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# Mechanical Performance of Mortar with Partial Replacement of Cement by Laterite Stone Powder

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**Abstract**

**Background:** Cement is a key component in mortar production due to its calcium-rich composition, which plays an essential role in pozzolanic reactions. However, the extensive use of cement contributes to high carbon emissions and limestone exploitation. The incorporation of laterite stone powder as a partial cement replacement offers a potential alternative to enhance mortar performance while promoting sustainable construction practices.
**Aims:** This study aims to evaluate the effect of laterite stone powder as a partial substitute for cement on the compressive strength and density of mortar.
**Methods:** A quantitative experimental approach was employed through laboratory testing. Laterite stone powder passing a 200-mesh sieve was used as a partial cement replacement at substitution levels ranging from 0% to 10% by weight of cement. The mortar mixture was prepared with a cement-to-sand ratio of 1:3 and a water–cement ratio of 0.5. Compressive strength and density tests were conducted on 50 mm × 50 mm × 50 mm cube specimens at curing ages of 7, 14, 21, and 28 days.
**Result:** The results showed that the highest compressive strength, reaching 20.33 MPa, was obtained at a 3% laterite stone powder substitution after 28 days of curing. Substitution levels exceeding 3% resulted in a gradual decrease in compressive strength, indicating a reduction in mortar performance at higher replacement ratios.
**Conclusion:** The study concludes that laterite stone powder can be effectively utilized as a partial cement replacement in mortar at an optimum level of 3%. This substitution not only improves compressive strength but also contributes to sustainable construction by reducing cement consumption and minimizing limestone exploitation in Indonesia.

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## INTRODUCTION

Development in Indonesia in the field of construction and infrastructure continues to increase, in line with the growing demand for construction materials and infrastructure, which consequently raises the need for raw materials (Zuraidah & Hastono, 2018; Soemardi & Pribadi, 2018). Numerous studies have therefore been conducted to develop construction materials with improved quality and performance (Setyahati, 2020). One of the most widely used materials in construction is mortar, which consists of cement, sand, and water mixed in specific proportions (Sujatmiko, 2014; Sakir et al., 2020). The mixing of materials in mortar follows defined ratio standards that significantly influence its mechanical properties (Wesli et al., 2021; Popov, 2018). It is well established that the strength and durability of mortar can be enhanced through the incorporation of supplementary materials or fine particles, including nanoparticle-sized additives (Salah et al., 2023). Cement primarily derives its binding capability from calcium compounds originating from limestone and similar sources (Supit et al., 2019).

Along with technological advancement, numerous innovations have emerged in mortar formulation through the addition of alternative materials (Yue et al., 2020; Modolo et al., 2013). These materials commonly include adhesive components and fine aggregates intended to modify the physical and mechanical behavior of mortar (Rahman et al., 2020). One potential alternative adhesive material is *laterite stone*, which can be incorporated in certain proportions. *Laterite stone* contains chemical compounds such as $CaCO_3$, MgO, $Al_2O_3$, and $SiO_2$, which are relevant to cementitious reactions (Sembiring et al., 2021). The incorporation of *laterite stone* aims to increase the calcium content required for *pozzolanic* reactions when interacting with $SiO_2$ present in the material (Martadiastuti et al., 2023; Lawane, 2011).

Supporting evidence for this approach can be found in studies examining the effect of fiber volume fractions on compressive strength and impact resistance in construction materials (Kim et al., 2023). These studies demonstrated that increasing fiber volume fractions resulted in improved bending stress and impact resistance (Yamaguchi et al., 2008). Similarly, comparative studies on the use of wood ash and fly ash as partial cement replacements in paving blocks revealed that such additions can significantly enhance compressive strength (Adib et al., 2023).

Based on these findings, it is assumed that the addition of *laterite stone* to mortar may enhance its compressive strength, comparable to improvements observed when construction waste materials are incorporated into cementitious systems (Nurdin et al., 2019). Previous research has shown that building waste can increase the shear strength of bentonite, suggesting similar performance gains may occur in mortar systems (Nurdin et al., 2019). Consequently, substituting cement with *laterite stone* presents potential for improving compressive performance, although further experimental investigation is required to validate this hypothesis and determine the precise influence of *laterite stone* content (Chen et al., 2021). This study specifically examines the effect of *laterite stone* as a cement substitute on the compressive strength of mortar used in construction materials (Budihardjo, 2018). While earlier studies on fiber volume fractions did not directly address the role of *laterite stone* (Kim et al., 2023), this research seeks to determine whether such substitution can improve mortar strength, with the expectation that *laterite stone* addition will result in higher compressive strength.

The construction industry has also shown increasing interest in sustainable materials to mitigate environmental impacts, particularly those associated with cement production, which is a major contributor to $CO_2$ emissions. Previous studies have investigated alternative materials such as fly ash, silica fume, and recycled aggregates as partial cement replacements in mortar and concrete (Yue et al., 2020; Salah et al., 2023). For example, Chen et al. (2021) demonstrated that oyster shell ash improved mortar strength, while Adib et al. (2023) examined the effects of wood ash and fly ash in paving block applications. Despite these advances, limited research has focused on *laterite stone powder*, a naturally abundant material in tropical regions, as a cement substitute, even though its high calcium content may promote *pozzolanic* reactions (Martadiastuti et al., 2023).

A clear research gap remains in identifying the optimal proportion of *laterite stone powder* required to maximize mortar compressive strength. While studies by Supit et al. (2019) explored tailings in cement composites and Sembiring et al. (2021) examined volcanic ash in ceramics, no systematic evaluation has been conducted on *laterite stone* substitution in mortar across varying replacement levels (1–10%). Moreover, the interaction between the chemical composition of *laterite stone* (e.g., $CaCO_3$ and $SiO_2$) and curing duration has received limited attention, leaving uncertainties regarding long-term performance and durability. This study addresses these gaps by experimentally evaluating *laterite stone powder* at incremental substitution levels and curing periods of 7–28 days.

The novelty of this research lies in its comprehensive assessment of *laterite stone powder* as a partial cement replacement, identifying an optimum substitution level of 3%, which yields the highest compressive strength of 20.33 MPa at 28 days—representing a 19.58% improvement compared with conventional mortar. By confirming the effectiveness of *laterite stone*, this study offers dual benefits of reducing cement consumption and limestone exploitation while enhancing mortar performance. The findings support global sustainability objectives and provide practical insights for construction practices in *laterite-rich* regions.

Therefore, the objective of this study is to experimentally evaluate the mechanical performance of mortar incorporating *laterite stone powder* as a partial replacement for cement by determining the optimum substitution percentage that maximizes compressive strength while supporting sustainable construction practices.

## METHOD

The research method used is the quantitative experiment method. With primary data collection. The primary data used in this study are data taken from research in the laboratory, namely: *Fineness modulus* SNI 03-1750-1990; *Bulk specific graphvity, Bulk specific graphvity (SSD), Apparent specific gravity, Absorption* SK SNI T-15-1990-03; Moisture content SK SNI 15-1990-30; Mud and clay content of SK SNI S-04-1989-F; Organic matter content SNI 03-2816-1992; water testing SNI 7974: 2013. The research conducted was cement substitution using latitude stone powder that passed the 200 sieve, in a mortar mixture with percentage variations of 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7%, 8%, 9% and 10%. The proportion of mortar mixture in this study uses a 1:3 (Cement: Sand) with a cement water factor (FAS) of 0.5. This study was carried out using a compressive strength tool on a cube-shaped test piece (mortar) measuring 5cm x 5cm x 5cm at the time (age) of 7, 14, 21 and 28 days. The test results are continued to the data processing and data analysis stages using the Compressive Strength Analysis and Contents Weight Analysis methods to obtain optimal results.

### Material Testing

Parameters that can be done to determine the testing of fine aggregate materials are;
Some of the stages that are tested are;

1. Screening analysis testing
   Determine the grain size and aggregate gradation from fine for concrete mix design purposes as well as its fineness level expressed in fineness modulus. SNI 03-1750-1990.
2. Specific gravity and water absorption testing
   To get the figures in dry base specific gravity, SSD dry specific gravity, pseudospecific gravity and water absorption on fine aggregates. Decree SNI T-15-1990-03.
3. Sludge content testing
   This test is carried out by minimizing the mud content contained in the fine aggregate obtained high compressive strength. Decree SNI S-04-1989-F.
4. Organic matter content testing
   Knowing the content of organic matter contained in fine aggregates that will be used as a mixture of mortar or concrete. SNI 03-2816-1992.
5. Water Testing
   Water testing is carried out to determine the alkalinity value contained in the sample. SNI 7974:2013.

### Test piece testing

The test piece test is used to obtain the estimated value of the compressive strength of the mortar on the existing structure, by applying pressure to the mortar sample of the structure that has been implemented.

1. Compressive strength test of mortar

The compressive strength of concrete and mortar is the maximum force per unit area acting on concrete and mortar test pieces. The compressive strength test of mortar is carried out based on SNI 03-6825-2002 (BSN 2002b).

$$f'c = \frac{P}{A}$$

Information:
f'c = Compressive strength (MPa)
P = Maximum test load (crush) indicated by compressive strength test (N)
A = Cross-sectional area of the test piece (mm2)

2. Mortar fill weight
The weight of the content is the ratio of the mass of the object to the volume of the object.

$$?m = \frac{Bm}{V}$$

Information:
$?m$ = Filling weight (g/cm3)
$Bm$ = Weight of the test piece (g)
$V$ = Specimen volume (cm3)

**Data analysis and processing techniques**

The data that has been obtained will then be analyzed using the theory that has been determined in the study to simplify the steps to prepare research in the form of a methodology that aims to direct and optimize the time and results to be achieved.

1. Compressive strength analysis

Compare the results of mortar compressive strength data on each type of substitution mixture through graphs so that the results of each planned age can be known. From the analysis, it can be known that the characteristics of the mortar in each percentage are influenced by the properties of the cement mixture.

2. Analysis of the weight of mortar contents

Compare the results of the mortar content weight data on each type of substitution mixture through a graph so that the results of each plan age can be known. From the analysis, it can be known that the characteristics of the mortar in each percentage are influenced by the properties of the cement substitution.

## RESULTS AND DISCUSSION

### Result

### Fine aggregate test results

From the results of the fine aggregate test, the results in table 1 are obtained. In the test, a qualified standard value was obtained.

**Table 1.** Fine Aggregate Testing Indicators

| Description | Value | Standard Requirements | Information |
|---|---|---|---|
| Fineness Modulus | 3,578 | SNI 03-1750-1990 | Filled |
| Bulk Specific Gravity | 2,526 | SK SNI T-15-1990-03 | Filled |
| Bulk Specific Gravity (SSD) | 2,631 | SK SNI T-15-1990-03 | Filled |
| Apparent Specific Gravity | 2,666 | SK SNI T-15-1990-03 | Filled |
| Absorption (%) | 0,020 | SK SNI T-15-1990-03 | Filled |
| Water Content *(%)* | 5,820 | SK SNI 15-1990-30 | Filled |
| Sludge Content *(%)* | 2,320 | SK SNI S-04-1989-F | Filled |
| Organic matter content | No. 1 | SNI 03-2816-1992 | Filled |

Source: Processed data (2025)

Table 1 presents comprehensive quality parameters of fine aggregate used in the mortar mixture, encompassing physical and chemical characteristics essential for ensuring material compliance with Indonesian national standards. The results demonstrate that all eight tested parameters including fineness modulus, specific gravity variations (bulk, SSD, and apparent), absorption capacity, moisture content, sludge content, and organic matter meet the specified threshold values established standards. This comprehensive characterization provides baseline material quality assurance, confirming the suitability of the fine aggregate for controlled experimental conditions in subsequent mortar mixture preparations.

**Water Test Results**

From the results of the water indicator test, the results are in the table. In the test, a qualified standard value was obtained.

**Table 2.** Water Testing Indicators

| Description | Value | Standard Requirements | Information |
|---|---|---|---|
| Water Condition | Clear | SNI 7974:2013 | Filled |
| Water Taste | Insipid | SNI 7974:2013 | Filled |
| Smell Water | Odorless | SNI 7974:2013 | Filled |
| Water Ph | 4,5 - 8,5 | SNI 7974:2013 | Filled |

Source: Processed data (2025)

Table 2 documents the qualitative assessment of water used in mortar preparation, evaluating four critical parameters that influence cement hydration and mortar performance. The testing protocol follows SNI 7974:2013 standards, examining physical characteristics (clarity, taste, odor) and chemical properties (pH range). All parameters satisfy the specified requirements, with pH values falling within the acceptable range of 4.5-8.5, indicating that the water quality will not adversely affect the chemical reactions during cement hydration or introduce contaminants that could compromise the durability and mechanical properties of the hardened mortar specimens.

**Mix Design Mortar**

Mix design is carried out to determine the proportion of each mixture of materials that make up the mortar. In this study, 11 variations of mixtures with a size of 5x5x5 cm were made where the mixture referred to the normal mortar mix design. The proportion of mortar mixture in this study uses a ratio of 1:3 between cement and sand with a cement water factor of 0.5. This value becomes a constant value because it wants to know the change in the characteristics of the mortar only from the influence of cement substitution.

**Table 3.** Mix Design

| NO | Mixed Variations | ***Mix Design Mortar 5x5x5 cm*** | | | |
|---|---|---|---|---|---|
| | | **Cement** | **Sand** | **Water** | **Stone Latitude** |
| | | **(gram)** | **(gram)** | **(gram)** | **(gram)** |
| 1 | Normal Mortar | 820 | 2945 | 401 | 0 |
| 2 | Mortar 1% Stone Lattice | 811,8 | 2945 | 401 | 8,2 |
| 3 | Mortar 2% Stone Lattice | 803,6 | 2945 | 401 | 16,4 |
| 4 | Mortar 3% Stone Lattice | 795,4 | 2945 | 401 | 24,6 |
| 5 | Mortar 4% Stone Lattice | 787,2 | 2945 | 401 | 32,8 |
| 6 | Mortar 5% Stone Lattice | 779,0 | 2945 | 401 | 41,0 |
| 7 | Mortar 6% Stone Lattice | 770,8 | 2945 | 401 | 49,2 |
| 8 | Mortar 7% Stone Lattice | 762,6 | 2945 | 401 | 57,4 |
| 9 | Mortar 8% Stone Lattice | 754,4 | 2945 | 401 | 65,6 |
| 10 | Mortar 9% Stone Lattice | 746,2 | 2945 | 401 | 73,8 |
| 11 | Mortar 10% Stone Lattice | 738,0 | 2945 | 401 | 82,0 |
| | Amount | 8569 | 32395 | 4411 | 451,0 |

Source: Processed data (2025)

Table 3 systematically presents the precise proportioning of constituent materials across eleven experimental mortar variations, maintaining a constant cement-to-sand ratio of 1:3 and water-cement factor of 0.5 while incrementally varying the laterite stone substitution from 0% (control) to 10% in 1% increments. The tabulation specifies exact material quantities in grams for each 5×5×5 cm specimen, with cement content progressively decreasing from 820 grams in the control mix to 738 grams at 10% substitution, while laterite stone correspondingly increases from 0 to 82 grams. This systematic gradation enables isolation of the laterite stone variable's influence on mortar characteristics, while the cumulative material quantities (bottom row) facilitate quality control and reproducibility verification for the experimental program.

**Mortar Contents Weight Test Results**

The average weight of the contents in normal mortar was 2.32 g/cm3 at 7 days of age; 2.42 g/cm3 at 14 days of age; 2.32 g/cm3 at 21 days of age; and 2.48 g/cm3 at 28 days of age, this value is an initial reference for other average weight comparisons. The average fill weight of the various variations of the mixture can be seen in Table 4.

**Table 4.** Recapitulation of Contents Weight

| No. | Mixed Variations | Contents Weight (gram) | | | |
|---|---|---|---|---|---|
| | | 7 Days | 14 Days | 21 Days | 28 Days |
| 1 | Normal Mortar | 2,32 | 2,42 | 2,32 | 2,48 |
| 2 | Mortar 1% Stone Lattice | 2,16 | 2,30 | 2,24 | 2,26 |
| 3 | Mortar 2% Stone Lattice | 2,37 | 2,43 | 2,39 | 2,53 |
| 4 | Mortar 3% Stone Lattice | 2,41 | 2,41 | 2,37 | 2,4 |
| 5 | Mortar 4% Stone Lattice | 2,30 | 2,13 | 2,35 | 2,15 |
| 6 | Mortar 5% Stone Lattice | 2,30 | 2,31 | 2,34 | 2,28 |
| 7 | Mortar 6% Stone Lattice | 2,27 | 2,23 | 2,29 | 2,33 |
| 8 | Mortar 7% Stone Lattice | 2,22 | 2,23 | 2,27 | 2,3 |
| 9 | Mortar 8% Stone Lattice | 2,14 | 2,12 | 2,24 | 2,2 |
| 10 | Mortar 9% Stone Lattice | 2,14 | 2,15 | 2,16 | 2,1 |
| 11 | Mortar 10% Stone Lattice | 2,28 | 2,28 | 2,28 | 2,28 |

Source: Processed data (2025)

Table 4 compiles density measurements across all mixture variations at four curing ages (7, 14, 21, and 28 days), revealing temporal and compositional patterns in mortar densification. The control mortar exhibits density values ranging from 2.32 to 2.48 g/cm$^3$ across the curing period, establishing a reference baseline for comparative evaluation. Notably, the data demonstrates considerable variability among laterite-substituted specimens, with values spanning from 2.10 g/cm$^3$ (9% substitution at 28 days) to 2.53 g/cm$^3$ (2% substitution at 28 days), suggesting that density changes are influenced by complex interactions between substitution level, curing duration, and specimen preparation variables rather than exhibiting a simple linear relationship with laterite content.

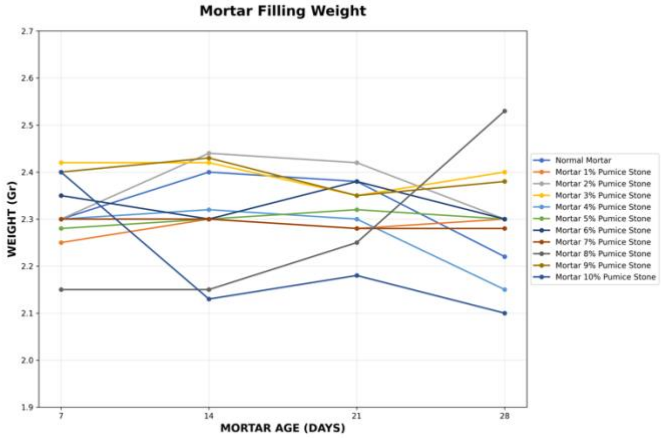


**Figure 1.** Contents Weight Chart
Source: Processed data (2025)

Figure 1 graphically illustrates the density evolution patterns across the experimental matrix, plotting content weight values against curing age for all eleven mixture variations. The visualization employs distinct line markers for each substitution percentage, enabling simultaneous comparison of temporal trends and compositional effects. The chart reveals that density trajectories do not follow consistent monotonic patterns, with various mixtures exhibiting fluctuations across curing ages.

The weight value of the content obtained at each addition of latitude stones did not get significant results. This is because latitude stone as a partial substitution of cement is used with a small amount and latitude stone has a specific gravity that is almost equal to the weight of cement. The compaction process on the test piece certainly has a role in the test weight results, less perfect compaction will result in the mortar having pores that affect the weight of the mortar content.

**Mortar Compressive Strength Test Results**

The compressive strength test of the mortar is carried out after the test piece is 7, 14, 21 and 28 days old after passing through the *curing* process. The average compressive strength of normal mortar without latitude stone substitution (0% latitude stone) at the age of 7, 14, 21, and 28 days was 8.66 MPa; 13.66 MPa; 16.00 MPa; and 17.00 MPa where the value is compared with the average compressive strength value of mortar of various mixtures and day life. The average compressive strength value of mortar of various mixtures can be seen in Table 5.

**Table 5.** Recapitulation of Compressive Strength

| No. | Mixed Variations | Average Compressive Strength (Mpa) | | | |
|---|---|---|---|---|---|
| | | **7 Days** | **14 Days** | **21 Days** | **28 Days** |
| 1 | Normal Mortar | 8,66 | 13,66 | 16,00 | 17,00 |
| 2 | Mortar 1% Stone Lattice | 8,00 | 14,33 | 16,33 | 17,33 |
| 3 | Mortar 2% Stone Lattice | 8,50 | 14,66 | 16,46 | 17,50 |
| 4 | Mortar 3% Stone Lattice | 10,66 | 15,00 | 17,33 | 20,33 |
| 5 | Mortar 4% Stone Lattice | 9,93 | 13,66 | 16,33 | 17,00 |
| 6 | Mortar 5% Stone Lattice | 8,66 | 13,33 | 16,66 | 17,00 |
| 7 | Mortar 6% Stone Lattice | 7,66 | 12,66 | 15,00 | 16,33 |
| 8 | Mortar 7% Stone Lattice | 6,53 | 12,33 | 14,66 | 16,00 |
| 9 | Mortar 8% Stone Lattice | 6,50 | 12,00 | 13,00 | 15,00 |
| 10 | Mortar 9% Stone Lattice | 6,33 | 12,00 | 12,66 | 13,66 |
| 11 | Mortar 10% Stone Lattice | 6,00 | 9,33 | 11,33 | 13,00 |

Source: Processed data (2025)

Table 5 consolidates the mechanical performance data, documenting compressive strength development across all experimental conditions from early-age (7 days) to mature-age (28 days) curing periods. The control mortar demonstrates progressive strength gain from 8.66 MPa to 17.00 MPa over 28 days, following typical cement hydration kinetics. The data reveals that 3% laterite substitution achieves the highest 28-day strength (20.33 MPa), representing a 19.6% improvement over the control, while substitution levels exceeding 5% exhibit progressively diminishing performance, with 10% substitution yielding only 13.00 MPa (23.5% reduction). This tabulated strength progression enables identification of the optimal substitution threshold and quantifies the mechanical consequences of varying replacement ratios across the entire experimental range.

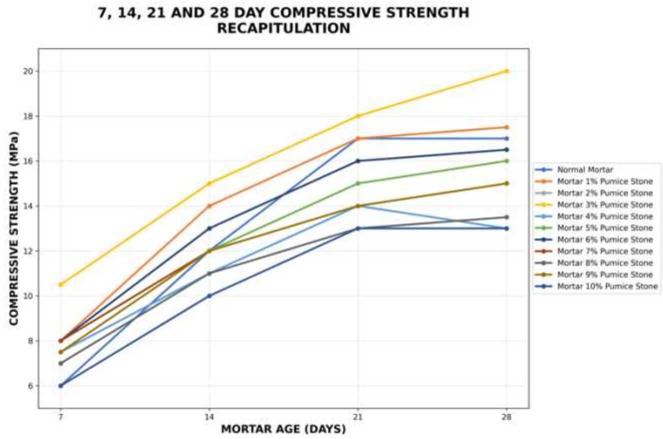


**Figure 2.** Compressive Strength Chart
Source: Processed data (2025)

Figure 2 shows that the compressive strength value of the mortar obtained is greatly influenced by the percentage of latitude stone used as a cement substitution material. The use of too much latitude stone percentage results in the compressive strength value of the mortar produced is not very significant.

**Discussion**

The enhancement in mechanical performance observed at low replacement ratios can be explained by the pozzolanic reaction mechanism. The silica-rich composition of laterite stone powder reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H), which is the primary contributor to strength in cementitious systems. This secondary C–S–H formation improves particle packing and strengthens the interfacial transition zone (ITZ), thereby increasing load transfer efficiency within the mortar matrix. Similar microstructural improvements have been widely reported for other mineral-based supplementary materials, such as fly ash, biomass ash, and oyster shell ash, where controlled substitution enhances compressive performance (Modolo et al., 2013; Sakir et al., 2020; Chen et al., 2021).

Excessive reduction of cement content limits the availability of calcium hydroxide required for sustained hydration and pozzolanic reactions, resulting in a less cohesive binder matrix. As a consequence, the formation of strength-contributing hydration products becomes insufficient to compensate for the reduced cement content. This behavior aligns with the findings of Yue et al. (2020), who reported that excessive incorporation of supplementary materials may compromise mechanical properties despite their environmental advantages.

The relatively stable density across different substitution levels indicates that variations in mechanical performance are not primarily influenced by mass or volumetric changes, but rather by internal microstructural development. This suggests that laterite stone powder has a physical compatibility with cement in terms of particle density, allowing it to be integrated into mortar without adversely affecting bulk properties. Similar observations were reported by Popov (2018), who emphasized that particle interaction and mixing homogeneity play a more decisive role in strength development than density alone.

From a practical standpoint, the results underscore the importance of dosage control when incorporating laterite stone powder into mortar. The identification of an optimal substitution threshold provides actionable guidance for practitioners, enabling the reduction of cement consumption without compromising performance. This is particularly relevant for developing regions where laterite stone is readily available and construction demand continues to rise. The findings contribute to both the scientific understanding and practical implementation of sustainable mortar design, bridging the gap between material innovation and real-world construction practices.

## CONCLUSION

The utilization of laterite stone powder represents a technological innovation in construction materials, particularly as a partial replacement for cement in mortar. In this study, the cement–sand ratio and water–cement ratio was kept constant to ensure that changes in mechanical properties were solely attributed to variations in laterite stone content. This approach allowed for a clear evaluation of the influence of laterite stone powder on mortar performance. The experimental results demonstrated that the highest compressive strength was achieved at 28 days with a 3% laterite stone substitution, reaching 20.33 MPa. This value represents an increase of 3.33 MPa, or approximately 19.58%, compared with conventional mortar, which exhibited a compressive strength of 17.00 MPa. However, substitution levels exceeding 3% resulted in a reduction in compressive strength, indicating that excessive laterite stone content adversely affects the binding efficiency and hydration process of the mortar constituents.

Based on these findings, the optimal proportion of laterite stone powder as a cement substitute is identified as 3% by volume of cement. The application of laterite stone at this level offers a viable solution for reducing cement consumption while simultaneously minimizing limestone exploitation associated with cement production in Indonesia. Further research is recommended to investigate the influence of different cement types or brands on mortar performance when combined with laterite stone powder. Such studies would provide deeper insight into material compatibility and help determine whether variations in cement characteristics produce different mechanical responses in mortar with identical mix proportions.

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## AUTHOR CONTRIBUTION STATEMENT

MHFG was responsible for the conceptualization and design of the study, conducted the experimental work, collected the data, and prepared the original draft of the manuscript. BA contributed to data analysis, interpretation of the experimental results, and critically revised the manuscript for important intellectual content. AP assisted in laboratory testing, specimen preparation, data validation, and contributed to the methodological framework of the study. TR contributed to the literature review, data interpretation, and manuscript editing and formatting. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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