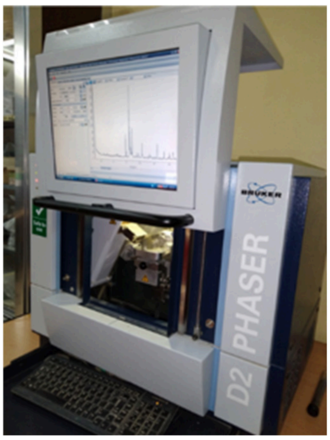


Figure 9. X-ray diffractometer (Bruker D2 PHASER) used for mineralogical analysis.

2.5. Mechanical and Physical Testing of Blocks

Compressive strength tests were carried out on the stabilised earth blocks at two intervals: 7 days and 28 days. A universal compression machine was used to ensure precise measurements. For each mix and curing age, three individual blocks were tested, and the mean compressive strength and standard deviation were calculated. Error bars in the relevant figures represent the standard deviation of the three replicates. Owing to the limited number of specimens per group (n = 3), the statistical treatment was restricted to descriptive statistics and regression-based trend analysis rather than inferential significance testing. This approach was adopted to present variability transparently while avoiding overinterpretation of small-sample data.

The procedure, illustrated in Figure 10, was aligned with the principles of ASTM C140/C140M [28], which is commonly used for determining the compressive strength of masonry units. The loading rate, specimen orientation and bearing conditions were kept constant for all tests to ensure comparability.

Figure 10. Testing procedure of stabilised earth blocks: (**a**) curing of earth blocks; (**b**) labelling of specimens (three per group, labelled as *X*, *Y*, and *Z*); (**c**) measurement of block weight; (**d**) compressive strength testing.

The gross density of the blocks was determined from the measured mass and geometric dimensions after curing, following the density determination approach described in the aforementioned standard.

2.6. Environmental Impact Assessment (Embodied CO_2)

The environmental performance of ISSA-stabilised earth blocks was evaluated using a simplified embodied CO_2 emissions calculation, Equation (1). This assessment was intended to compare the effect of reducing cement or lime content within the binder fraction; it should not be interpreted as a full life-cycle assessment.

$$\mathrm{CO_2} = \sum(m_i \times EF_i) \quad (1)$$

where m_i represents the mass fraction of each binder component, and EF_i is the corresponding emission factor (kg CO_2/kg). Emission factors for cement and lime were adopted from the widely reported literature values, with cement at 0.90 kg CO_2/kg and lime at 0.75 kg CO_2/kg. In the original screening calculation, ISSA was treated as a waste-derived input with no additional allocated binder-production emissions. However, ISSA production involves sludge collection, transport, sun drying, carbonisation, grinding, and incineration at 600 °C for 2 h, all of which may generate emissions. Because site-specific energy consumption and transport data were not evaluated adequately, the present study does not assign a definitive emission factor to ISSA. Instead, the calculation is reported as a binder substitution screening estimate, and the general equation should include an ISSA processing term when such data are available.

For illustration, the embodied CO_2 of mix C4 (40% cement + 60% ISSA) is calculated as:

$$\mathrm{CO_2} = 0.40 \times 0.90 + 0.60 \times 0 = 0.36 \text{ kg CO}_2/\text{kg binder} \quad (2)$$

The same procedure was applied to all mix compositions for comparative screening of binder substitution. The resulting values should therefore be interpreted as lower-bound estimates of potential CO_2 reduction associated with cement or lime replacement, excluding unquantified ISSA processing emissions. A full cradle-to-gate life-cycle assessment is required to quantify the net environmental benefit of ISSA after accounting for sludge collection, drying, carbonisation, incineration, grinding, transport and possible allocation between waste management and material production.

Accordingly, the embodied CO_2 values reported in Table 2 are presented as screening indicators of binder substitution only. They are not intended to represent the full embodied carbon of ISSA-based blocks. A full assessment should include energy consumption during incineration at 600 °C for 2 h, emissions associated with sludge handling and drying, and allocation rules for whether the thermal treatment burden is assigned to waste management, material production, or both.

Table 2. Simplified embodied CO_2 emissions of ISSA–cement and ISSA–lime stabilised systems based on binder substitution only.

Mix ID	Composition	CO_2 (kg/kg Binder)	Reduction (%)
C5	100% Cement	0.90	–
C4	40%C + 60% ISSA	0.36	60
L5	100% Lime	0.75	–
L3	30%L + 70% ISSA	0.225	70

3. Results

3.1. Physical Characterisation of the Laterite Soil

The particle size distribution curve shows a continuous, well-graded profile, indicating a wide range of particle sizes with no significant gaps (Figure 11). The calculated coefficient of uniformity ($Cu \approx 40$) confirms that the material is well graded and has good packing characteristics. The substantial fine fraction suggests improved soil skeleton cohesion, as the fine particles fill voids between coarse aggregates, thereby reducing permeability and increasing density, making the material suitable for stabilised earth block production [29]. This gradation is expected to contribute positively to the development of compressive strength when combined with ISSA and a stabilising binder.

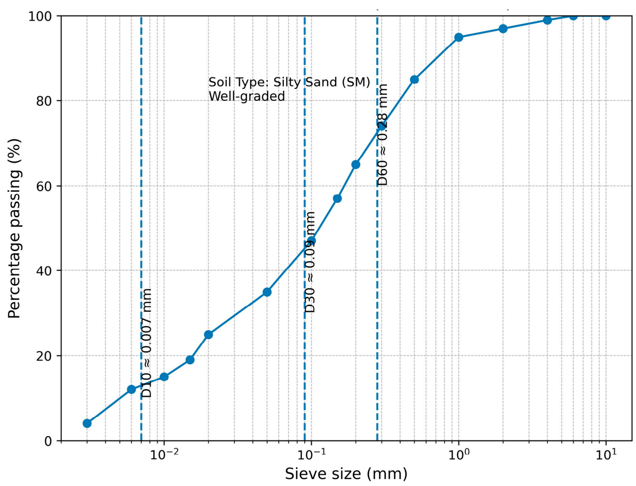


Figure 11. Particle size distribution curve of laterite soil (the horizontal axis uses a logarithmic scale).

The compaction characteristic curve of laterite soil in Figure 12 exhibits a typical parabolic trend, in which dry density increases with moisture content up to an optimum point, then decreases with further addition of water. The Proctor curve indicates that the maximum dry density (MDD) is approximately 1.88 Mg/m^3, achieved at an optimum moisture content (OMC) of about 11.1%. The initial increase in dry density is attributed to improved particle lubrication, which enhances particle rearrangement and packing efficiency. Beyond the optimum moisture content, excess water occupies pore spaces and generates pore-water pressure during compaction, reducing dry density.

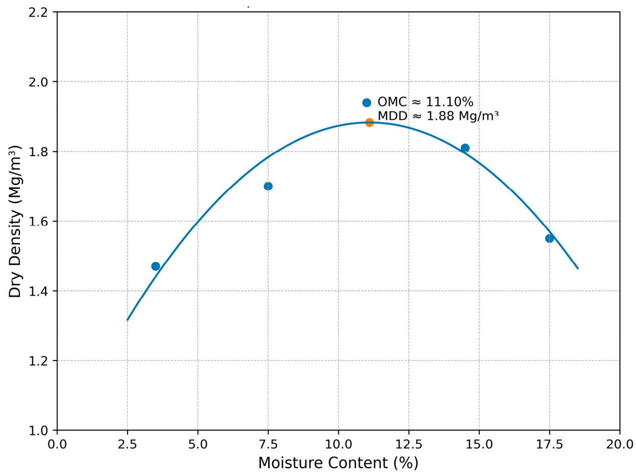


Figure 12. Compaction curve showing the relationship between moisture content and dry density.

These results demonstrate favourable compaction characteristics of the material, indicating its suitability for stabilised earth block production with adequate strength and density development.

The Atterberg limit test results shown in Figure 13 indicate that the laterite soil has a liquid limit (LL) of 31%, a plastic limit (PL) of 15%, and a plasticity index (PI = LL − PL) of 16%. These values are within the recommended ranges for stabilised earth blocks specified in the ARS 1333:2018 standard [30], which states a liquid limit range of 25–46% and a plasticity index range of 2–30%. The plasticity characteristic (PI = 16%) indicates that the soil is within the ideal range for stabilisation, where an adequate clay fraction supports interparticle bonding while avoiding excessive volumetric instability. The liquid limit also indicates that the soil contains enough fines to aid binding without compromising workability.

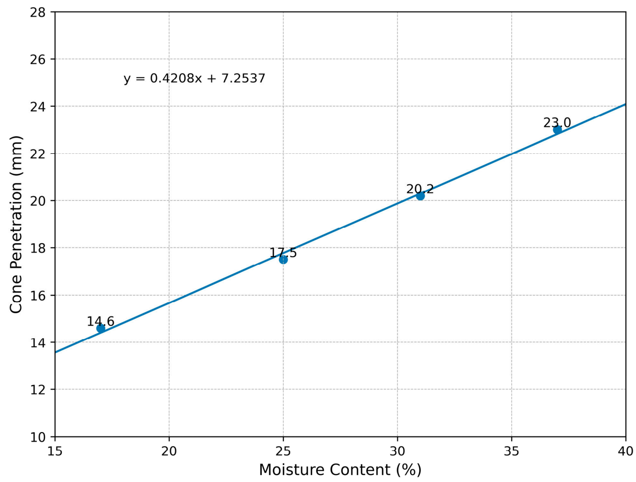


Figure 13. Variation in cone penetration with moisture content shows a linear increase in penetration depth as moisture increases.

3.2. Chemical and Mineralogical Characteristics of ISSA

XRF analysis revealed that ISSA contains significant amounts of oxides, including SiO_2 (43.2%), Al_2O_3 (18.0%), and CaO (14.1%), as indicated in Figure 14. The combined content of SiO_2, Al_2O_3, and Fe_2O_3 is about 64%, which is below the 70% threshold specified in the ASTM C618 standard for pozzolanic materials [31]. This indicates that ISSA has moderate pozzolanic potential and may require activation with cement or lime to enhance its reactivity. Although ISSA does not meet the ASTM C618 compositional threshold, this threshold was originally developed for conventional pozzolans such as fly ash and should therefore be used only as an indicative benchmark rather than as an absolute classification criterion for sewage sludge ash.

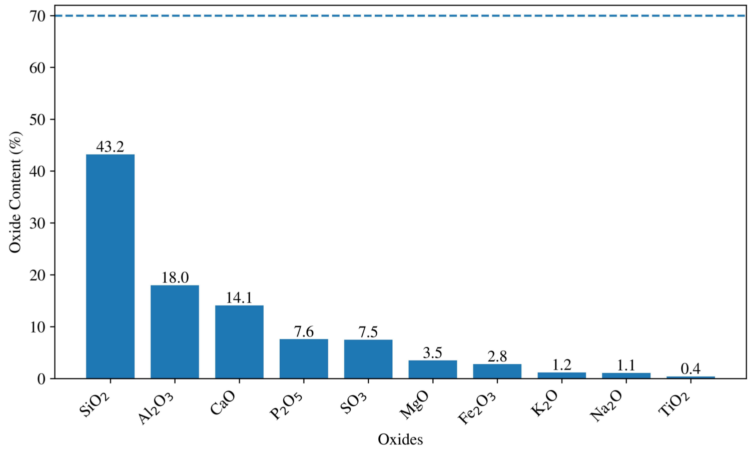


Figure 14. XRF chemical composition of incinerated sanitary sludge ash (ISSA). The blue dashed line represents the 70% threshold specified in the ASTM C618 standard [31].

The ISSA sample plots near the SiO_2–Al_2O_3 edge in both ternary systems (Figure 15), indicating a silica–alumina dominant composition with relatively low Fe_2O_3 and moderate CaO content. This composition differs from lime-rich binders and highly siliceous agricultural ashes, confirming that ISSA should not be treated as directly equivalent to conventional SCMs. Rather, its performance must be interpreted in relation to its own chemical composition, mineralogy, fineness, carbon content, thermal history and interaction with the stabilising binder.

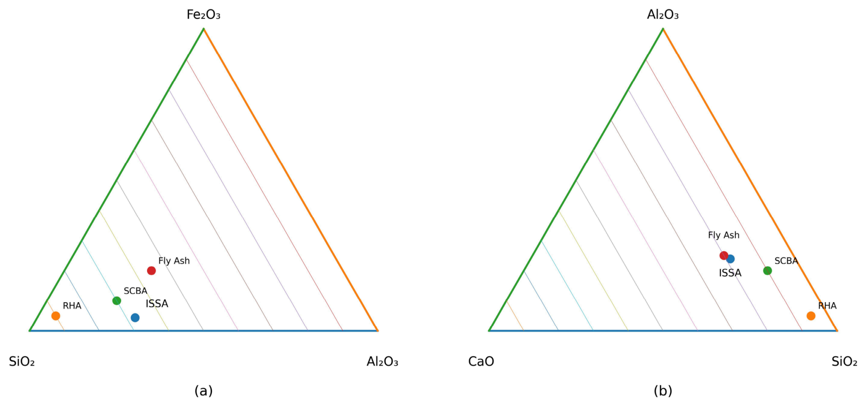


Figure 15. Dual ternary diagrams: (**a**) SiO_2–Al_2O_3–Fe_2O_3 system; (**b**) CaO–SiO_2–Al_2O_3 system showing compositional positioning of ISSA relative to conventional SCMs.

In comparison, conventional supplementary cementitious materials (SCMs) exhibit distinct compositional characteristics. Rice husk ash (RHA) is highly siliceous and typically plots near the SiO_2 apex, reflecting its strong pozzolanic reactivity. Sugarcane bagasse ash (SCBA) occupies an intermediate aluminosilicate region, while Class F fly ash (FA) shows a more balanced distribution of silica, alumina, and iron oxides. By contrast, ISSA contains appreciable CaO and P_2O_5 in addition to SiO_2 and Al_2O_3, which may influence reactivity and strength development differently from agricultural or coal-derived SCMs.

ISSA generally fall within or near the high-silica pozzolanic domain, confirming their well-established reactivity as reported in the literature [16,32,33].

XRD analysis identified crystalline phases, including quartz and calcite, as well as amorphous phases responsible for pozzolanic reactions, as illustrated in Figure 16. The presence of amorphous silica and alumina supports the formation of C–S–H and C–A–H gels. The dominant peak at approximately 26.6° 2θ corresponds to quartz (SiO_2), while peaks near 29.4° and 33° are attributed to calcite ($CaCO_3$) and hematite (Fe_2O_3), respectively. A broad hump observed between 20° and 30° 2θ indicates the presence of amorphous phases, which are responsible for the pozzolanic reactivity of ISSA.

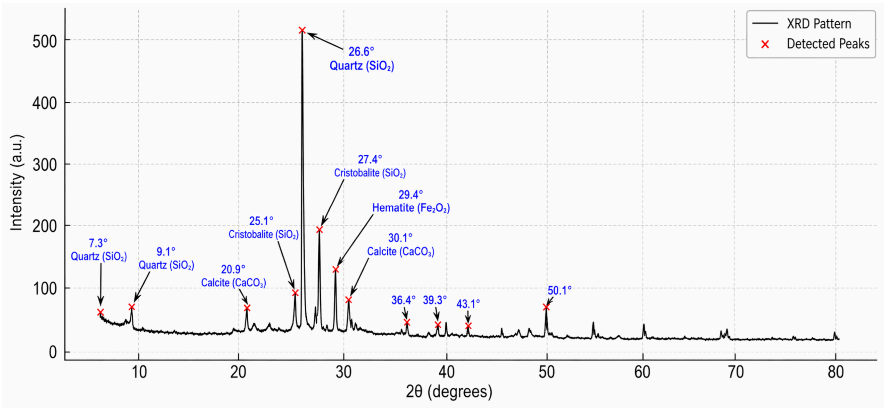


Figure 16. Annotated X-ray diffraction (XRD) pattern of incinerated sanitary sludge ash (ISSA).

3.3. Mechanical Performance of Cement-Stabilised Blocks

The compressive strength of cement-stabilised blocks showed a pronounced dependency on cement content within the binder matrix. Mixes containing 10–30% cement (C1–C3) developed relatively low compressive strengths, indicating insufficient binder hydration and incomplete matrix formation. A substantial increase in strength was observed at 40% cement content (C4), suggesting a threshold for effective strength gain, while the highest strength, approximately 7.7 MPa, was recorded for blocks stabilised with 100% cement (Figure 17). The results are presented as mean values from three specimens, with standard deviations shown in the corresponding figure. This descriptive statistical presentation indicates the level of variability within each mix.

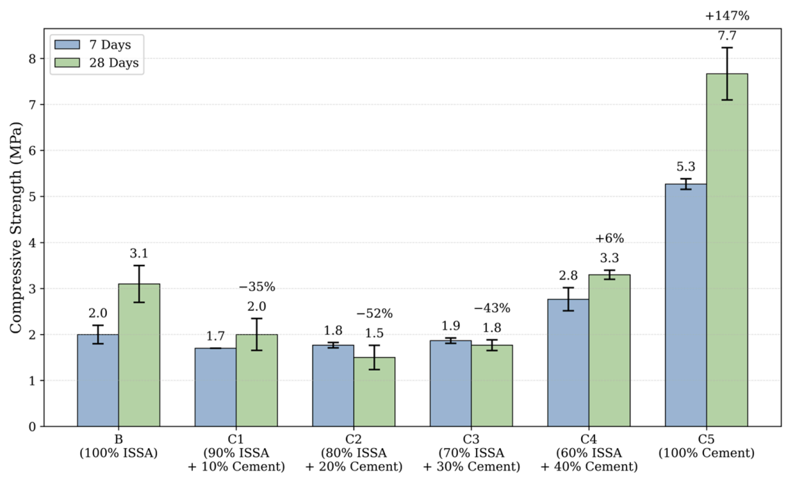


Figure 17. Compressive strength of ISSA–cement stabilised blocks at 7 and 28 days for different cement contents, illustrating the pronounced strength increase at and above 40% cement (C4) and the maximum strength of approximately 7.7 MPa at 100% cement (C5). Error bars represent the standard deviation of three specimens, indicating variability in measured compressive strength.

3.4. Mechanical Performance of Lime-Stabilised Blocks

Lime-stabilised blocks exhibited a consistent increase in compressive strength from 7 to 28 days across all mix designs, confirming ongoing pozzolanic reactions between ISSA and lime. The L5 mix (100% lime) achieved the highest compressive strength among the lime-based formulations, at 4.8 MPa. Blended mixes L3 (70% ISSA + 30% lime) and L4 (60% ISSA + 40% lime) also developed satisfactory strengths of 4.2 and 4.3 MPa, respectively (Figure 18), demonstrating effective stabilisation while maximising sludge ash utilisation.

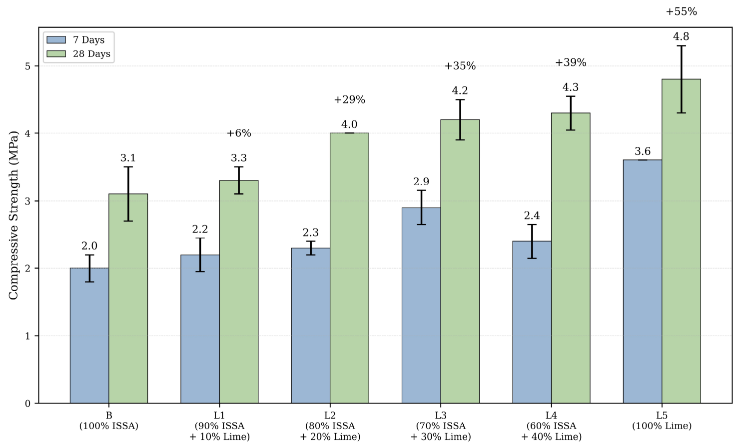


Figure 18. Compressive strength of ISSA–lime stabilised blocks at 7 and 28 days, showing gradual strength development and the optimal performance of mixes L3 (70% ISSA + 30% lime), L4 (60% ISSA + 40% lime), and L5 (100% lime). Error bars represent the standard deviation of three specimens, indicating variability in measured compressive strength.

3.5. Comparative Behaviour of Cement and Lime Binders

The mechanical performance of ISSA-stabilised earth blocks is governed by both binder type and binder content, with distinct hydration and reaction mechanisms controlling strength development.

Cement-stabilised systems exhibited threshold-dependent behaviour, whereby the compressive strength remained relatively low at cement contents below 30%, followed by a sharp increase at cement contents $\geq$ 40% (Figure 19). This behaviour indicates that a minimum cement fraction is required to form a continuous hydration matrix, enabling sufficient formation of calcium silicate hydrate (C–S–H) gel and effective interparticle bonding [34].

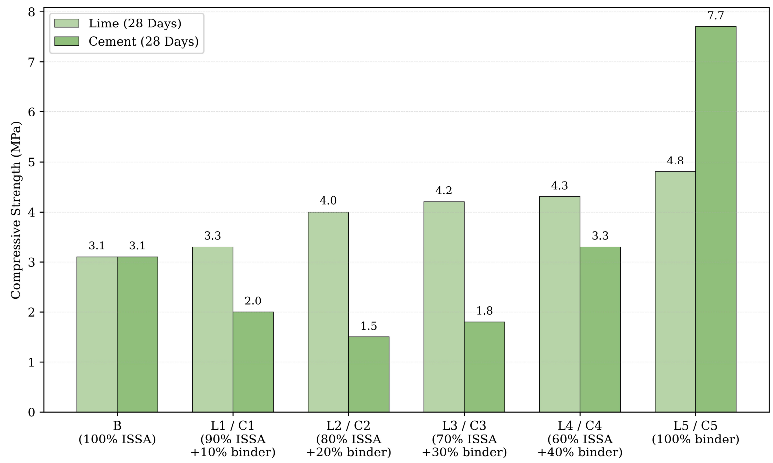


Figure 19. Comparison of compressive strength for ISSA–cement and ISSA–lime stabilised blocks at 28 days.

Moreover, some cement-stabilised systems showed a slight reduction in strength between 7 and 28 days, which contrasts with the monotonic strength gain typically reported for conventional cement-stabilised soil materials. This behaviour may be associated with the porous and absorptive nature of ISSA, which increases water demand and alters the hydration environment of the cement matrix under limited curing water. Previous studies have shown that incorporating sewage sludge ash may increase porosity and influence the development of mechanical properties in cementitious systems, particularly at higher replacement levels [35]. Furthermore, moisture-related deterioration and curing conditions are known to influence the long-term strength development of stabilised soils [36,37]. Consequently, any potential late-age strength gain from continued hydration may have been offset by microstructural deterioration, resulting in the slight reduction in compressive strength observed at 28 days. However, as no direct microstructural evidence, such as scanning electron microscopy (SEM), mercury intrusion porosimetry (MIP), or microcrack imaging, was conducted in the present study, this explanation is presented as a tentative interpretation rather than a confirmed mechanism.

In contrast, lime-stabilised systems demonstrated a progressive and consistent strength development, reflecting the slower kinetics of pozzolanic reactions between lime, ISSA, and the clay fraction of the laterite soil. Unlike cement systems, lime-based mixes did not exhibit a clear threshold effect but instead showed a gradual increase in strength as lime content increased.

At equivalent binder contents (10–30%), lime-based systems outperformed cement-based systems. This can be attributed to lime's ability to activate the aluminosilicate phases in ISSA, enhance the flocculation and aggregation of clay particles, and promote long-term pozzolanic reactions. Therefore, the results reflect practical curing approaches selected for each binder rather than a strictly identical curing environment.

However, at higher binder contents (≥40%), cement-based systems achieved significantly higher ultimate strengths, likely due to the rapid formation of cement hydration products such as C–S–H. This interpretation is consistent with the known behaviour of cementitious systems, although direct confirmation of reaction products would require microstructural or phase analysis evidence. The results demonstrate a clear transition from filler-dominated behaviour at low binder content to binder-controlled behaviour at higher binder content. In cement systems, the threshold observed at approximately 40% cement reflects the formation of a continuous C–S–H matrix necessary for effective load transfer. Below this threshold, ISSA acts primarily as an inert filler with limited contribution to bonding.

In contrast, lime-based systems exhibit a more gradual strength evolution governed by pozzolanic reactions. The absence of a threshold effect suggests that strength development is controlled by reaction kinetics rather than binder continuity. This distinction highlights the fundamentally different stabilisation mechanisms and supports the use of lime–ISSA systems for long-term performance optimisation.

This highlights that binder chemistry, rather than density alone, governs the mechanical performance of ISSA-stabilised systems.

3.6. Influence of Curing Conditions

The curing regime was critical to the observed mechanical performance. The monitored indoor conditions (29–36 °C and 60–75% RH) reflect a realistic field environment rather than controlled laboratory curing. However, the use of different curing regimes for cement and lime systems is an important limitation of the comparative interpretation. Cement-stabilised blocks were water cured to promote hydration by replacing the lost water through the hydration process, whereas lime-stabilised blocks were air cured to promote carbonation and longer-term pozzolanic reactions. Therefore, the study compares practical binder-specific curing responses rather than isolating binder chemistry under identical curing conditions.

For cement-stabilised blocks, elevated temperatures accelerated the hydration kinetics. However, moderate humidity limited the availability of moisture. This combination promoted early strength gain but may have induced moisture deficiency at later stages, contributing to microcracking.

For lime-stabilised blocks, strength development was less sensitive to short-term moisture fluctuations. The slower pozzolanic reactions allowed continued strength gain despite variable environmental conditions.

These findings highlight that ISSA-stabilised systems can perform effectively in practical, non-ideal curing environments. Nevertheless, the conclusions are limited to the curing conditions and testing ages considered in this study, and further controlled curing experiments are required to separate the effects of binder type, moisture availability and temperature, with a significant advantage for implementation in resource-constrained regions.

3.7. Density–Strength Relationship

Cement-stabilised blocks exhibited a clear positive correlation between density and compressive strength (R^2 = 72%). However, for lime-stabilised systems, no consistent correlation was observed, indicating that strength development is governed primarily by pozzolanic reactions rather than densification (Figure 20). The regression analysis was used as a descriptive tool to identify trends, while standard deviations from replicate specimens were used to express experimental variability.

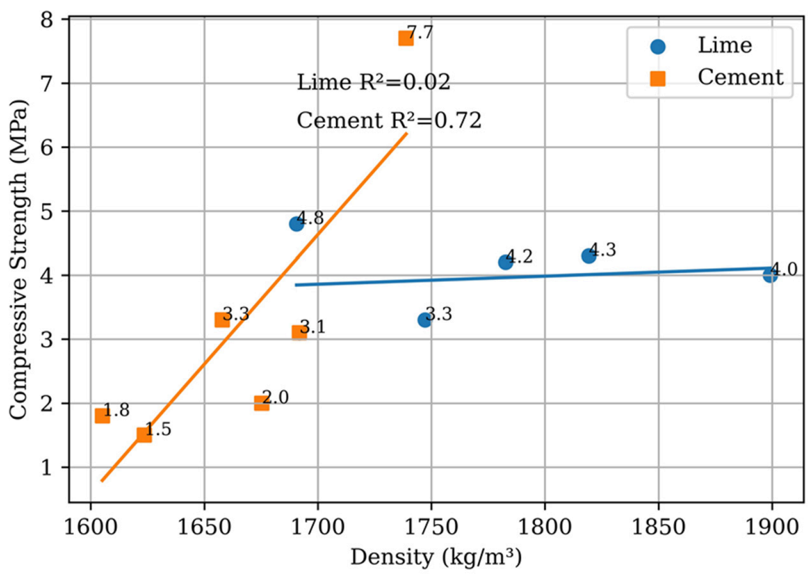


Figure 20. Relationship between density and compressive strength of ISSA–cement- and ISSA–lime-stabilised blocks. Cement-based systems show a clear positive correlation, while lime-based systems exhibit no consistent relationship.

Cement-stabilised blocks exhibited higher strength at comparable densities (Figure 21), due to chemical bonding via C–S–H formation. Lime-stabilised blocks showed lower strength despite similar densities (Figure 22), reflecting the slower development of cementitious products.

This demonstrates that mechanical performance is governed by both physical densification and chemical reactions, with chemical bonding playing a dominant role in cement-based systems.

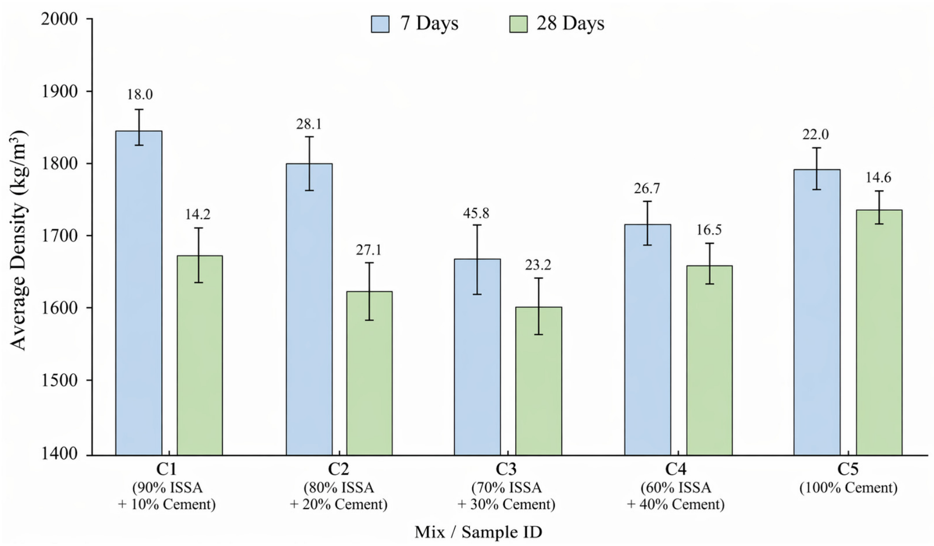


Figure 21. Average density of ISSA–cement-stabilised earth blocks at 7 and 28 days. Error bars represent the standard deviation of three replicates. Error values are displayed above each bar.

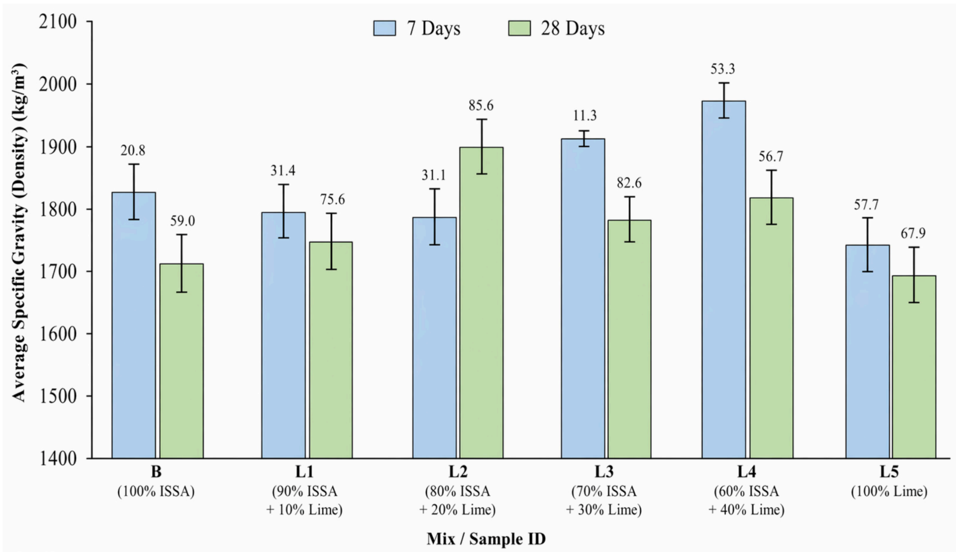


Figure 22. Average density of ISSA–lime stabilised earth blocks at 7 and 28 days. Error bars represent the standard deviation of three replicates. Error values are displayed above each bar.

3.8. Sustainability–Performance Trade-Off

The incorporation of ISSA introduces a clear trade-off between mechanical performance and environmental sustainability. The results demonstrate that partial replacement of conventional binders with ISSA can reduce the demand for cement or lime while retaining promising compressive strength. In particular, cement-based systems incorporating 60% ISSA achieve approximately 60% CO_2 reduction, while lime-based systems with 70% ISSA achieve up to 70% CO_2 reduction, as presented in Table 2. However, the environmental calculations presented here are simplified binder substitution estimates and do not quantify the energy and emissions associated with ISSA collection, drying, carbonisation, incineration, grinding, and transport.

The findings indicate that ISSA incorporation enables a significant sustainability–performance balance, achieving promising mechanical strength alongside substantial environmental benefits. This highlights the potential of ISSA-stabilised earth blocks as low-carbon construction materials, particularly suitable for regions aiming to reduce reliance on clinker-based binders.

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4. Conclusions

This study demonstrates that incinerated sanitary sludge ash (ISSA) can be effectively utilised as a supplementary material in stabilised earth blocks, contributing to binder reduction, mechanical performance and environmental sustainability when activated with cement or lime.

The results show that cement-stabilised systems require a minimum cement content of approximately 40% of binder fraction to achieve significant strength development, reaching compressive strengths of up to 7.7 MPa. Lime-stabilised systems showed more gradual strength development and achieved approximately 4.2–4.3 MPa at 30% lime content. ISSA contributes to the strength development through both filler effects and pozzolanic reactions, although its performance depends on activation by cement or lime.

The study further demonstrates that ISSA replacement levels of 60–70% can reduce conventional binder consumption while maintaining promising compressive strength. The simplified embodied CO_2 screening suggests potential reductions of approximately 60% (cement systems) and 70% (lime systems) emissions; however, these values exclude unquantified emissions from sludge collection, drying, carbonisation, incineration, grinding and transport. Therefore, the environmental findings should be regarded as preliminary and should be verified through a full life-cycle assessment. Adequate strength can be achieved under realistic indoor curing conditions investigated, but practical applicability cannot be confirmed from the strength results alone. Durability performance, including water absorption, wetting and drying resistance, leaching behaviour and long-term weathering, was not evaluated in the present study.

Overall, the findings highlight the potential of ISSA-stabilised earth blocks as a resource-efficient construction material, particularly for regions seeking to reduce conventional binder consumption and valorise wastewater treatment residues. This potential remains subject to future durability testing, controlled curing studies and complete environmental assessment. Future research should further investigate the long-term durability and environmental performance of ISSA-stabilised earth blocks, including water resistance, wetting and drying effects, freeze–thaw behaviour where relevant, and leaching of potentially harmful constituents under realistic exposure conditions. Microstructural analyses such as SEM, MIP, thermogravimetric analysis and XRD/Rietveld quantification are also recommended to verify the mechanisms responsible for strength development and late-age strength reduction. In addition, optimisation studies covering a wider range of ISSA replacement levels, soil types, and curing regimes are recommended to support the development of design guidelines and standardised specifications for ISSA-based stabilised blocks in sustainable construction.

The findings indicate that ISSA-stabilised earth blocks can achieve a practical balance between mechanical performance and binder reduction under the investigated conditions. Nevertheless, the absence of durability testing, the use of different curing regimes, and the simplified environmental assessment require conservative interpretation before field-scale implementation. This demonstrates strong potential for field application, particularly in resource-constrained regions where controlled curing is not feasible.

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