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Experimental Investigation of Compressive and Flexural Strength of Lime-Surkhi Mortar

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Abstract

Lime-surkhi mortar is a traditional binder used in historic masonry structures in Nepal. Despite its widespread application, compressive and flexural properties of lime-surkhi mortar remain poorly quantified, limiting its reliable use in heritage conservation and structural assessment. This study experimentally investigates the compressive and flexural behavior of lime-surkhi mortar prepared with quicklime-based lime putty, varying surkhi and sand proportions at a constant lime content. Following initial screening of thirteen mix ratios, the 1:1:2 and 1:2:2 mixes were selected for detailed analysis. Specimens were air-cured at 70–80% relative humidity and tested at 7 and 28 days. Cube compressive strength increased by approximately 22 times for the 1:1:2 mix and 14 times for the 1:2:2 mix between 7 and 28 days. Masonry prism compressive strength increased by about 1.7 times for both mixes. While the 1:2:2 mix showed higher cube compressive strength, the 1:1:2 mix exhibited superior prism performance, highlighting the significance of mortar–unit interaction. The flexural strength of the 1:1:2 mix increased slightly with curing, whereas the 1:2:2 mix showed a decline at 28 days. These findings provide empirical data for selecting lime-surkhi mortars in heritage repair and low-load masonry applications.

Keywords: lime mortar, surkhi, pozzolanic material, hydraulicity, sustainable conservation, heritage repair

1. Introduction

1.1 Background

Lime-based mortars have served as a foundational binder in masonry construction. The durability of lime-based mortars is evidenced by historic buildings in India, some of which are over 2,000 years old and have withstood diverse environmental conditions [1]. In South Asia, traditional masonry commonly uses lime mixed with sand, brick dust (surkhi), and organic materials (such as molasses or pulses) to produce lime-based mortars [2][3]. These formulations relied primarily on locally available materials, making lime mortars an economical choice for builders. For instance, lime production in developing countries is generally less expensive and less technologically demanding than modern cement manufacture, which often relies on advanced technology and fuels [4]. Additionally, unlike Portland cement, lime production and carbonation result in relatively low embodied carbon. Lime mortars emit little CO_2 during manufacture and can reabsorb carbon over time, resulting in a very low carbon footprint during use[3][5]. These historical and environmental advantages have contributed to renewed academic and practical interest in lime mortars for sustainable construction and heritage conservation [3][5].

1.2 Literature Review

Despite these advantages, several technical challenges constrain the direct application of lime mortars in contemporary construction. Lime mortars inherently set and gain strength much more slowly than cement mortars. As noted in Indian standards, hardening of lime mortars is slower than that of cement mortars, and they generally do not achieve the high early strength required for modern structural applications [6]. The

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mechanical properties of lime mortars also exhibit considerable variability depending on raw material composition and preparation methods. Geological differences and processing methods can cause significant variation in lime quality across regions [1], and Experimental studies report significant variation in compressive strength even among mortars prepared with similar nominal mix proportions.[7]. The use of traditional admixtures further complicates performance prediction. Recent reviews highlight that, despite growing interest in the natural advantage of lime, there has been little research on its implementation in new construction [8]. Collectively, these issues, including strength variability, long curing times, and uncertainty in durability, indicate that lime-surkhi mortars cannot be assumed to perform identically to modern mortars. Their application, therefore, requires case-by-case evaluation.

1.3 Problem Statement and Objectives

This study addresses these gaps by experimentally evaluating lime-surkhi mortars under controlled conditions, with particular emphasis on their applicability in the Nepalese context. Drawing on heritage restoration practice, the research systematically assesses lime-surkhi mortars with various mix ratios to measure workability, strength, water absorption, and related properties. As highlighted in a recent case study, a primary goal of such work is to comprehensively understand and analyze the strength of antiquated materials and traditional mortars used in historical construction [9]. Accordingly, the objective is to generate empirical data on the influence of different lime-sand-surkhi mix ratios on performance under realistic curing and loading conditions. The findings are intended to inform both sustainable building and conservation efforts, supporting the formulation of lime-surkhi mortar in accordance with relevant standards rather than promoting a single material without critical evaluation [6][9].

2. Materials and Methods

2.1 Materials

The materials used in this study include:

- **Hydrated lime ($Ca(OH)_2$):** Lime is a calcium-based binder obtained from limestone and used in mortar. In lime–surkhi–sand mortar, lime serves as a binding agent. The hardening of mortar through the carbonation of lime and pozzolanic reactions with surkhi results in the formation of cementitious compounds such as calcium silicate hydrate, which progressively enhance compressive strength and durability.

  In the case of lime, some fundamental chemical reactions are:

  Lime Hydration:

  CaO (Quicklime) + $H_2O \rightarrow Ca(OH)_2$ (Slaked Lime) + Heat (Equation 1)

  Pozzolanic Reactions:

  $Ca(OH)_2 + SiO_2$ (from Surkhi) + $H_2O \rightarrow$ C-S-H (Binder Gel) (Equation 2)

  $Ca(OH)_2 + Al_2O_3$ (from Surkhi) $\rightarrow$ C-A-H (Binder Gel) (Equation 3)

  Carbonation:

  $Ca(OH)_2 + CO_2 \rightarrow CaCO_3$ (Calcium Carbonate) + H_2O (Equation 4)

- **Surkhi:** Surkhi is a fine powder produced by grinding burnt clay bricks. It contains reactive silica and alumina, imparting pozzolanic properties. The fineness of surkhi significantly affects its reactivity; finer particles provide greater surface area for pozzolanic reactions. The specific gravity of surkhi typically ranges from 2.4 to 2.6, and its pozzolanic activity varies with firing temperature and brick composition, which may differ across geographic locations. When combined with lime and water, surkhi reacts with calcium hydroxide to form cementitious compounds, thereby increasing strength, reducing shrinkage, and enhancing the durability of lime mortar.

- **Sand**: Sand serves as the fine aggregate in lime-surkhi-sand mortar. It provides bulk, improves strength, and reduces shrinkage and cracking during drying. Sand does not participate in chemical reactions; it enhances mechanical stability and durability by contributing to a dense, well-graded structure. The fineness modulus and the sand zone influence workability and packing density. Zone II or Zone III sand conforming to IS 383 is generally preferred for mortar applications. The use of clean, well-graded sand free of organic impurities is essential to ensure optimal bonding and workability. Sand properties may vary significantly by location, and local quarry material should be characterized before use.

- **Water:** Water is a critical component in lime-surkhi-sand mortar, facilitating the slaking of lime and enabling the chemical reactions required for strength development. It also imparts workability, allowing proper mixing and placement. Adequate water ensures effective carbonation and pozzolanic reactions, whereas excessive water increases porosity and reduces compressive strength. Therefore, clean and potable water should be used in controlled quantities.

- **Brick:** First-class local brick measuring 240 mm × 110 mm × 55 mm was used to prepare the masonry prisms. The compressive strength of the bricks was determined by cutting each brick into three 50 mm × 50 mm × 50 mm cubes and testing them individually on the UTM. The three specimens yielded compressive strengths of 14.190 MPa, 13.105 MPa, and 10.715 MPa, giving a mean compressive strength of 12.670 MPa with a standard deviation of 1.778 MPa (coefficient of variation 14.0%). The variability is consistent with the expected natural variation in hand-made or locally fired bricks. This means brick strength forms the basis for interpreting prism efficiency ratios discussed in Section 3.2.

2.2 Mix proportions selection

All mix proportions for the material tests were specified by weight in the lime: surkhi: sand sequence, as shown in Table 1. For each mix, the water content was adjusted to achieve appropriate workability while ensuring consistent mixing conditions. Among these thirteen mix proportions, preliminary compressive strength testing at 7 days was used to identify the most promising candidates. The 1:1:2 and 1:2:2 mixes were selected for detailed study because they consistently exhibited relatively higher cube compressive strength at 7 days compared to other mixes, while also demonstrating balanced workability and material proportioning (see Section 3.1). Mixes with very low sand content showed excessive cracking during drying, and those with very high sand content exhibited poor cohesion; the two selected mixes avoided both extremes.

Table 1. Ratios used in the test

1:1:0.5	1:1:0.75	1:1:1	1:1:1.5
1:1:2	1:1:2.5	1:1:3	1:0.25:2
1:0.5:2	1:0.75:2	1:1.25:2	1:1.5:2
1:2:2	-	-	-

2.2 Experimental program

A series of material and masonry prism characterisation tests was conducted to establish the mechanical properties. These tests were carried out at the Laboratory of Civil Engineering at Khwopa College of Engineering.

2.2.1 Compressive strength test of masonry prism and mortar

For each mix proportion, mortar was prepared by thoroughly mixing lime, surkhi, sand, and water to achieve a uniform, workable consistency. The water-to-binder ratio was controlled by visual and manual workability assessment, targeting a flow consistent with standard mortar workability requirements per IS 2250:1981. To assess compressive behavior, six mortar cubes (76 mm × 76 mm × 76 mm) (Figure 1) and six three-layer brick prisms were prepared per mix (Figure 4). The masonry prisms were assembled by laying bricks in a stack-bonded configuration with mortar joints of approximately 10–12 mm thick. Mortar for the cubes was placed in molds in three equal layers, each compacted with 25 tamping strokes to minimize air entrapment and ensure densification. Specimens were demolded after 48 hours. After demolding, all specimens were air-cured under controlled conditions at 70 - 80% relative humidity and 21 - 23 °C. For each type, three specimens were cured for 7 days and three for 28 days.

After air-curing, specimens were removed and measured before testing. Mortar cubes and brick prisms were placed centrally between the platens of a Universal Testing Machine (UTM) for uniform load transfer (Figures 2 and 5). Compressive load was applied at a uniform rate of 0.05 MPa/s until failure (Figures 3 and 6), in accordance with IS 2250:1981. The maximum load at failure was recorded, and the compressive strength was calculated as the load divided by the loaded cross-sectional area. Standard deviation was calculated across the three specimens tested at each age.

The compressive strengths were calculated by dividing the maximum load by the cross-sectional area of the surface to which the load is applied:

$$\text{Compressive Strength } (f_c) = \frac{P}{A} \qquad \text{(Equation 5)}$$

where, P = Maximum load at failure (N)
A = Cross-sectional area of the loaded surface (mm²)

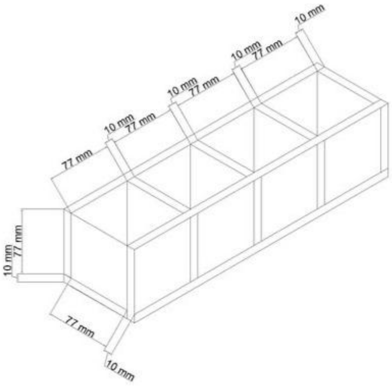

Figure 1. Cube Mold


Figure 2. Cube specimen under axial loading


Figure 3. Failed cube after testing


Figure 4. Masonry prism


Figure 5. Prism test setup


Figure 6. Vertical cracks on the masonry prism

2.2.2 Flexural test

For each mix proportion, mortar was prepared by thoroughly mixing lime, surkhi, sand, and water to achieve a uniform, workable consistency. Six prism specimens (160 mm × 40 mm × 40 mm) were cast per mix (Figures 7 and 8). The mortar was placed in molds in three equal layers, each compacted with 25 tamping strokes to reduce air entrapment and ensure densification. After casting, specimens were cured at 70-80% relative humidity and 21-23 °C. Three specimens were cured for 7 days, and three for 28 days.

After air-curing, specimens were demolded and measured before testing. Each prism was centrally positioned in the three-point bending fixture of the UTM with a span length of 100 mm (Figure 9). Load was applied at a controlled rate of 0.05 MPa/s until failure (Figure 10). The maximum failure load, along with load and deflection responses, was recorded to assess flexural performance and failure characteristics. Standard deviation was calculated for each set of three specimens.

The flexural strengths were calculated by

$$\text{Flexural Strength } (f_b) = 1.5 \times \frac{PL}{bd^2} \qquad \text{(Equation 6)}$$

where, P = Maximum load (N)
L = Span length (mm)

b = Width (mm)
d = Depth (mm)

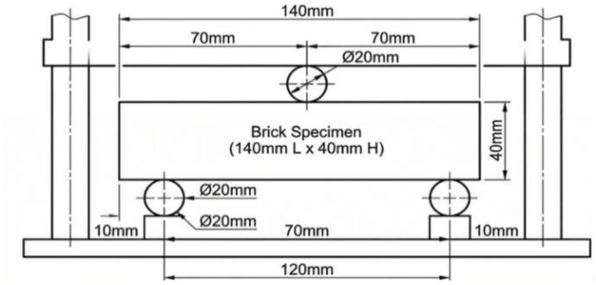

Figure 7. Cuboid specimen mold

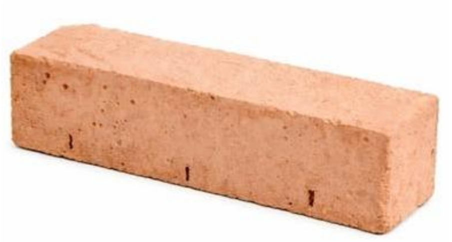

Figure 8. Cuboid specimen

Figure 9. Cuboid specimen under axial loading in UTM

Figure 10. Failed cuboid after testing

2.2.3 Triplet Shear Test and 90-Day Strength Testing

In addition to the compressive and flexural test program reported in this study, two supplementary test programs were initiated concurrently and are currently in progress.

Triplet Shear Test: Triplet specimens were prepared for both the 1:1:2 and 1:2:2 mixes to evaluate the shear bond strength at the mortar–brick interface in accordance with EN 1052-3. Each triplet consists of three bricks bonded in a stack-bond configuration with two mortar joints of approximately 10–12 mm thickness, identical to those used in the prism specimens. Three triplet specimens were cast per mix per curing age, giving a total of 18 triplet specimens (2 mixes × 3 curing ages × 3 specimens). Specimens designated for 7-day and 28-day testing are currently completing their curing periods, while those assigned to the 90-day program remain under air-curing. The triplet test will provide shear bond strength and friction coefficient values, which, together with the compressive and flexural data reported here, will enable a more complete mechanical characterization of the lime-surkhi mortar–brick system.

90-Day Strength Testing: For all specimen types tested in this study — mortar cubes, masonry prisms, and flexural prisms — an additional set of three specimens per mix was cast and set aside for testing at 90 days of air-curing. Lime-surkhi mortars are known to exhibit continued pozzolanic strength gain well beyond 28 days due to the slow reaction between calcium hydroxide and reactive silica and alumina in surkhi. The 90-day test program will allow direct comparison with the 7-day and 28-day results reported here, providing a more complete picture of long-term strength development. These specimens are currently under air-curing, and results will be reported in a subsequent publication.

3. Test Results and Discussion

3.1 Compressive strength of mortar

The compressive strength of mortar cube specimens increased with curing age for both mix proportions. This aligns with the hardening mechanism of lime-surkhi mortars, in which reactive silica and alumina in surkhi react with calcium hydroxide from lime to form cementitious products, primarily calcium silicate and calcium aluminate hydrates. These compounds densify the mortar matrix, enhance cohesion, and support ongoing strength development, especially with proper moisture and curing. Lime-based mortars typically harden more slowly at early ages than cement-based systems, with strength continuing to develop beyond the first week.

In this study, the 1:1:2 mix increased in cube compressive strength from 0.155 MPa at 7 days to 3.454 MPa at 28 days. The 1:2:2 mix increased from 0.289 MPa to 4.107 MPa over the same period. These results confirm ongoing pozzolanic development in the lime-surkhi mortar system. The 1:2:2 mix achieved higher compressive strength at both ages, likely due to a greater pozzolanic contribution from its higher surkhi content. Overall, both mixes developed substantial strength with curing, but the 1:2:2 mix showed a stronger response under uniaxial compression.

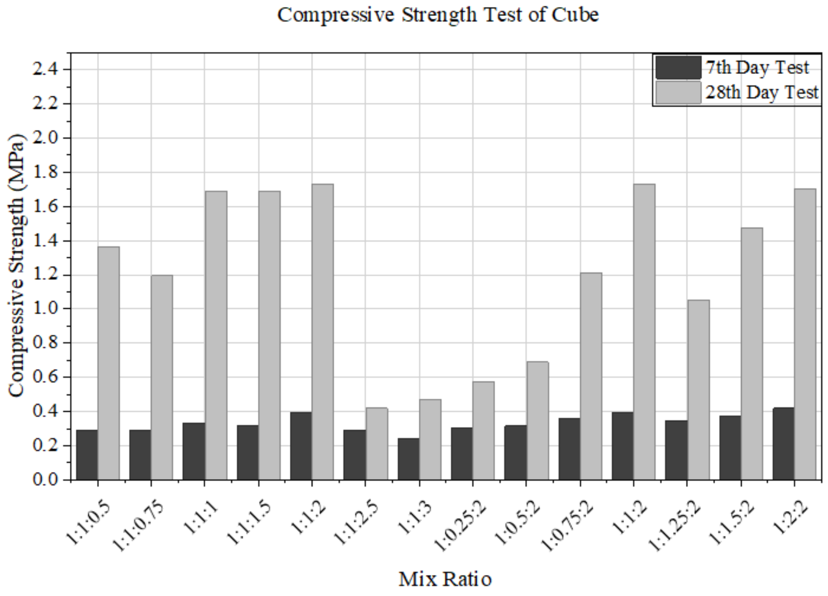

Figure 11. Bar diagram of compressive strength test of cube comparing 7-day and 28-day tests

As shown in Figure 11, the compressive strength of cube specimens for different lime-surkhi-sand mix ratios at 7 and 28 days of curing. In all cases, the 28-day strength is higher than the 7-day strength, showing that the mortar gains strength with curing time. Among the tested mixes, 1:1:2 and 1:2:2 exhibited relatively higher compressive strength and more consistent performance, indicating better bonding and material balance. Therefore, these two ratios were selected for further prism and flexural tests to evaluate their mechanical behavior in more detail.

3.2 Compressive strength of masonry prism

The compressive strength results of the masonry prism specimens also increased with curing age for both selected mixes, indicating improved structural integration of the brick-mortar assemblage over time. For the 1:1:2 mix, prism compressive strength increased from 4.179 MPa at 7 days to 6.947 MPa at 28 days, whereas for the 1:2:2 mix, it increased from 3.129 MPa to 5.306 MPa. These results confirm that curing enhanced the load-carrying capacity of the masonry prisms, not only through mortar hardening but also through improved interaction between the mortar joints and the brick units. The mean brick compressive strength was 12.670 MPa (see Section 2.1). The prism-to-brick strength ratios at 28 days were 0.55 for the 1:1:2 mix and 0.42 for the 1:2:2 mix, which are within the typical range reported for lime mortar masonry (0.25–0.65) and indicate that the brick units contributed meaningfully to the composite strength. The higher ratio for the 1:1:2 mix reflects better mortar–brick compatibility and more efficient load transfer.

In contrast to the cube results, the prism tests showed that the 1:1:2 mix achieved higher compressive strength than the 1:2:2 mix at both curing ages. This suggests that masonry prism behavior cannot be determined solely by mortar cube strength. The compressive response of masonry depends on the combined actions of brick units, mortar joints, and their interface properties, including relative strength, stiffness, joint deformability, confinement, and load transfer efficiency. Previous studies confirm that prism strength is governed by the interaction between units and mortar, and that the properties of each material can significantly affect stress distribution and failure mechanisms.

Mechanically, this occurs because mortar expands more laterally than brick units under compression. The bricks restrain this expansion, creating confinement in the mortar joint and tensile stresses in the masonry units, which affect crack development, load transfer, and ultimate strength. Therefore, a mix that performs well in cube tests may not yield the strongest masonry prism. In this study, the superior prism performance of the 1:1:2 mix suggests better compatibility with the brick units and more effective stress transfer across the joints, despite the higher compressive strength of the 1:2:2 mortar.

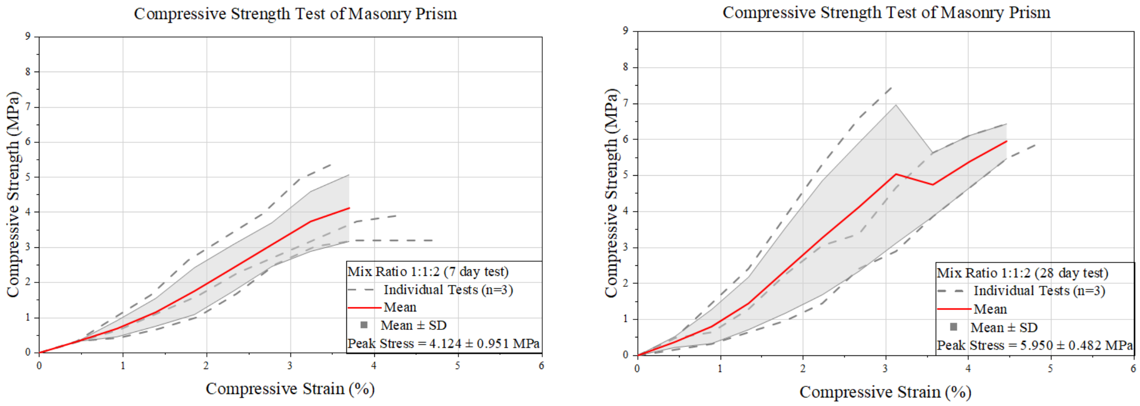

Figure 12. Stress-Strain diagram of a masonry prism compression test ratio 1:1:2

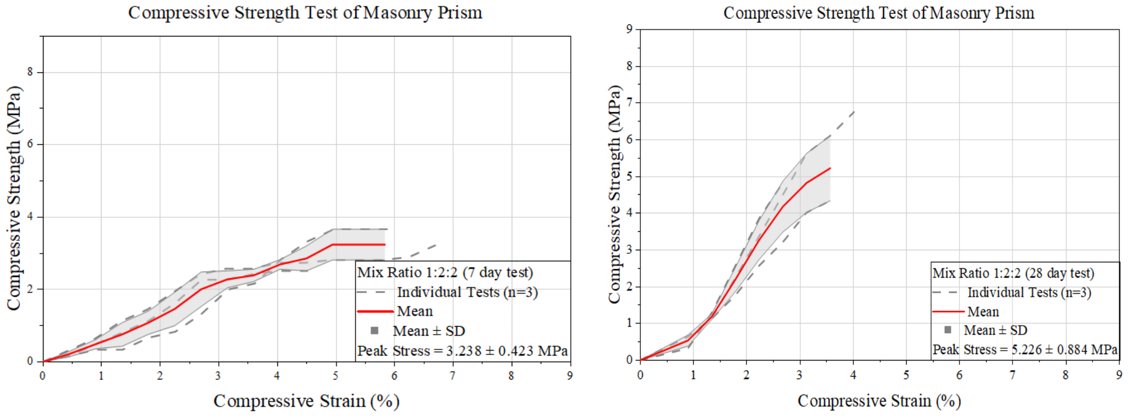

Figure 13. Stress-Strain diagram of a masonry prism compression test ratio 1:2:2

The 1:1:2 (Figure 12) masonry prism develops a higher compressive response than 1:2:2 (Figure 13), with peak stresses of about 4.124 MPa at 7 days and 5.950 MPa at 28 days. The same trend is seen in ratio 1:1:2, which again performs better than 1:2:2, reaching about 3.238 MPa at 7 days and 5.226 MPa at 28 days. In both figures, the 28-day prisms are stronger than the 7-day prisms, showing continued strength gain with curing.

These masonry prism results represent the combined behavior of mortar and masonry units, so the values are more indicative of actual structural performance than mortar alone. The 1:1:2 mix gives the best overall prism strength and more stable stress-strain behavior, which suggests better bonding and load transfer. Overall, Figures 12 and 13 show that longer curing and the richer 1:1:2 mix improve masonry prism strength more effectively than 1:2:2.

3.3 Flexural test

Flexural tests were performed on mortar prism specimens air-cured for 7 and 28 days to assess the bending performance of the selected lime-surkhi mixes. During flexural loading, cracks initiated near the mid-span and propagated through the specimen, culminating in a relatively sudden failure after the peak flexural load was reached. The 1:1:2 mix demonstrated a modest increase in flexural strength from 0.260 MPa at 7 days to

0.295 MPa at 28 days, reflecting ongoing strength development with air-curing. Conversely, the 1:2:2 mix exhibited a decrease in flexural strength from 0.357 MPa at 7 days to 0.222 MPa at 28 days. This reduction may be attributed to the higher surkhi content in the 1:2:2 mix, which, despite promoting early pozzolanic reactivity, can lead to microcracking at later stages due to differential shrinkage between the binder matrix and aggregate. Additionally, the carbonation-driven volume change in lime-rich binders may create internal tensile stresses that reduce flexural resistance over time in mixes with a lower sand-to-surkhi ratio. The relatively small specimen size (40 mm × 40 mm cross-section) may also amplify specimen-to-specimen variability under bending, and the results should be interpreted with this limitation in mind. These findings demonstrate that the flexural response of lime-surkhi mortar is sensitive to mix proportion, and that strength development under bending did not follow a consistent trend for the two selected mixes.

This mix-dependent behavior aligns with the established understanding of lime-based and lime-pozzolan mortars, in which ongoing pozzolanic and carbonation reactions influence mechanical properties and vary with binder-to-aggregate ratio and curing conditions. Previous research has demonstrated that lime mortars typically gain strength with age, especially during early curing, although certain compositions may experience fluctuations or reductions in mechanical resistance at later stages depending on their chemical composition and mix proportions. Within this framework, the current results indicate that the 1:1:2 mix exhibited a more stable flexural response up to 28 days, while the 1:2:2 mix, despite higher initial strength at 7 days, did not retain this advantage at later ages.

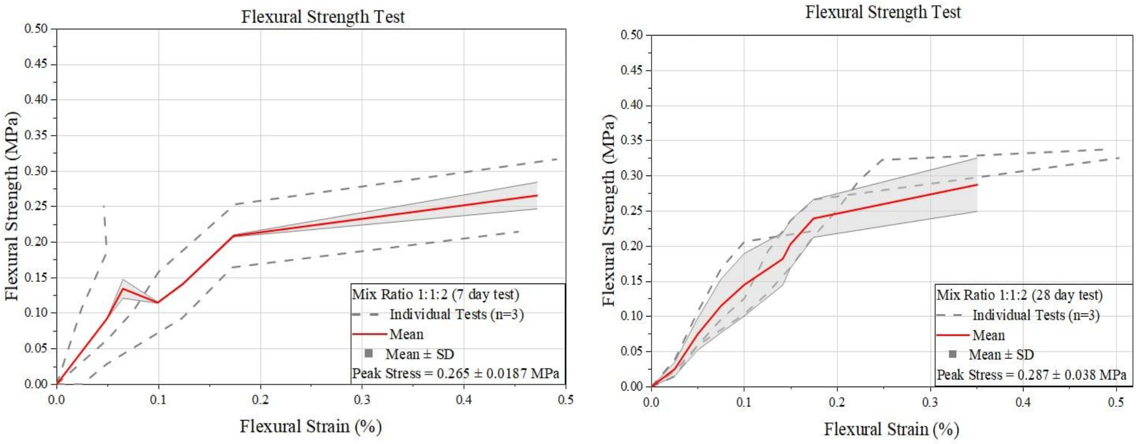

Figure 14. Stress-Strain diagram of a flexural test of ratio 1:1:2

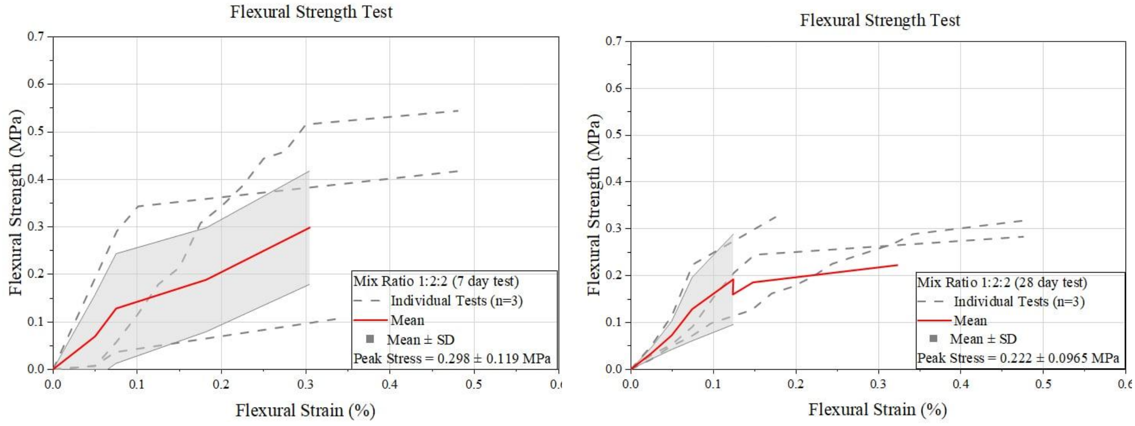

Figure 15. Stress-Strain diagram of a flexural test of ratio 1:2:2

Figure 14 demonstrates the flexural behavior of mortar specimens (160 mm × 40 mm × 40 mm) with a 1:1:2 mix ratio at 7 and 28 days, showing peak flexural strengths of 0.265 MPa and 0.287 MPa , respectively, with a steeper initial stress-strain curve indicating faster strength development. Figure 15 presents the same tests for a 1:2:2 mix ratio, revealing lower peak strengths of 0.298 MPa and 0.222 MPa at 7 and 28 days, with more gradual and variable stress-strain responses. Comparing both figures, the 1:1:2 ratio demonstrates more consistent and stable flexural performance with better 28-day strength gain, while the 1:2:2 ratio exhibits greater variability and lower overall flexural capacity. These flexural strength tests are essential for evaluating the tensile and bending resistance of mortar specimens, highlighting how different lime-surkhi-sand proportions directly affect the material's ability to withstand tensile stresses in structural applications.

4. Conclusion

The findings indicate that lime-surkhi mortar develops substantial compressive and flexural strength with air-curing and is a viable binder for heritage masonry repair and low-load structural applications. The results should not be generalized to high-load modern structural applications, where cement-based mortars remain more appropriate. Between 7 and 28 days, mortar cube compressive strength increased by approximately 22.3 times for the 1:1:2 mix and 14.2 times for the 1:2:2 mix. At the masonry level, prism compressive strength increased by about 1.66 times for the 1:1:2 mix and 1.70 times for the 1:2:2 mix, indicating improved composite action and load transfer with age. The flexural strength of the 1:1:2 mix increased slightly by about 1.13 times, while the 1:2:2 mix decreased to approximately 0.62 times its 7-day value, suggesting that higher surkhi content does not necessarily improve long-term bending resistance. The 1:1:2 mix demonstrated more consistent and superior overall performance in both prism compression and flexural tests, making it the recommended formulation for heritage conservation work in the Nepalese context. These results demonstrate that properly proportioned lime-surkhi mortar can achieve significant strength development and reliable masonry performance with adequate air-curing.

Limitations

This study has several limitations that should be acknowledged. Only compressive and flexural strengths are reported at this stage; triplet shear test results and 90-day strength data for all specimen types are currently under testing and will be reported in a subsequent publication. Durability properties such as water absorption, freeze-thaw resistance, and long-term carbonation depth were not assessed. The material properties of the lime, surkhi, and sand used are specific to locally sourced materials in Bhaktapur, Nepal, and results may not be directly transferable to mortars prepared with materials from other regions. The brick compressive strength was determined by testing three 50 mm cube specimens cut from a single brick; a larger sample would improve the reliability of this value. The small sample size (three specimens per test condition for mortar and prism tests) also limits the statistical confidence of reported means, and the absence of standard deviation data in the result tables constrains rigorous comparison. Equations 5 and 6 in the text require complete symbolic notation to be reproducible.

Future Scope

The triplet shear tests and 90-day strength data currently under testing (Section 2.2.3) will be reported in a follow-up study and will significantly extend the findings presented here. The 90-day results will clarify the long-term pozzolanic strength development of both selected mixes, while the triplet shear data will provide shear bond strength and friction coefficient values essential for in-plane masonry analysis and heritage structural assessment. Future research should also determine the elastic modulus of the brick units used to enable fuller analytical modeling of prism failure mechanisms. Durability studies, including water absorption, sorptivity, and freeze-thaw resistance, are recommended for assessing field performance. Microstructural investigations using SEM and XRD would help clarify the pozzolanic reaction products and their evolution with curing. A larger sample of brick specimens (minimum 5–10 cubes per brick type) would reduce the uncertainty in the brick compressive strength value. Studies using surkhi sourced from different regions of Nepal would provide broader data for national standardization. Finally, the development of a standard test protocol for lime-surkhi mortars adapted to Nepalese conditions would support consistent quality control in heritage conservation practice.

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