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Consistency of Compressive Strength in Concrete with 10% Rice Husk Ash Substitution

S. A. Pasya[1], Z. B. Mahardana[2], I. Mustofa[3], A. I. Candra[4*]

[1,2,3,4*]*Civil Engineering Departement, Faculty of Engineering, Kadiri University, Kediri, Indonesia.*

Email: [1]salman.apasya@gmail.com, [2]zmahardana@unik-kediri.ac.id, [3]imammustofa@unik-kediri.ac.id, [4*]iwan_candra@unik-kediri.ac.id.

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A B S T R A C T

Using rice husk ash (RHA) in concrete technology represents a significant innovation in promoting sustainability. The pozzolanic properties of RHA enhance concrete quality through microstructural refinement while mitigating environmental impacts. However, replacing 10% of cement with RHA has inconsistent effects on compressive strength. Such variability may limit the broader application of RHA in structural concrete due to uncertainties in performance prediction, quality assurance, and design safety. While some studies report strength improvements, others note reductions often attributed to limited samples size, material inconsistencies, and variations in mixing or curing processes. This study aims to statistically validate the consistency of compressive strength in concrete with 10% RHA substitution by increasing the sample size and controlling key variables. Nine specimens per test condition were evaluated using a water-cement ratio of 0.53, submersion curing and ASTM C39 testing standards. Compressive strength assessment was conducted at 7 days. The result show a 7.54% increase in compressive strength, from 22.71 MPa to 24.42 MPa, with a coefficient of variation (CV) of 2.26%, well below the 10% threshold. In contrast, earlier studies with smaller sample sizes reported CVs as high as 42.65%, indicating greater statistical variability. This improvement is attributed to the increased sample size, material quality control, and uniform mixing, which ensured homogeneous RHA distribution and optimized pozzolanic reactions. By applying a controlled-variable approach and increasing the sample size, this study addresses prior inconsistencies and reinforces the validity of RHA as a viable cement substitute in concrete.

1. Introduction

Cement manufacturing is responsible for approximately 8–10% of global CO_2 emissions annually [1], with each ton of cement producing nearly one ton of CO_2. These emissions primarily result from limestone decomposition and fossil fuel combustion,

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highlighting the urgent need for more sustainable alternative materials [2], [3]. Global cement consumption reached 4.1 billion tons in 2020 [4] and is projected to rise by 23% by 2050 due to increasing infrastructure demands [5]. The increasing emissions from the construction industry exacerbate the climate crisis, leading to global warming and excessive resource exploitation [6]. Implementing sustainable solutions, such as pozzolanic and recycled materials, can reduce CO_2 emissions by up to 40% and lower energy consumption by 30% [7].

Rice husk ash (RHA) holds significant potential as a supplementary material for partial cement replacement in concrete applications [8]. Approximately 20 million tons of RHA are generated yearly, often contributing to environmental pollution due to uncontrolled open-field burning [9], [10]. This ash predominantly comprises amorphous silica, which actively reacts pozzolanically with calcium hydroxide in cementitious systems [11]. Due to this property, RHA can substitute 5–20% of cement, leading to a compressive strength improvement of up to 18.7%, enhancing microstructural refinement, and lowering porosity by promoting the development of calcium silicate hydrate (C-S-H) gel [12], [13]. A 10% cement replacement with RHA reduces CO_2 emissions by 8%, energy consumption by 11%, and methane emissions through controlled incineration [14]. Economically, it lowers costs by up to 12.5%, with a 20% replacement saving USD 74.6 per 10 m^3 and a 30% replacement reducing costs by USD 112. These results establish RHA as a sustainable, cost-effective alternative for eco-friendly concrete production [15].

The 10% RHA replacement level has been identified as optimal for enhancing concrete compressive strength before adverse effects occur at higher proportions. Bhowmik & Pal (2023) reported an 8% strength gain, from 29.3 MPa to 32 MPa [16], while Al-Alwan et al. (2024) recorded a 10% increase, from 29.3 MPa to 32.57 MPa [17]. However, despite these reported improvements, some studies have demonstrated inconsistencies in compressive strength results when incorporating 10% RHA. Zhao et al. [18] documented a strength enhancement of 2.81%, whereas Avudaiappan et al. [19] observed an improvement reaching 7.75%. Conversely, several studies have reported declines in compressive strength by 7.81% [20], 22.33% [21], and 26.81% [22]. These variations are likely attributed to differences in sample quantity, material properties, and disparities in mixing and curing procedures [23], [24], [25].

Most previous studies relied on only 2–3 samples per variable, increasing result variability [26], [27]. For example, Zhao et al. used only two samples per variable, while Avudaiappan et al. and Al-Alwan et al. used three samples. This limited sample size may have contributed to the observed inconsistencies. Additionally, many studies focused solely on

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average strength values without assessing consistency using statistical methods such as the coefficient of variation (CV), essential for evaluating data reliability [28]. These limitations indicate that factors like sample size, unaddressed material variability, and the absence of rigorous statistical evaluation have hindered the reliability and generalizability of previous findings.

There remains a need for research that explicitly integrates controlled-variable methods and comprehensive statistical analyses to validate the consistency and predictability of RHA-concrete performance under standardized conditions. This study aims to evaluate the consistency of compressive strength results through statistical validation, emphasizing the role of sample size and controlled testing conditions in minimizing variability. International standards, such as ASTM C39/C39M, recommend an adequate sample size for statistical analysis, while SNI 1974:2011 requires a minimum of two samples, and ACI 318, 2019 sets five as the lower threshold. Based on these standards, this study employs nine samples per variable, not only exceeding these benchmarks but also tripling the average used in previous studies to enhance data accuracy and consistency. This approach aims to ensure more stable results and minimize variability [29]. Practically, the consistency of RHA's effect on compressive strength is crucial to ensure its reliability and sustainability as a cement substitute. Consistent results will reduce variability in concrete performance, providing a stable and efficient alternative, and supporting its widespread application in sustainable construction.

2. Research Method

This research utilizes a controlled laboratory experiment to investigate the influence of replacing 10% cement with RHA on concrete's compressive strength. A statistical analysis evaluates data consistency, utilizing nine samples per variable to improve result reliability [30]. The samples were prepared in three separate mixing processes, each producing three specimens, ensuring uniform material distribution. Controlled variables were consistently maintained to enhance data stability, including water-cement ratio (0.53), curing method, material quality, and mixing duration. The assessment of compressive strength is performed at an early curing stage of 7 days, following ASTM C39/C39M, to assess early-age strength, a crucial factor in structural performance.

2.1 Population and Samples

This study uses nine concrete specimens per variable to ensure statistical reliability, exceeding the minimum standards set by ASTM C39/C39M [31], SNI 1974:2011 [32], and ACI 318 [33]. Each specimen was cylindrical with a diameter of 15 cm and a height of 30 cm. This

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sample size enhances accuracy and enables coefficient of variation (CV) analysis to assess data consistency.

2.2 Materials

The materials in this study were selected to meet construction standards and ensure concrete performance consistency. Each material was characterized based on its physical properties and suitability for concrete production, as detailed in **Table 1**.

Table 1. Material Properties

Material	Properties
Cement	Portland Composite Cement Type 1.
Fine Aggregate (Natural Sand)	Contains 0.83% fine dust (ASTM C40, max 5%). Classified as Zone 3 (IS:383-2016), ensuring optimal gradation.
Coarse Aggregate (Crushed Stone)	Crushed stone (20 mm max), 0.4% fine dust (ASTM C40, max 1%), 29.3% abrasion loss (ASTM C131, max 40%).
Water	Clean, suitable for concrete mixing, and compliant with SNI 03-6825-2002.
Rice Husk Ash (RHA)	Sourced from a supplier, processed at 450–650°C, and ground to a cement-like powder with >87.6% amorphous silica.

Source: Data Analysis (2025).

2.3 Mix Design

The concrete mix followed SNI 03-2834-2002, with one mix replacing 10% cement with RHA and another as the control. Material proportions are detailed below:

Table 2. Mix Design

Mix Type	Coarse Aggregate (Kg)	Fine Aggregate (Kg)	Cement (Kg)	RHA (Kg)	Water (Kg)
Normal	6.764	5.103	2.648	-	1.413
RHA 10%	6.764	5.103	2.383	0.265	1.413

Source: Data Analysis (2025).

The water-cement ratio (0.53) was maintained for both mixtures to ensure consistent workability, hydration, and strength development.

2.4 Instruments

The primary equipment utilized in this study includes a universal testing machine (UTM) to assess compressive strength, a precision balance for material measurement, and sieves for particle size analysis. Rice Husk Ash (RHA) is obtained through the combustion of rice husks at temperatures ranging from 450–650°C, aiming to produce amorphous silica with high reactivity. The process begins with cleaning and drying the husks, then combustion in a

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dual-chamber furnace using wood or charcoal as fuel. After combustion, the ash is slowly cooled to maintain the stability of its silica structure, then ground to achieve a particle size similar to cement [3]. Although the chemical composition of RHA in this study was not analyzed in the laboratory, literature indicates that optimally processed RHA typically contains more than 87,6% amorphous silica, which functions as a pozzolanic material [34], [35]. The processed RHA is then used as a partial replacement for cement in concrete, while a slump test is conducted to assess the workability of fresh concrete before hardening.

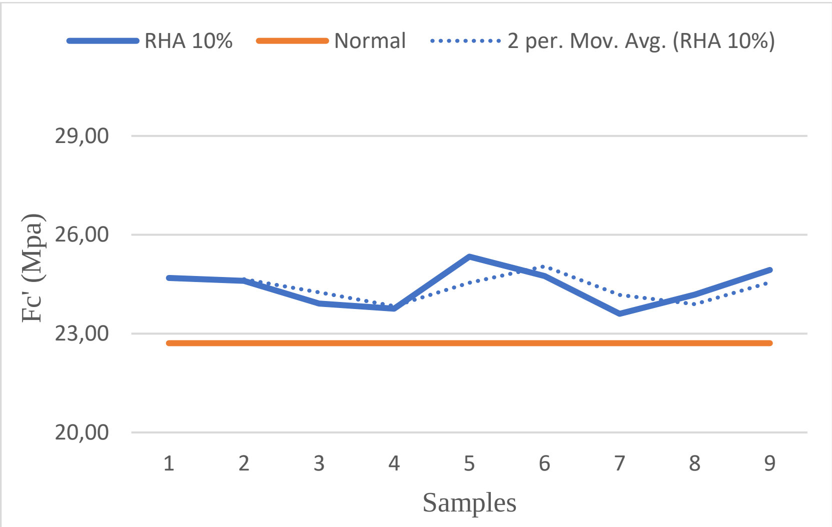
2.5 Methods of Data Collection and Analysis

All materials, including Ordinary Portland Cement [36], aggregates [37], and mixing water [38], undergo preliminary quality testing to ensure standard compliance. Concrete mixing follows a controlled process to maintain a uniform water-cement ratio (0.53), material proportions, and curing conditions. Data analysis involves descriptive statistics, including mean, standard deviation, and coefficient of variation (CV), to assess data consistency. The coefficient of variation (CV) is particularly used to measure relative dispersion, ensuring result reliability. Consistency assessment follows guidelines from ACI 214R-11, ASTM E691, and ISO 5725-2, which define acceptable variability in material testing.

3. Results and Discussions

3.1 Effect of 10% RHA on Strength and Stress-Strain Behavior

The substitution of 10% RHA increased the average compressive strength from 22.71 MPa to 24.42 MPa (**Figure 1**).



Source: Data Analysis (2025).

Figure 1. Comparison of Normal Compressive Strength With 10% RHA

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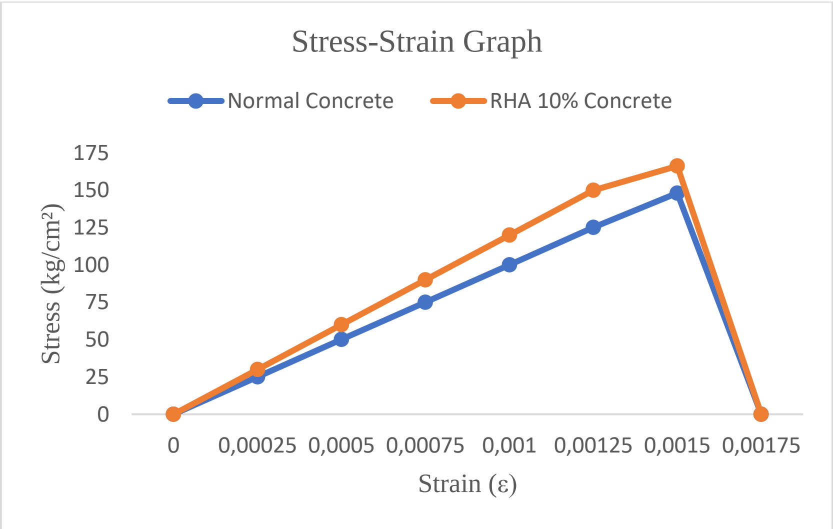
As reported in previous studies, the 7.54% improvement in compressive strength is strongly suspected to be related to the pozzolanic activity of amorphous silica in RHA. This silica is known to react with calcium hydroxide ($Ca(OH)_2$) to form calcium silicate hydrate (C-S-H) gel [39]. This C-S-H compound occupies micropores, enhances density, and reduces porosity [40]. These results are consistent with the studies of Zhao et al. (2022) and Avudaiappan et al. (2021), who reported compressive strength increases of 2.81% [18] and 7.75% [19], respectively, with RHA substitution.

However, some studies have shown varying results. Sahoo et al. (2021) reported a 7.81% decrease in compressive strength [20], while Zaid et al. (2021) and Morato et al. (2023) observed reductions of 22.33% and 26.81% [22], respectively. Zaid et al. (2021) found that RHA with 62.3% SiO_2 reduced strength by 22.33% [21], whereas Garrett et al. (2020) reported an 8.11% strength increase with RHA containing 94.3% SiO_2 [9]. Additionally, inadequate mixing disrupts the uniform distribution of calcium hydroxide and silica, leading to a heterogeneous microstructure and weak zones that compromise durability. In contrast, proper mixing enhances C-S-H formation, resulting in a denser and stronger microstructure [41], [42].

10% RHA substitution improves compressive strength and enhances deformation resistance before failure. Maximum stress in 10% RHA-substituted concrete increased to 166.16 kg/cm² from 148.07 kg/cm², while maximum strain rose to 0.00220. **Figure 2** illustrates the stress-strain relationship derived from the experimental results.



Source: Data Analysis (2025).

Figure 2. Stress-Strain Graph.

Higher maximum stress and strain values compared to control concrete indicate better deformation capability and material resistance to loads before damage [43]. The validity of

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these results is reinforced by prior studies conducted by Zhang et al. (2021) and Su & Xu (2024), which show that RHA substitution enhances deformation resistance through microstructural improvements in concrete [44], [45].

Quantitative analysis of the stress-strain curve (**Figure 2**) reinforces this conclusion. The RHA concrete shows a 12.22% increase in peak stress (from 148.07 to 166.16 kg/cm²) and a strain increase from 0.0015 to 0.00220, indicating higher load capacity and better deformation tolerance. Its less abrupt post-peak drop suggests greater ductility and a more controlled failure than normal concrete's brittle behavior. Additionally, the wider area under the curve reflects better energy absorption, essential for structures under dynamic or seismic loads.

The increase in maximum stress demonstrates that RHA incorporation enhances load-bearing capacity and ensures greater consistency in mechanical performance. This stability is attributed to a more refined and homogeneous microstructure, where the pozzolanic reaction of RHA promotes the formation of Calcium Silicate Hydrate (C-S-H) [46], effectively reducing porosity and enhancing stress distribution uniformity [47]. Consequently, the improved structural integrity minimizes variability in deformation behavior, leading to more predictable mechanical responses under applied loads. This correlation confirms that 10% RHA is an optimal proportion for enhancing stress-strain consistency, ensuring greater mechanical stability and reliability in concrete applications. These findings confirm that 10% RHA substitution is optimal. It enhances compressive strength, mechanical stability, consistent deformation, and structural resilience, making it ideal for sustainable and high-performance concrete.

3.2 Data Consistency

The coefficient of variation (CV) for concrete with 10% RHA substitution reflects the consistency of the test results, as detailed in **Table 3**.

Table 3. Descriptive Statistical Analysis.

Statistic	Value
Sample Size (n)	9
Mean	24,42 MPa
Median	24,60 MPa
Standard Deviation (SD)	0,56 MPa
Coefficient of Variation (CV)	2,26 %

Source: Data Analysis (2025).

A CV of 2.26% in this study demonstrates significantly higher result stability compared to previous studies, which reported a CV of 42.65%, indicating a high degree of variability relative to the mean [21], [22]. According to ACI 214R-11, a CV of ≤ 7% is

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considered very good, reflecting highly consistent concrete strength test results. Using nine samples significantly reduces variability, enhancing data stability and reliability [48], [49]. These findings confirm that a larger sample size produces more representative data, supporting more accurate concrete testing practices in the construction industry [26], [27].

The consistency of these findings can be attributed to strict control over key variables. The RHA used was produced via indirect combustion at 500–700 °C to ensure a high silica (SiO_2) content in amorphous form, avoiding crystallization above 800 °C that reduces pozzolanic reactivity [3], and was sieved using a #30 sieve (600 µm) to remove unburnt residues and coarse particles [50]. Controlled oxidation during slow cooling further preserved the amorphous structure. RHA was then ground to a particle size <45 µm, increasing surface area and enhancing C-S-H formation. For uniform distribution, RHA was dry-mixed with cement before water addition using high-shear mixing to prevent agglomeration and ensure homogeneity. These controls effectively minimized variability, resulting in stable compressive strength and reinforcing the importance of methodological precision in concrete research.

3.3 Comparison with Previous Research

Table 4 presents a comparative analysis of this study and prior research on 10% RHA substitution in concrete.

Table 4. Comparison of Previous Research Findings.

Author	Compressive Strength (MPa)	Percentage Increase (%)	Sample Size
Zhao et al. [18]	37,40 → 38,45	2,81	3
Avudaiappan et al. [19]	17,81 → 19,19	7,75	3
Sahoo et al. [20]	25,60 → 23,60	-7,81	3
Zaid et al. [21]	17,60 → 13,67	-22,33	2
Morato et al. [22]	24,06 → 17,61	-26,81	3
This Study	22,71 → 24,42	7,54	9

Source: Data Analysis (2025).

These results highlight those previous studies used a limited number of samples (2–3 per variable), which, as supported by the literature, may introduce greater variability and lower result stability. O'Neill [26] and Cong Vu [27] emphasize that small sample sizes increase variability and reduce precision, leading to less stable outcomes. In contrast, this study employs nine samples per variable, resulting in a coefficient of variation (CV) of 2.26%, significantly lower than the 42.65% CV observed in previous research. This finding aligns with statistical principles, confirming that a larger sample size enhances data consistency and reliability. By focusing on sample size as the primary variable, this study demonstrates that increasing the

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number of samples leads to improved result stability, reinforcing the importance of adequate sample sizes in concrete testing methodologies.

4. Conclusion

The study showed that using nine samples per variable significantly improved the consistency of compressive strength data in concrete with 10% RHA substitution. The coefficient of variation (CV) achieved in this study is 2.26%, substantially lower than the CV range of 25–45% observed in previous research, confirming improved data stability. The larger sample size reduces variability and increases result reliability, supporting more accurate concrete testing methodologies. To ensure such consistency, it is critical to control several key variables, including the quality and fineness of RHA, the water-cement ratio, uniform mixing procedures, curing method, and standard-compliant material selection. Strict control of these variables minimizes microstructural variability and enhances the uniformity of pozzolanic reactions, leading to more reliable results. Furthermore, compressive strength testing at 28, 56, and 90 days, durability evaluation under extreme conditions, performance validation at real-world project scale, and microstructure analysis using SEM or MIP are essential for obtaining a deeper understanding of concrete behavior with RHA substitution. The findings confirm that 10% RHA substitution enhances compressive strength and significantly improves data consistency, making it a reliable and sustainable cement substitute. Consistent results reduce variability in concrete performance, offering a stable and efficient alternative for construction, particularly in earthquake-prone or dynamically loaded environments where mechanical stability is crucial.

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