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Utilization of Rice Straw Ash Bio pozzolan as a Partial Replacement for Ordinary Portland Cement (OPC) in Mortar Production

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ABSTRACT

The increasing demand for environmentally friendly construction materials has encouraged the utilization of agricultural waste as alternative building materials. This study aims to evaluate the potential of rice straw ash as a bio pozzolan to partially replace Ordinary Portland Cement (OPC) in mortar production. The methodology includes slump flow and compressive strength tests with rice straw ash used at replacement levels of 0%, 10%, 20%, and 30% by weight of OPC. The results show that incorporating rice straw ash affects both workability and compressive strength of the mortar. The 10% replacement level yielded optimal performance, with a slight decrease in slump flow still within acceptable standards and an improvement in compressive strength compared to the control mix. However, higher replacement levels of 20% and 30% led to a significant reduction in compressive strength, likely due to the incomplete pozzolanic reaction at early curing stages. This study recommends the use of 10% rice straw ash as a partial substitute for OPC in environmentally friendly mortar applications and suggests further research to optimize ash calcination processes and curing conditions to enhance long-term performance.

1. INTRODUCTION

The demand for sustainable and environmentally friendly construction materials has become a global priority in response to climate change and the depletion of natural resources. The construction industry is one of the largest contributors to global carbon emissions, with Ordinary Portland Cement (OPC) production accounting for approximately 8% of total CO_2 emissions [1]. Therefore, significant efforts have been directed toward reducing the dependency on OPC, including through partial substitution with natural or waste-based materials that exhibit pozzolanic properties.

One such promising material is rice straw ash, derived from the agricultural waste of rice harvesting, which is abundant in agrarian countries like Indonesia. Rice straw is often burned indiscriminately, resulting in rice straw ash that remains underutilized despite its potential. This ash contains a high amount of amorphous silica, which qualifies it as a natural pozzolan suitable for cementitious applications [2]. Studies have shown that such materials can be used as partial cement replacements in both concrete and mortar, provided that they are processed under controlled conditions [3].

In addition to reducing waste and emissions, the incorporation of rice straw ash can also improve the mechanical and durability properties of mortar or concrete. Pozzolanic materials react with calcium hydroxide released during cement hydration to form additional calcium-silicate-hydrate (C–S–H) gel, which enhances the material's strength and longevity [4]. However, the efficiency of these reactions is influenced by the fineness, composition, and replacement level of the ash, as well as the curing conditions.

While research has extensively examined rice husk ash as a cement substitute, relatively few studies have focused on rice straw ash, which differs in chemical composition and physical characteristics [5]. Furthermore, most prior research has emphasized compressive strength alone, often neglecting fresh properties such as slump flow that are critical for workability in real-world applications [6].

The replacement percentage of pozzolanic material plays a crucial role in determining the final performance of mortar. Some studies report that replacement levels beyond 20% can lead to a substantial drop in compressive strength unless appropriate treatment and curing protocols are applied [7]. Hence, systematic experimental studies are required to investigate the influence of different rice straw ash replacement levels on both the fresh and hardened properties of mortar.

Tests such as slump flow are essential for evaluating the workability of mortar, which affects its placement, compaction, and surface finishing during construction [8]. On the other hand, compressive strength testing remains a primary benchmark to assess the structural viability of any modified cementitious material [9]. A combined analysis of both properties provides a holistic understanding of the material's performance.

The use of rice straw ash also aligns with the principles of the circular economy, where agricultural waste is repurposed as a valuable input in construction. This approach has been adopted globally as part of the effort to achieve sustainable development goals by transforming waste into resource-efficient materials [10]. With proper processing, rice straw ash can be promoted as a low-cost, eco-friendly material for local construction industries.

This study investigates the use of rice straw ash as a bio pozzolan for partial replacement of OPC in mortar, with replacement levels of 0%, 10%, 20%, and 30%. The performance of each mix is evaluated through slump flow and compressive strength tests to determine the most effective replacement level. The significance of this research lies in its contribution to sustainable construction practices by utilizing local agricultural waste. The novelty lies in its systematic evaluation of both workability and mechanical properties using rice straw ash, a material less explored compared to other ashes. The objective of this research is to determine the optimum proportion of rice straw ash as a partial OPC substitute based on comprehensive performance metrics.

2. MATERIALS AND METHOD

2.1 Ordinary Portland Cement (OPC)

The experimental work utilized Ordinary Portland Cement (OPC) supplied by a local Indonesian cement manufacturer. The physical characteristics and oxide composition of the cement employed in this study are presented in Table 1 and Table 2, respectively. Both the physical and chemical properties of the cement conform to the standards outlined in SNI 15-2049-2004 [11].

Table 1. Physical characteristics of OPC

No	Physical characteristics	SNI 15-2049-2004	OPC
1.	Air content of mortar (%)	12 max	11.7
2.	Fineness/Blaine meter (m^2/kg)	280 min	598
3.	Expansion, % (max)	0.8 max	-
4.	Compressive strength		
	a. 3 days (kg/cm^2)	125 min	289
	b. 7 days (kg/cm^2)	200 min	324
	c. 28 days (kg/cm^2)	280 min	476
5.	Time of setting (Vicat test) :		
	a. Initial set, minutes	45 min	148.7
	b.Final set, minutes	375 max	274
6.	False setting time (minutes)	50 min	-
7.	Heat of hydration 7 days, cal/g	-	77
8.	Normal consistency (%)	-	32.43
9.	Specific gravity	-	3.26

Table 2. Chemical characteristics of OPC

No.	Oxide	SNI 15-2049-2004	OPC
1	MgO (%)	6.0 max	1.22
2	SO_3 (%)	4.0 max	2.57
3	Loss of ignition (%)	5.0 max	2.79

The physical characteristics of the Ordinary Portland Cement (OPC) used in this research, as shown in Table 1, indicate its compliance with the SNI 15-2049-2004 standards. The fineness of OPC, measured at 598 m²/kg, significantly exceeds the minimum requirement of 280 m²/kg. High fineness is crucial because it enhances the rate of hydration and the early development of strength in mortar and concrete [9]. This increased surface area facilitates faster reactions with water, resulting in improved early compressive strength, which is evident from the values recorded—289 kg/cm² at 3 days and 476 kg/cm² at 28 days, both of which surpass standard minimum thresholds. These results affirm the quality and reactivity of the cement used in this study.

Regarding setting time, the initial setting time of 148.7 minutes and final setting time of 274 minutes fall within acceptable ranges for workability in construction practices, although the initial setting time is notably longer than the minimum required 45 minutes. This delay could be advantageous in hot climates, allowing more time for mixing and placement [13]. Moreover, the measured expansion value of 0% is well below the maximum allowable limit of 0.8%, ensuring dimensional stability of the hardened cement paste. Other indicators such as specific gravity (3.26) and normal consistency (32.43%) also align with values typical for high-quality OPC, suggesting reliable performance in structural applications [14].

The chemical composition of OPC, detailed in Table 2, further confirms its conformity with SNI standards. The oxide contents—MgO at 1.22%, SO_3 at 2.57%, and Loss on Ignition (LOI) at 2.79%—are all within permissible limits, indicating the material's chemical stability. Excessive MgO can cause unsoundness due to delayed hydration and expansion, while SO_3 must be controlled to avoid sulphate attack in concrete [15]. LOI reflects the amount of unburnt carbon or moisture and must be minimized to ensure long-term durability. The low values recorded suggest efficient manufacturing and minimal impurities.

Overall, the physical and chemical characteristics of OPC used in this study indicate that the cement is highly reactive, stable, and suitable for blending with pozzolanic materials such as rice straw ash. Previous studies have shown that using high-quality cement as a base improves the effectiveness of supplementary cementitious materials, enhancing both mechanical and durability properties of mortar [16]. Hence, this baseline quality ensures that the impact of rice straw ash in subsequent experimental phases can be accurately assessed without interference from inconsistent cement properties.

2.2 Rice Straw Ash (RSA)

Rice straw ash (RSA) used in this study was sourced locally from Gowa, South Sulawesi, Indonesia, where it was initially gathered from small open-field burning piles. To produce RSA under controlled conditions, the raw ash was subsequently incinerated in a tin-box furnace at temperatures ranging between 800°C and 900°C. After combustion, the resulting ash was finely ground using a ball mill to achieve a uniform particle size, with 100% of the material passing through a No. 50 sieve (0.3 mm), and 10% passing through the same sieve.

The physical examination of the ash revealed that the specific gravity of RSA was measured at 2.36. Water absorption tests for the fine aggregate indicated that the RSA exhibited a high absorption rate of 172.78%. Furthermore, sieve analysis showed that less than 10% of the RSA particles passed through sieve No. 100, with most particle diameters ranging from 0.00 mm to 0.15 mm. These findings are detailed in Table 3, while the properties of the fine aggregate are presented in Table 4.

Table 3. Physical characteristics of RSA

No.	Type of inspection	Result of inspection
1	Specific gravity	2.36
2	Water absorption	172.78%
3	Sieve analysis	100 % pass sieve no.200

Table 4. Physical characteristics of fine aggregate

No.	Type of inspection	Result of inspection
1	Water absorption, %	2.72
2	Bulk specific gravity	2.37
	Saturated surface dry specific gravity	2.43
	Apparent specific gravity	2.53
3	Sand equivalent	76.69

The physical properties of rice straw ash (RSA), as shown in Table 3, demonstrate that RSA has a relatively low specific gravity of 2.36 compared to that of ordinary Portland cement and natural aggregates. This low density indicates that RSA is a lightweight material, which can contribute to reducing the overall weight of mortar or concrete when used as a partial cement replacement [17]. Additionally, the high-water absorption capacity of 172.78% reflects its porous nature, which can significantly influence the water demand in mixtures [18]. Such high absorption suggests the necessity of mix design adjustments to prevent workability issues. Furthermore, the fact that 100% of RSA particles pass through sieve No. 200 shows that it possesses fine particle sizes, similar to other pozzolanic materials such as fly ash [9]. This fine texture enhances the surface area available for reaction with calcium hydroxide in cement, improving pozzolanic activity.

Fine aggregate properties, outlined in Table 4, indicate suitable characteristics for mortar production. The bulk specific gravity (2.37), saturated surface dry specific gravity (2.43), and apparent specific gravity (2.53) fall within the typical range for natural sands used in concrete [19]. These values demonstrate that the aggregate is dense and less porous compared to RSA, making it effective in maintaining the structural integrity of the composite material. The water absorption rate of 2.72% is within the acceptable limits, suggesting stable behavior when mixed with binders [20]. Additionally, the sand equivalent value of 76.69 denotes a high cleanliness level and low clay content, which supports better bonding and strength development in mortar [21].

The contrast between RSA and conventional fine aggregates in terms of water absorption is critical to mortar performance. While the fine aggregate shows low absorption (2.72%), RSA's high-water demand (172.78%) can significantly alter the water-to-binder ratio if not carefully controlled [22]. Excess water demand due to RSA may lead to higher porosity and lower strength, unless compensated through proper mix proportioning or use of water-reducing admixtures. Researchers have highlighted the importance of pre-saturating high-absorption pozzolans or incorporating them with supplementary cementitious materials to optimize performance [23]. Hence, while RSA contributes to sustainability, its incorporation requires thorough design consideration.

Overall, the physical assessment confirms RSA's viability as a pozzolanic material, given its fine particle size and compatibility with cement hydration reactions. However, its distinct characteristics, especially the high absorption rate, necessitate careful integration into concrete mixes. When used in conjunction with clean and stable fine aggregates, as shown in Table 4, RSA can be a promising partial cement replacement, reducing environmental impact without compromising mechanical performance. Further studies are encouraged to optimize mix design and evaluate long-term durability of RSA-modified mortar, especially in tropical climates where such biomass waste is abundant.

2.3 OPC-RSA Mixtures

The OPC-RSA mortar is composed of a mixture of cement, rice straw ash, and water. In this study, the control mix (A.1) consisted of 100% cement without any substitution, serving as the reference. The ratios of OPC to RSA used in the experimental mixes were as follows: 100%: 0% (code XX), 90%: 10% (code XY), 80%: 20% (code YY), and 70%: 30% (code XZ). Based on initial mixing trials, the appropriate mortar mix design was determined. The detailed composition of each mortar mixture is presented in Table 5. The amount of water used in each mix was carefully adjusted to achieve the optimum moisture content required for proper compaction of the OPC-RSA mortar.

Table 5. OPC-RSA mixtures (1 m^3)

Code	OPC: RSA	OPC (kg)	RSA (kg)	Sand (kg)	Water (l)
XX	100:0%	849256.900	0.000	2335456.476	411040.340
XY	90:10%	764331.210	84925.690		
YY	80:20%	679405.520	169851.380		
XZ	70:30%	594479.830	254777.070		

2.4 Mixing Procedures

The mixing procedure employed in this study followed a structured sequence to ensure uniform distribution of materials and consistent quality of the mortar. Initially, ordinary Portland cement (OPC) and rice straw ash (RSA) were combined in dry form and mixed at a low speed for one minute. This step aimed to homogenize the dry components before water was introduced. Following this, water was gradually added to the mixture, and the blending process continued for an additional two minutes, allowing the binder to be evenly distributed throughout the dry mix. Proper sequencing in mixing is essential to prevent clumping and to enhance the interaction between cement particles and pozzolanic materials.

After this initial blending phase, the mixture underwent manual mixing for one minute to ensure any residual dry materials were incorporated thoroughly. Subsequently, the combined materials — OPC, RSA, and water — were subjected to high-speed mixing using a mechanical mixer for ten minutes. This prolonged high-speed mixing ensured a consistent and workable mortar mix. The entire mixing process totalled eleven minutes, providing sufficient time to produce a homogeneous and cohesive mortar blend suitable for testing and analysis. Such a method not only improves the performance of the mortar but also enhances its long-term durability and strength characteristics.

2.5 Slump Flow-Compaction-Curing-Compressive Strength Method

Flow testing in this study was conducted immediately after mixing, following the guidelines set out in SNI 03-6825-2002 [24]. A water-to-solid ratio of 0.2 was applied, calculated by dividing the weight of water by the total weight of the mix. The target flow value was maintained at 110 ± 5%, ensuring that each mixture exhibited consistent workability and fresh-state performance. This approach helped guarantee that all tested mortar mixes started from a similar condition in terms of consistency.

The mortar specimens were cast using cylindrical moulds measuring 5 cm in diameter and 10 cm in height. After demoulding, the specimens underwent curing under controlled conditions. Two curing methods were applied: the first involved storing specimens at ambient room temperature (air curing), which served as the standard curing method. The second method involved cooling the samples to room temperature for 24 hours, after which they were submerged in water until the compressive strength test was performed. All specimens were maintained under their respective curing conditions until the scheduled testing age.

According to SNI 03-6825-2002 [24], compressive strength testing was carried out using a Universal Testing Machine (UTM), which applied a continuous, monotonic, and static load at a constant rate to produce compressive stress. For each mortar mix, three cylindrical specimens were prepared, and their test results were averaged to obtain representative values. A Linear Variable Differential Transformer (LVDT) was also used to monitor displacement under the applied load. The data obtained from the LVDT helped calculate strain, allowing for analysis of deformation behaviour under compressive stress.

3. RESULTS AND DISCUSSION

3.1 Chemical Characteristics of RSA

Table 6 presents the chemical composition of the rice straw ash, highlighting its oxide content. The rice straw ash utilized in this research contains significant amounts of SiO_2, P_2O_5, CaO, and K_2O.

Table 6. Chemical characteristics of RSA

Oxide Content	Concentration RSA (%)
Fe_2O_3	2.31
SiO_2	70.80
K_2O	15.89
CaO	5.34
P_2O_5	3.61

The chemical composition of Rice Straw Ash (RSA) shown in Table 6 reveals a high content of silica (SiO_2) at 70.80%, which is a critical component in pozzolanic materials. The elevated silica content contributes significantly to the pozzolanic reaction when RSA is blended with cement, forming additional calcium silicate hydrate (C-S-H) that enhances the strength and durability of mortar or concrete [22]. This high percentage indicates that RSA can act as an effective supplementary cementitious material (SCM), comparable to fly ash or silica fume. According to Bui et al. [22], a silica content of more than 70% in agricultural ash is suitable for pozzolanic activity. Therefore, the RSA in this study has the potential to improve the mechanical performance and sustainability of cementitious composites.

In addition to SiO_2, RSA also contains potassium oxide (K_2O) at 15.89%, which is relatively high for ash-based materials. Although potassium can influence early setting times, excessive K_2O may lead to alkali-silica reactions (ASR) when reactive aggregates are present [23]. Nonetheless, its presence at this level does not necessarily hinder the pozzolanic performance of RSA if the mixture design and aggregate reactivity are properly controlled. Moreover, potassium can play a role in modifying hydration kinetics and enhancing certain durability aspects of concrete [24]. As such, the use of RSA should be carefully evaluated in relation to the overall chemical balance in the binder matrix.

Calcium oxide (CaO) in RSA was found to be 5.34%, which, although lower than in Ordinary Portland Cement (OPC), still contributes to the development of early strength through limited hydraulic reactivity. The presence of CaO supports the pozzolanic reaction with SiO_2, albeit in a less dominant manner compared to OPC [1]. According to Chusilp et al. [2], CaO levels around 5% are typical for rice straw ash and help form stable compounds that contribute to the densification of the microstructure. The low to moderate calcium content also implies that RSA behaves more as a pozzolan than a self-cementing material, thus complementing rather than replacing OPC entirely.

The other oxide components, namely Fe_2O_3 (2.31%) and P_2O_5 (3.61%), also have implications for the use of RSA. While Fe_2O_3 can contribute to the colour and minor strength properties of the mix, its influence is relatively limited in pozzolanic activity [22]. On the other hand, the presence of phosphorus pentoxide (P_2O_5) is more common in biomass ash and may influence setting times and early strength gain, although further study is needed to clarify its exact impact [25]. Collectively, the oxide profile of RSA in this study confirms its viability as a pozzolanic additive, especially when used in partial replacement of OPC, promoting a more sustainable and resource-efficient construction material.

3.2 Slump Flow Testing of OPC-RSA

Table 7 presents the flow values of the fresh mortar mixtures. The blended mortar demonstrated the ability to effectively bind both cement and rice straw ash, allowing the mixture to spread uniformly without central accumulation or bleeding. The flow measurements recorded for mixtures XX, XY, YY, and XZ were 230 mm, 185 mm, 170 mm, and 120 mm, respectively. The RSA-containing mortar exhibited good flowability and distribution, maintaining consistency across the spread area. Both the paste composed solely of OPC and the blend of OPC with RSA showed a strong capacity to bond with fine aggregates. However, as the proportion of RSA increased in the mix, the flowability tended to decrease. This reduction in flow is attributed to the rapid reaction of CaO present in RSA with water, which leads to a thicker and less workable fresh mortar.

The slump flow test results shown in Table 7 indicate a decreasing trend in flow values as the proportion of rice straw ash (RSA) in the mortar mixture increases. The control mixture (XX), which only used Ordinary Portland Cement (OPC), recorded the highest slump value of 230 mm. When RSA was added at 10% (XY), the slump value dropped to 185 mm, then to 170 mm with 20% RSA (YY), and finally to 120 mm at 30% RSA (XZ). This decline indicates that the higher the RSA content in the mortar, the lower the flowability of the fresh mortar [1].

This slump flow reduction phenomenon is closely related to the physical properties of RSA, particularly its high-water absorption capacity. As previously discussed in the physical characteristics, RSA has a water absorption value of 172.78%, which is significantly higher than that of conventional fine aggregates. As a result, more water in the mortar mixture is absorbed by RSA, making the mix stiffer and increasing its viscosity, thereby limiting its flowability [3]. This is consistent with findings by Chusilp et al. (2009), who stated that pozzolanic materials with high surface area and porosity can reduce the workability of fresh mortar or concrete [2].

In addition, the CaO content in RSA also affects the properties of fresh mortar. CaO in RSA reacts rapidly with water, triggering an early exothermic reaction and accelerating the setting of the mixture. This process increases the viscosity of the mix more quickly, resulting in a significant reduction in mortar slump flow as RSA content increases [4]. The combination of high-water absorption and fast reactivity is the primary cause of the decreased slump flow value.

Although the slump flow decreases with RSA addition, it does not necessarily have a negative impact on the final performance of the mortar. From the perspective of sustainability and resource efficiency, the use of RSA offers added value in terms of biomass waste utilization and improved long-term strength development of mortar at certain ages [5]. With proper adjustments to the water ratio and chemical admixtures, the negative effects on workability can be minimized, as demonstrated in various studies on mix optimization using natural supplementary materials.

Furthermore, the high silica (SiO_2) content in RSA, as shown in the chemical characteristics table (70.80%), also plays a crucial role in influencing the flowability of the mixture. Silica, in the form of amorphous or reactive silica found in RSA, tends to interact with calcium hydroxide during the early stages of hydration, which may accelerate the setting process and contribute to the stiffening of the paste. According to Bui et al. (2005), finely divided silica particles can increase the surface area in the mixture, which demands more water to maintain the same level of workability [11]. Without additional water or plasticizers, this leads to lower slump flow values in mixtures with higher RSA content.

Despite the reduction in workability, the inclusion of RSA in mortar can contribute positively to the mechanical performance and durability of the material, especially at later curing ages. Studies by Ganesan et al. (2008) and Mehta (1999) have demonstrated that pozzolanic materials such as RSA enhance the microstructure by reducing the amount of calcium hydroxide and increasing the formation of calcium silicate hydrate (C-S-H), which densifies the matrix [14, 15]. Thus, although workability initially decreases, proper mixture design and curing can still yield mortars with satisfactory performance, both in strength and sustainability aspects.

Table 7. Slump flow of OPC-RSA

No.	OPC-RSA	Slump flow (mm)
1	XX (100:0%)	230
2	XY (90:10%)	185
3	YY (80:20%)	170
4	XZ (70:30%)	120

3.3 Compressive Strength of Mortar by OPC-RSA

Table 8 presents the average compressive strength of mortar specimens that were subjected to water curing for 7 days.

Table 8. Compressive strength of OPC-RSA

No.	OPC-RSA	Compressive strength (MPa)
1	XX (100:0%)	0.17
2	XY (90:10%)	0.20
3	YY (80:20%)	0.26
4	XZ (70:30%)	0.35

The results shown in Table 8 demonstrate a gradual increase in compressive strength of mortar samples as the proportion of rice straw ash (RSA) increases in the OPC-RSA mixture. The control mixture (XX) with 100% OPC and no RSA yielded the lowest compressive strength at 0.17 MPa. As RSA was introduced at 10% (XY), the strength increased to 0.20 MPa, and further to 0.26 MPa for 20% RSA (YY), reaching the highest value of 0.35 MPa in the mixture with 30% RSA (XZ). This trend reveals a positive correlation between RSA content and compressive strength during early curing periods.

This phenomenon may be attributed to the pozzolanic activity of RSA, especially its high SiO_2 content, which can react with calcium hydroxide ($Ca(OH)_2$) released from cement hydration. The pozzolanic reaction forms additional calcium silicate hydrate (C-S-H) gel, which enhances the binding properties and ultimately contributes to increased compressive strength [1]. As shown in Table 6, RSA contains 70.80% SiO_2, which is significantly high and supports its reactivity in the cementitious matrix.

Moreover, the particle fineness and porous structure of RSA may contribute to the filler effect, enhancing the packing density of the mortar mix. Finer particles fill the micro voids between cement grains and aggregates, thereby reducing porosity and increasing matrix cohesion [2]. As a result, the mortar becomes denser and stronger over time, particularly when optimal RSA percentages are used.

The increasing strength trend up to 30% RSA suggests that the RSA not only acts as a filler but also participates actively in the hydration process. This is further supported by the presence of CaO and K_2O in RSA, which may accelerate early hydration and formation of C-S-H, even though RSA itself is a pozzolanic material and not inherently hydraulic [3]. The high K_2O content (15.89%) could also contribute to early setting reactions.

In comparison to the control specimen (XX), the mixtures containing RSA demonstrated superior strength, which indicates that partial replacement of OPC with RSA does not compromise the structural integrity at early ages, and may even enhance it. This finding aligns with previous research by Chusilp et al. (2009), who reported that up to 30% replacement of cement with agricultural waste ash can improve early and later-age strength in mortar and concrete [4].

However, it should be noted that the strength values in this study are relatively low, even at their peak (0.35 MPa), likely due to the low water-to-solid ratio of 0.2 and the absence of fine aggregates. This suggests that the mixture was designed more for paste-based analysis rather than practical load-bearing applications. Nevertheless, the trend remains significant in illustrating the impact of RSA on early strength development.

The increased strength observed at 30% RSA (XZ) also suggests that RSA contributes to pore refinement, which in turn reduces water permeability and enhances durability. The additional C-S-H gel formed via pozzolanic reaction may fill the capillary pores, making the microstructure denser and more resistant to cracking [5]. This structural densification is key in improving mechanical performance.

Another explanation for the strength gain is the internal curing effect. Due to the high-water absorption capacity of RSA (as previously noted), it may act as an internal reservoir, slowly releasing absorbed water during the curing process. This internal moisture availability can support continued hydration beyond the initial curing phase, promoting strength gain even with a low external water supply [6].

It is also possible that the RSA undergoes surface modifications during mixing and hydration, forming reaction products that act as nucleation sites for C-S-H formation. This nucleation effect may enhance the early development of a denser hydration structure, which is beneficial for strength [7]. The interaction between RSA and cement particles thus contributes to a synergistic hardening process.

Overall, these findings support the potential use of RSA as a sustainable and functional supplementary cementitious material (SCM). By partially replacing OPC, RSA not only improves early compressive strength but also provides environmental benefits by utilizing agricultural waste and reducing carbon emissions from cement production [8].

4. CONCLUSIONS

The experimental results demonstrate that incorporating Rice Straw Ash (RSA) as a partial replacement for Ordinary Portland Cement (OPC) significantly influences the early compressive strength of mortar. A steady increase in compressive strength was observed as the RSA content increased, reaching the highest value at 30% replacement. This improvement is primarily attributed to the pozzolanic activity of RSA, its high silica content, filler effects, and its ability to enhance microstructural density through pore refinement and internal curing. Despite the initial reduction in workability due to RSA's high-water absorption, the mechanical performance of the hardened mortar benefitted from the synergistic interaction between RSA and cement hydration products. These findings support the potential of RSA as a sustainable and effective supplementary cementitious material, contributing not only to improved strength but also to environmental conservation by reducing cement usage and utilizing agricultural waste. Future research is encouraged to explore long-term durability, optimized mix designs, and large-scale applications of RSA-based mortars in sustainable construction practices.

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