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ORIGINAL ARTICLE

Effect of high rice husk ash replacement on the mechanical performance of Limestone-Modified CEM II/A-LL 32.5R concrete

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Abstract: This study investigates the influence of rice husk ash (RHA) characteristics and replacement level on the fresh and hardened performance of mortars incorporating Portland limestone cement (CEM II/A-LL 32.5R). Four RHA types (RHA-A, RHA-B, RHA-C, and RHA-D) with different physicochemical characteristics were incorporated at replacement levels of 5–60% at a constant water-to-binder ratio of 0.50. The effects of silica structure and content, loss on ignition, and particle fineness on mortar flowability, compressive strength, and tensile strength were evaluated at 7, 28, and 91 days. The results demonstrate that RHA performance is strongly dependent on its physicochemical characteristics and replacement level. RHA-A and RHA-B exhibited a progressive reduction in mechanical performance at high replacement levels, whereas RHA-C and RHA-D maintained or enhanced strength over a substantially wider replacement range. Notably, RHA-C and RHA-D achieved substantial strength enhancement at replacement levels of up to 40%, with RHA-D exhibiting the highest later-age performance. Based on the combined assessment of compressive strength and microhardness, the optimum replacement levels were identified as 30% for RHA-A, 20% for RHA-B, 50% for RHA-C, and 60% for RHA-D. At these levels, the 28-day compressive strength was comparable to the reference cement mortar for RHA-A and increased by 2.18%, 10.45%, and 7.43% for RHA-B, RHA-C, and RHA-D, respectively. The findings demonstrate that the suitability of RHA as a high-volume supplementary cementitious material is governed not only by its replacement level but also by its physicochemical characteristics, highlighting the importance of RHA-specific characterization when designing sustainable cementitious systems.

Keywords: rice husk ash, portland limestone cement, supplementary cementitious materials, physicochemical characteristics, compressive and tensile strengths, sustainable cementitious materials

1 Introduction

The cement industry is facing increasing pressure to conserve raw materials and energy while reducing greenhouse-gas emissions associated with cement production. Among the available strategies, reducing the clinker factor through the incorporation of supplementary cementitious materials (SCMs) is considered one of the most effective approaches for lowering the environmental impact of cement-based construction. In this context, blended cements such as CEM II have gained increasing importance because a portion of the clinker can be replaced by other mineral constituents while maintaining the

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required performance of the cement. Portland limestone cement (PLC), particularly CEM II/A-LL, is therefore increasingly used as an alternative to conventional CEM I cement. According to EN 197-1, CEM II/A-LL contains approximately 6–20% limestone by mass, in addition to clinker and minor constituents. The incorporation of limestone reduces the clinker content and can consequently contribute to reductions in the material and environmental footprint of cement production. However, the reduction in clinker content may also influence the early-age development and hydration characteristics of the resulting cementitious system. Further reductions in the environmental impact of cement-based materials can be achieved by replacing a portion of cement with industrial and agricultural by-products, including fly ash, silica fume, ground-granulated blast-furnace slag, calcined clays, and rice husk ash [1-3]. Among these materials, RHA has attracted considerable attention because it is an abundant agro-industrial by-product containing a high proportion of silica and can exhibit substantial pozzolanic reactivity when produced under appropriate combustion and grinding conditions [4,5]. Recent reviews have demonstrated that the performance of RHA as a supplementary cementitious material is strongly governed by its amorphous silica content, particle size, specific surface area, combustion temperature and duration, and carbon content [5-8]. Controlled processing can produce RHA with a highly reactive amorphous silica phase, whereas uncontrolled combustion may result in crystallization of silica and/or excessive residual carbon, reducing its effectiveness as a cementitious material [6, 7].

The incorporation of RHA into cementitious materials has been widely investigated in recent years. Experimental and review studies have reported that appropriately processed RHA can improve compressive, tensile, and flexural strength, while also reduce water absorption and refine the pore structure of cement-based materials [7–10]. For example, recent investigations have demonstrated that RHA can promote hydration and contribute to the development of a denser cementitious matrix because of its high specific surface area and pozzolanic reactivity [5, 9]. A detailed study of RHA-containing mortars reported improved strength and durability at replacement levels of up to 25%, together with evidence of accelerated early hydration and pozzolanic activity [6]. Similarly, experimental research has shown that the incorporation of RHA can improve compressive, tensile, and flexural performance while reducing chloride penetration, although the magnitude of the improvement depends strongly on RHA fineness, replacement level, and water-to-binder ratio [7, 10]. Despite these developments, most studies have focused on ordinary Portland cement or relatively low-to-moderate RHA replacement levels. Reviews published in recent years indicate that replacement levels of approximately 5–15% are commonly investigated, whereas the behavior of systems containing larger quantities of RHA remains less clearly established [5, 6]. More recent research has begun to investigate high-volume RHA systems, demonstrating that considerably higher replacement levels can be technically feasible when the ash characteristics and mixture design are appropriately controlled. For instance, Yang et al. [11] reported acceptable mechanical performance with 40 wt.% RHA in a high-performance cementitious system, although increasing RHA content also affected workability and strength development. These findings suggest that the applicability of high-volume RHA cannot be evaluated solely based on replacement percentage; rather, the physicochemical characteristics of the particular RHA and its interaction with the cement matrix must also be considered [5, 8, 9, 11].

The use of RHA in Portland limestone cement systems presents an additional scientific and technological challenge. CEM II/A-LL contains a significant proportion of limestone and consequently has a lower clinker content than CEM I. Although limestone can provide beneficial filler and hydration effects, the lower clinker content may contribute to slower early-age strength development. The incorporation of RHA introduces additional mechanisms that may either compensate for or amplify these effects. The highly porous structure and large specific surface area of RHA can increase water demand, whereas its reactive amorphous silica can participate in pozzolanic reactions and modify the development of hydration products [5, 8, 9]. Recent studies have demonstrated that RHA can accelerate early hydration and contribute to pore refinement, but its effectiveness depends substantially on ash quality and dosage [5, 9]. Consequently, the interaction between RHA and limestone-containing cement requires further investigation, particularly when relatively high RHA replacement levels are considered. Another important issue is that the physicochemical characteristics of RHA can vary considerably depending on the source of the rice husk and the conditions of combustion, cooling, and subsequent grinding [6–9]. Consequently, RHAs obtained from different sources may exhibit substantially different

silica phase compositions, fineness, specific surface areas, porosity, and pozzolanic activities, even when nominally used at the same replacement level [5–9]. Recent research has emphasized that these differences can significantly influence hydration, strength development, pore structure, and durability [5, 7-9]. In addition, the potential benefits of RHA must be balanced against possible limitations associated with excessive water demand, clinker dilution, reduced workability, and, depending on ash chemistry, potential alkali–silica-related effects [8, 10]. Therefore, evaluating RHA solely according to its replacement percentage may not adequately describe its performance in blended cement systems.

Although RHA has been extensively investigated as an SCM, there remains a limited understanding of how variations in the physicochemical characteristics of different RHAs affect the mechanical performance of Portland limestone cement systems, particularly at relatively high replacement levels. This research gap is especially relevant for CEM II/A-LL 32.5 R, where the combination of reduced clinker content, limestone incorporation, and RHA replacement may produce competing dilution, filler, hydration, and pozzolanic effects. Furthermore, most previous investigations have considered individual RHA sources, making it difficult to distinguish the influence of RHA characteristics from that of the nominal replacement level. A systematic comparison of different RHAs within the same CEM II/A-LL 32.5 R matrix can therefore provide valuable insight into the factors governing the performance of these low-carbon cementitious systems [5, 8, 9, 12]. Accordingly, the present study investigates the influence of four different RHAs with distinct physicochemical characteristics on the mechanical performance of mortars based on CEM II/A-LL 32.5 R. Particular attention is given to relatively high RHA replacement levels, with the objective of evaluating both the benefits and limitations associated with increasing RHA incorporation. The experimental program includes compressive and tensile strength testing of mortars together with microhardness measurements of hardened cement paste to assess the development of mechanical performance at both the macroscopic and local scales. The study further examines the relationship between the physicochemical characteristics of RHA and the resulting mechanical behavior of the blended cementitious systems.

The results are intended to provide a better understanding of the compatibility between RHA and CEM II/A-LL 32.5 R and to identify the conditions under which RHA can be effectively incorporated into limestone-containing cement systems. The CEM II/A-LL 32.5 R used in this study contains approximately 12.4% limestone, providing a representative matrix for evaluating the combined use of limestone and RHA as clinker-reducing constituents. From a sustainability perspective, this approach has the potential to simultaneously valorize an agricultural by-product and reduce the amount of clinker required in cementitious materials. Recent life-cycle research has further indicated that RHA-containing concrete can provide environmental benefits when mechanical performance and service-life considerations are incorporated into the assessment [13]. Thus, the combined use of Portland limestone cement and RHA represents a promising pathway toward lower-carbon cementitious materials while maintaining the mechanical performance required for practical construction applications [13-15].

2 Materials

2.1 Cement

The Portland limestone cement used in this study was CEM II/A-LL 32.5R, containing 12.4% limestone in compliance with BS EN 197-1. The physical properties and chemical composition of the cement were provided by the manufacturer (Hanson Multi-Cement, Heidelberg Group) and are presented in **Table 1**.

Table 1. Physical Properties and chemical composition of Portland limestone cement CEM II/A-LL 32.5R

Physical properties	Chemical composition % of total weight									
Specific surface area	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	Cl^-	LOI*
0.3650 m^2/g	64.76	17.92	4.29	2.89	1.10	0.69	0.21	3.01	0.06	5.5

LOI*: loss on ignition

2.2 Rice Husk Ash (RHA)

Four types of rice husk ash (RHA) were used in experimental research. Three types designated as

RHA-A, RHA-B, and RHA-C, were sourced from Navdanya Food PVT. LTD., Odisha, India. Additionally, a fourth type, labeled RHA-D, was produced by re-incinerating RHA-C at 600 °C for 2 hours. The physical properties, particle size distribution, and chemical composition of the rice husk ashes presented in **Table 2**. X-ray diffraction was used to determine the physical properties (specific surface area, and mean particle size), while X-Ray Fluorescence (XRF) to determine the RHAs chemical composition. The RHAs exhibited varying fineness and silica content, which significantly influenced their performance as supplementary cementitious materials. The mean particle size decreased progressively from RHA-A to RHA-D, while the specific surface area increased accordingly. Chemical analysis indicated that all RHA samples were rich in amorphous silica (SiO_2) contents ranging from 84.30% to 93.49%. Loss on ignition values varied among the RHAs, reflecting differences in combustion efficiency and residual carbon content.

Table 2. Physical properties and particle size distribution of RHAs

Physical properties	RHA types			
	A	B	C	D
Specific surface area (m^2/g)	0.537	0.587	0.692	0.808
Mean particle size (μm)	23.397	20.948	15.804	12.64.
Particle size (μm)	% of total volume			
	RHA-A	RHA-B	RHA-C	RHA-D
0.060	6.850	7.920	9.750	12.08
3.900	8.710	10.19	14.33	17.90
7.800	17.51	19.72	25.39	29.48
15.60	30.92	30.17	26.68	25.21
31.00	29.16	25.02	17.35	12.22
63.00	6.830	6.720	5.190	3.010
125.0	0.020	0.250	0.680	0.110
250.0	0.000	0.000	0.530	0.000
Mean particle size	23.39	20.94	15.80	12.64

2.3 Microstructure of RHAs

Understanding the morphology, particle size, and surface characteristics of RHA is essential for interpreting its influence on the flowability, strength development, and shrinkage of cementitious mixtures. The microstructure of RHA-A, RHA-B, RHA-C, and RHA-D were examined using scanning electron microscopy (SEM; ZEISS GeminiSEM 500). SEM micrographs obtained at 5.00 kX magnification and resolutions of 2 μm are presented in Figure 1. The SEM images demonstrate clear morphological differences among the RHA types. RHA-A exhibits a heterogeneous, overlapping sheet-like morphology with surface protuberances and a relatively broad particle-size distribution. RHA-B shows a more dispersed and irregular vesicular structure, characterized by a greater degree of surface roughness and porosity. RHA-C presents a comparatively uniform particle morphology with a highly developed porous structure, indicating a greater internal surface area than RHA-A and RHA-B. RHA-D exhibits a particularly porous and fragmented morphology. The thermal treatment at 550 °C for 6 h appears to have caused localized deformation and partial collapse of the internal cellular structure of RHA-C, producing finer particles and additional pores. Pore dimensions ranging approximately from 0.060 to 7.80 μm were observed in the fractured regions, indicating the presence of both meso- and microporous features.

The SEM observations provide a microstructural explanation for the differences in particle-size distribution and specific surface area measured for the RHA samples. The extensive internal porosity and irregular surfaces of RHA-C and RHA-D contribute to their higher specific surface areas, whereas the lower values observed for RHA-A and RHA-B can be associated with greater particle agglomeration, relatively larger secondary particles, and less developed internal porosity. These morphological characteristics are expected to influence water demand, particle packing, flowability, and the extent of interaction between RHA and the cementitious matrix. Overall, the SEM results confirm that RHA performance is governed not only by particle size but also by particle morphology, agglomeration, surface texture, and internal porosity. These characteristics provide an important basis for explaining the differences in fresh and hardened properties observed among the RHA types investigated.

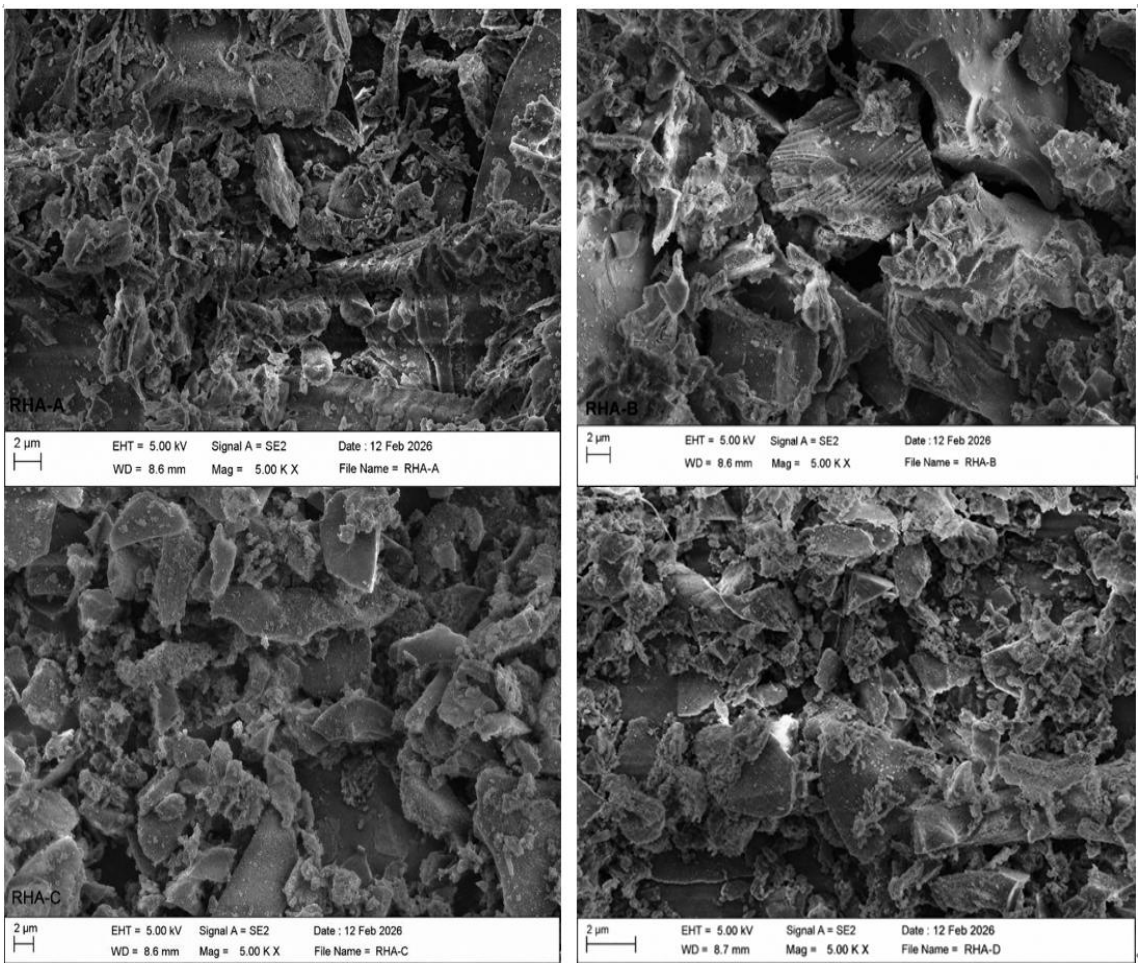

Fig. 1. Scanning electron micrograph (SEM) of RHA particles ground for RHA-A, RHA-B, RHA-C and RHA-D at 2µm**.**

2.4 Silica sand

The silica sand used in the experimental program conformed to standard grading requirements for mortar production. The particle size distribution is presented in **Table 3**. The sand exhibited a well-graded distribution suitable for achieving consistent workability and mechanical performance in all mortar mixtures.

Table 3. Silica sand particle size distribution

Sieve No:	Weight (g)	Weight percentage (%)	Cumulative passing (%)
4mm	11	2.20	97.8
2.8mm	43	8.60	89.2
1.4mm	97	19.4	69.9
600µm	140	27.9	41.9
300µm	159	31.7	10.2
150µm	45	9.00	1.20
75µm	4	0.80	0.40
63µm	1	0.20	0.20
<63µm	-	-	-

3 Mix proportion

The mixed proportions and water cement ratio (w/c) used throughout the experimental program

are presented in **Table 4**. For each mixture, specimens were prepared as follows:

1. **Compressive strength specimens:**
   Fifty-millimeter cube specimens were cast, with five specimens prepared for each curing age. A total of 15 specimens were tested for each replacement ratio, resulting in 120 specimens for each RHA type. In addition, 15 ordinary Portland cement (OPC) mortar specimens were prepared as control samples.
2. **Tensile strength specimens:**
   Small dog-bone–shaped specimens were cast, with five specimens prepared for each curing age. A total of 15 specimens were tested for each replacement ratio, yielding 120 specimens for each RHA type. An additional 15 OPC mortar specimens were prepared for tensile strength comparison.

The mortar mixtures incorporated nine different RHA replacement ratios, ranging from 0% to 60% by mass of binder. A constant water-to-binder ratio of 0.50 was maintained for all mixtures. The dosage of superplasticizer (SP) was adjusted as required to achieve acceptable workability.

Table 4. RHA mortar mix proportions

RHA (% binder)	Cement(kg/m^3)	RHA (kg/m^3)	Silica Sand (kg/m^3)	Water (kg/m^3)	SP (%wt.)
0%	587	-	1320	293.5	0.25%
5%	558	29	1320	293.5	0.25%
10%	528	59	1320	293.5	0.25%
15%	499	88	1320	293.5	0.25%
20%	470	117	1320	293.5	0.25%
30%	411	176	1320	293.5	0.50%
40%	352	235	1300	293.5	1.00%
50%	294	294	1320	293.5	2.00%
60%	235	352	1320	293.5	4.00%

4 Curing/environmental conditions

All specimens were cast in a laboratory environment where the temperature was maintained at approximately 23 °C (±2) throughout the experimental program. Immediately after casting, the specimens were kept in the casting room under controlled conditions. After 24 h, the specimens were demolded and subjected to a single curing regime. All specimens were stored completely uncovered in the curing environment until the designated testing ages.

5 Results and discussion

5.1 Flow of RHA fresh mixture

The flowability of RHA mortar mixtures compared with the OPC control mortar is presented in **Fig. 2** and summarized in **Table 5**. The results indicate that the flow behavior of RHA mortars produced with CEM II/A-LL 32.5R exhibits trends like those observed for RHA mortars incorporating CEM I 52.5N; however, the mixtures were generally less flowable. This reduction in flowability can be attributed not only to the characteristics of RHA particles but also to the fineness of the limestone present in CEM II/A-LL 32.5R. Similar observations were reported by previous studies [16, 17, 18]. In contrast, Schmidt et al. [19] reported an increase in workability for mortars incorporating Portland limestone cement with limestone contents ranging from 13% to 17%. This observation is consistent with the findings reported by de Sensale et al. [20], Tran et al. [21], and Thiedeitz et al. [22].

As the RHA replacement level increased, higher dosages of superplasticizer were required to maintain acceptable workability. This behavior is primarily associated with the porous structure and high specific surface area of RHA particles. Additionally, the fine limestone particles in CEM II/A-LL 32.5R further contribute to water and superplasticizer adsorption. Consequently, at a constant water content, increased superplasticizer dosages were necessary to compensate for the reduced free water

available in the mixture. For RHA replacement levels between 5% and 20%, the workability of the mixtures decreased markedly when the superplasticizer dosage was maintained at 0.25%. When the RHA content exceeded 20%, the required superplasticizer dosage increased substantially, reaching 0.50%, 1.00%, 2.00%, and 4.00% for RHA replacement levels of 30%, 40%, 50%, and 60%, respectively.

Overall, the RHA content had a pronounced effect on the flowability of all blended mortars. This behavior can be attributed to the increase in total specific surface area of the binder system with increasing RHA content. For instance, CEM I 52.5N and RHA-A exhibit specific surface areas of approximately 0.415 m²/g and 0.537 m²/g, respectively. When 20% of cement is replaced by RHA-A, the total specific surface area of the blended binder increases to approximately 0.439 m²/g and further increases to 0.464 m²/g at a 40% replacement level. This increase in surface area adversely affects workability when the water content is kept constant, thereby necessitating higher superplasticizer dosages.

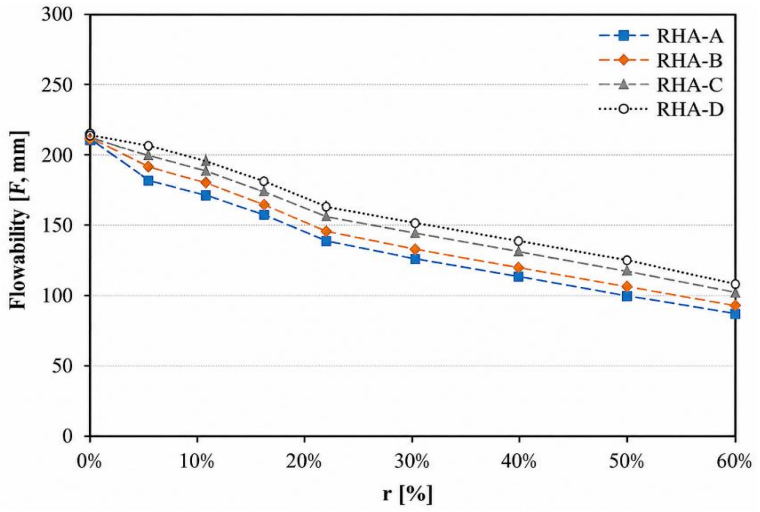

Fig. 2. Effect of RHA replacement ratio on the flowability of CEM II/A-LL 32.5R mixtures at w/b = 0.50.

In addition, RHA-C and RHA-D exhibited better flowability than RHA-A and RHA-B. This observation contrasts with findings reported in previous studies [23, 24, 25], which associated increased water demand with higher RHA specific surface area. Notably, RHA-C exhibited a higher specific surface area (0.692 m²/g) than RHA-A (0.537 m²/g) and RHA-B (0.587 m²/g), yet demonstrated improved workability, suggesting that factors other than surface area, such as particle morphology and pore structure, also influence flow behavior

Table 5. Flowability Characteristics of Fresh RHA–CEM II/A-LL 32.5R Mixtures at a Constant w/b Ratio of 0.50

RHA%	RHA-A	RHA-B	RHA-C	RHA-D	SP*(%wt. of binder)
5%	185	193	208	203	0.25
10%	174	181	196	189	0.25
15%	160	166	181	175	0.25
20%	143	146	163	158	0.25
30%	129	133	150	145	0.50
40%	116	122	137	131	1.00
50%	103	108	124	116	2.00
60%	91	95	109	102	4.00
OPC			215		

SP*: Superplasticizer

6.2 Compressive Strength of RHA Mortars Incorporating CEM II/A-LL 32.5R

6.2.1 Effect of Hydration Reactions of Portland Limestone Cement on Strength Development

Tables should also be numbered consecutively using Arabic numbers. They should be placed in the text soon after the point where they are referenced. Tables should be centered and should have a table caption placed above. Captions should be centered in the format "**Table 1**. The text caption …". For one example, see **Tab. 1**.

Calcium carbonate present in Portland limestone cement interacts with alumina-, iron-, and sulfate-containing phases to form carboalumination hydrates, commonly referred to as hemi-carboalumination and mono-carboalumination phases [26]. Extensive investigations into these reactions have been conducted by members of the nano-cement research network [27]. Their findings demonstrated the compatibility of hydrate phase assemblages within a ternary sub-system, as illustrated in **Fig 3**.

i. According to this phase diagram, the incorporation of limestone into Portland cement results in a sequence of hydration reactions: ettringite formation occurs through the consumption of mono-sulfate.
ii. Once mono-sulfate is depleted, mono-carbonate forms through the consumption of hemi-carbonate.
iii. After depletion of hemi-carbonate, additional calcium carbonate remains unreacted and persists as a stable phase.

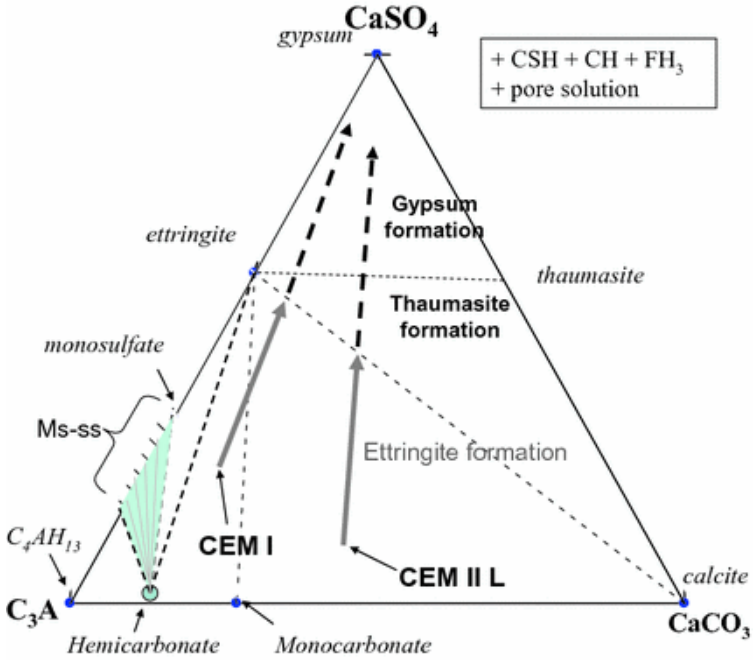

Fig. 3. Hydrate phase assemblages in the ternary sub-system for $CaSO_4$-C_3A-$CaCO_3$ with the multicomponent system for Portland limestone cement. Phases in this subsystem are given in Italic, and regions of stability are indicated by the 3-phases regions in which the composition of any given system (e.g., CEMII + additional $CaSO_4$) plots onto the diagram.

Reactions (i) and (ii) contribute to pore refinement and reduced porosity through space-filling effects, whereas further carbonate addition associated with reaction (iii) may increase porosity. The diagram also indicates that higher aluminate (C_3A) contents promote greater mono-carbonate formation, allowing larger quantities of calcium carbonate to react before excess limestone contributes to porosity increase. Hydrate phase assemblages in the $CaSO_4$–C_3A–$CaCO_3$ ternary sub-system within multicomponent Portland limestone cement systems shown in **Fig 2**.

6.2.2 Effect of RHA Content on Compressive Strength

To investigate the influence of RHA content on the compressive strength of Portland limestone cement (PLC) mortars, RHA replacement levels were varied across nine different proportions. The average compressive strength results are presented in **Table 6** and illustrated in **Fig 4**. The 7-day compressive-strength results demonstrate that the performance of RHA is governed by the combined influence of chemical composition and physical characteristics, rather than by SiO_2 content alone. RHA-

D exhibited the highest strength at 5% replacement (34.91 MPa), followed closely by RHA-C (34.11 MPa), whereas RHA-A and RHA-B achieved only 27.25 and 25.70 MPa, respectively. The superior performance of RHA-D is attributed to its favorable combination of high SiO_2 content (93.49%), very low LOI (1.65%), highest specific surface area (0.808 m^2/g), and smallest mean particle size (12.64 μm), which promotes greater silica reactivity and more effective interaction with the cementitious matrix. RHA-C, despite having the lowest SiO_2 content (84.30%) and highest LOI (11.35%), achieved comparable strength to RHA-D because of its relatively high fineness (0.692 m^2/g; 15.80 μm). This confirms that particle size and specific surface area substantially influence the effectiveness of RHA, by increasing the available reaction surface and enhancing particle packing. Conversely, RHA-A and particularly RHA-B showed lower strength development because of their coarser particles and, in the case of RHA-B, higher LOI (5.10%). At higher replacement levels, strength progressively decreased for all RHAs, reflecting increasing cement dilution and insufficient pozzolanic reaction to compensate for the reduction in clinker-derived hydration products. Thus, the results indicate that the optimum RHA content is controlled by the balance between pozzolanic reactivity, fineness, carbon content, and cement dilution, with RHA-D exhibiting the most favorable overall physicochemical characteristic.

The 28-day compressive-strength results provide further evidence that the chemical composition and physical characteristics of RHA strongly control strength development, with the influence becoming more pronounced with extended curing. Compared with the 7-day results, all RHA types show substantial strength development at 28 days, particularly RHA-C and RHA-D, indicating that the contribution of the pozzolanic reaction increases with curing time. On 28 days, RHA-D exhibited the highest compressive strength at all replacement levels, reaching 48.93 MPa at 10% replacement, compared with 32.15 MPa for the control. This corresponds to an increase of approximately 52%. At 7 days, RHA-D also provided the highest performance, reaching 34.91 MPa at 5% replacement and 33.56 MPa at 10%. The increase in strength from 7 to 28 days demonstrates the continued development of the cementitious matrix and suggests that the highly reactive silica in RHA-D contributed increasingly to secondary pozzolanic reactions. Its favorable characteristics—93.49% SiO_2, 1.65% LOI, 0.808 m^2/g specific surface area, and 12.64 μm mean particle size—provide an effective combination of chemical reactivity and physical fineness.

An important difference between the two curing ages is the shift in the optimum replacement level. At 7 days, the highest strengths of RHA-A, RHA-C, and RHA-D occurred at 5% replacement, whereas at 28 days, all four RHA types achieved their maximum strength at approximately 10% replacement. This shift indicates that the additional time available for pozzolanic reactions allows a higher RHA content to contribute effectively to strength development. At 10% replacement, the 28-day strengths of RHA-A, RHA-B, RHA-C, and RHA-D were 38.93, 37.19, 45.95, and 48.93 MPa, respectively, compared with the control value of 32.15 MPa. Beyond 10% replacement, however, strength progressively decreased for all RHA types. This reduction becomes particularly pronounced at 40–60% replacement and is attributable primarily to cement dilution, increased water demand, and the inability of the pozzolanic reaction to compensate fully for the reduced amount of Portland cement. Nevertheless, RHA-C and RHA-D retained substantially higher strengths than RHA-A and RHA-B at high replacement levels, demonstrating their superior overall reactivity.

Overall, comparison of the 7- and 28-day results indicates that RHA-D provides the most favorable combination of early- and later-age performance, followed by RHA-C. The results also demonstrate that RHA effectiveness is controlled by the interaction between SiO_2 content, LOI, particle size, and specific surface area, rather than by silica content alone. The stronger increase in strength between 7 and 28 days for the finer and chemically favorable RHAs further indicates that pozzolanic activity becomes increasingly important at later curing ages, supporting the selection of approximately 10% RHA as the optimum replacement level for 28-day strength development.

The 91-day compressive-strength results further demonstrate that the influence of RHA becomes more pronounced with prolonged curing, particularly for the finer and chemically favorable ashes. At 91 days, RHA-D exhibited the highest compressive strength across all replacement levels, reaching 54.21 MPa at 10% replacement, compared with 35.27 MPa for the control, corresponding to an increase of approximately 54%. This superior performance is consistent with its favorable physicochemical characteristics: the highest SiO_2 content (93.49%), lowest LOI (1.65%), highest specific surface area

(0.808 m²/g), and smallest mean particle size (12.64 μm). These characteristics provide a large reactive surface and a high availability of siliceous phases, facilitating progressive pozzolanic reactions and the development of additional binding products during extended curing. RHA-C also maintained a high level of performance, reaching 50.75 MPa at 10% replacement and 51.47 MPa at 15%. Although RHA-C contains the lowest SiO_2 content (84.30%) and the highest LOI (11.35%), its relatively high specific surface area (0.692 m²/g) and fine particle size (15.80 μm) appear to enhance its long-term reactivity. The relatively large increase in strength between 28 and 91 days indicates that the contribution of RHA-C is not limited to its filler effect but is associated with continuing pozzolanic reactions. Nevertheless, its high LOI may restrict its performance relative to RHA-D.

RHA-A and RHA-B showed comparatively lower 91-day strengths. Their maximum values were 43.33 MPa and 42.55 MPa, respectively, at 10% replacement. Their lower specific surface areas and larger particle sizes reduce the available reaction surface compared with RHA-C and RHA-D. In addition, RHA-B has a higher LOI (5.10%), which may indicate a greater proportion of residual carbonaceous matter and contribute to increased water demand and less efficient hydration. The results therefore reinforce that total SiO_2 concentration alone cannot be used as a reliable indicator of RHA performance; rather, chemical quality must be considered together with particle fineness and surface characteristics. The 91-day results also show that the 10% replacement level remains the principal optimum for all four RHA types, although RHA-C maintains almost equivalent performance at 15% replacement. This behavior differs from the 7-day results, where the maximum strength for RHA-A, RHA-C, and RHA-D occurred at 5%, while the 28-day results showed a clear shift toward 10%. The continued strength development from 28 to 91 days demonstrates that extended curing allows the pozzolanic contribution of RHA to become increasingly important. At 10% replacement, the strengths increased from 38.93 to 43.33 MPa for RHA-A, 37.19 to 42.55 MPa for RHA-B, 45.95 to 50.75 MPa for RHA-C, and 48.93 to 54.21 MPa for RHA-D between 28 and 91 days.

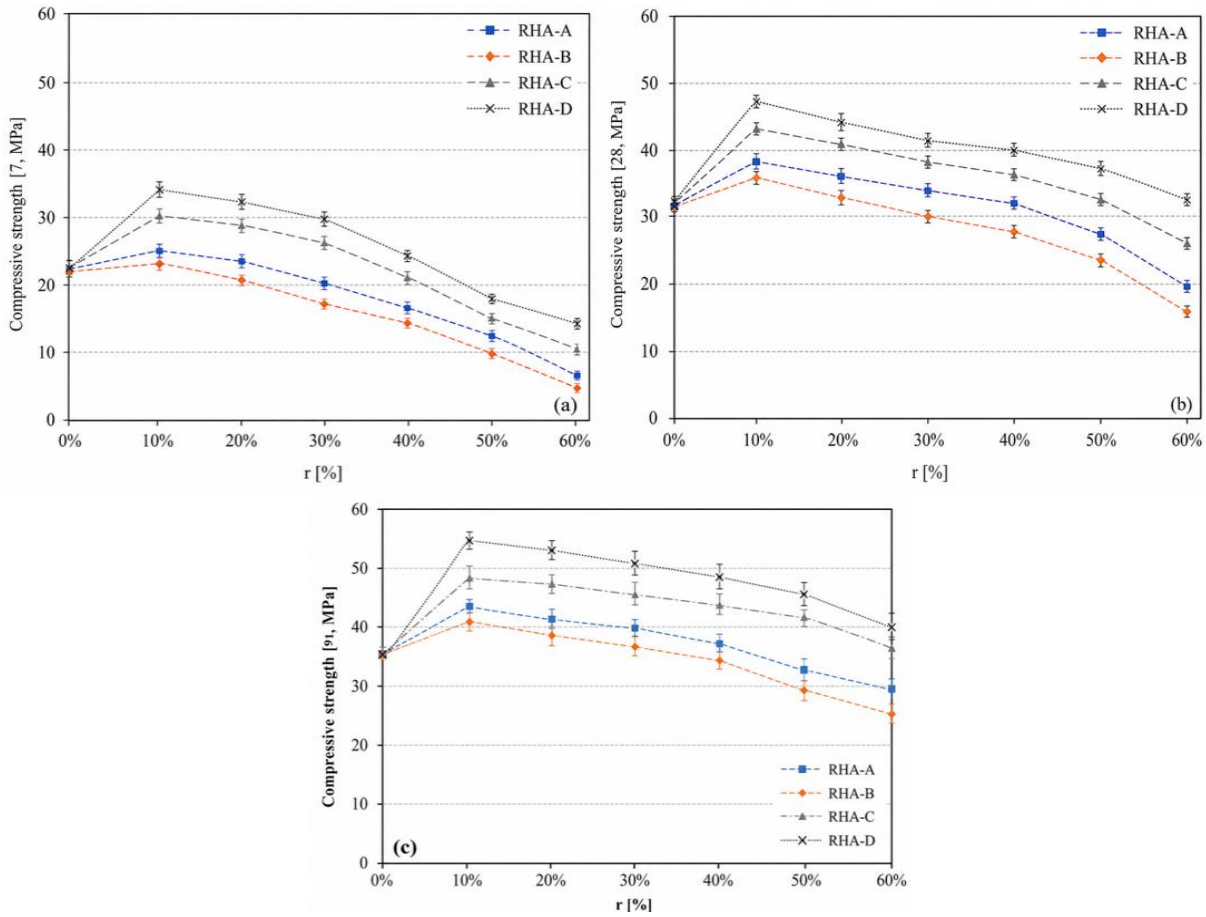

Fig. 4. Compressive strength of RHA mortar with cement type CEM II/A-LL 32.5R: (a) 7 days, (b) 28 days and (c) 91 days.

Beyond 10–15% replacement, however, compressive strength progressively decreases. At 60% replacement, the strengths were only 29.27, 26.54, 37.17, and 39.97 MPa for RHA-A, RHA-B, RHA-C, and RHA-D, respectively. This reduction reflects the increasing dominance of cement dilution and insufficient clinker-derived hydration products, which cannot be fully compensated by the slower pozzolanic reaction of the high RHA contents. Overall, comparison of the 28- and 91-day results confirms a sustained later-age strength advantage for RHA-D and RHA-C, particularly because of their finer particle size and greater specific surface area. RHA-D consistently provides the optimum combination of chemical and physical characteristics, while RHA-C demonstrates that high fineness can partially compensate for lower SiO_2 content. The progressive increase in strength from 28 to 91 days consequently indicates that RHA reactivity is time-dependent, with the contribution of secondary pozzolanic reactions becoming increasingly significant at later ages. Thus, the results collectively establish that the mechanical efficiency of RHA is governed by the interaction of silica availability, LOI, particle size, specific surface area, and cement dilution, rather than by any single physicochemical parameter.

Table 6. Compressive strength of RHA mortar with cement type CEM II/A-LL 32.5

RH A%	7 days				28 days				91 days			
	RHA-A	RHA-B	RHA-C	RHA-D	RHA-A	RHA-B	RHA-C	RHA-D	RHA-A	RHA-B	RHA-C	RHA-D
5%	27.25	25.7	34.11	34.91	36.72	35.67	44.25	47.15	42.93	42.25	48.57	51.14
10%	26.6	25.92	32.4	33.56	38.93	37.19	45.95	48.93	43.33	42.55	50.75	54.21
15%	23.17	23.5	31.96	32.89	36.53	33.34	44.2	47.72	41.45	39.76	51.47	53.55
20%	22.89	20.57	30.02	31.7	34.49	32.85	42.64	45.47	40.62	37.21	48.95	51.73
30%	20.15	19.13	28.65	30.13	32.03	29.98	40.95	42.78	38.48	35.53	47.61	49.67
40%	18.73	16.65	24.3	27.48	30.36	27.11	39.77	41.9	35.21	33.49	45.42	48.86
50%	13.63	10.76	17.18	21.59	27.61	24.38	35.51	38.28	31.48	29.67	41.32	46.22
60%	6.87	5.25	12.89	14.63	21.29	17.82	28.1	34.54	29.27	26.54	37.17	39.97
0%	24.65				32.15				35.27			

6.3. Tensile strength results

6.3.1. Effect of RHA properties on the tensile strength performance

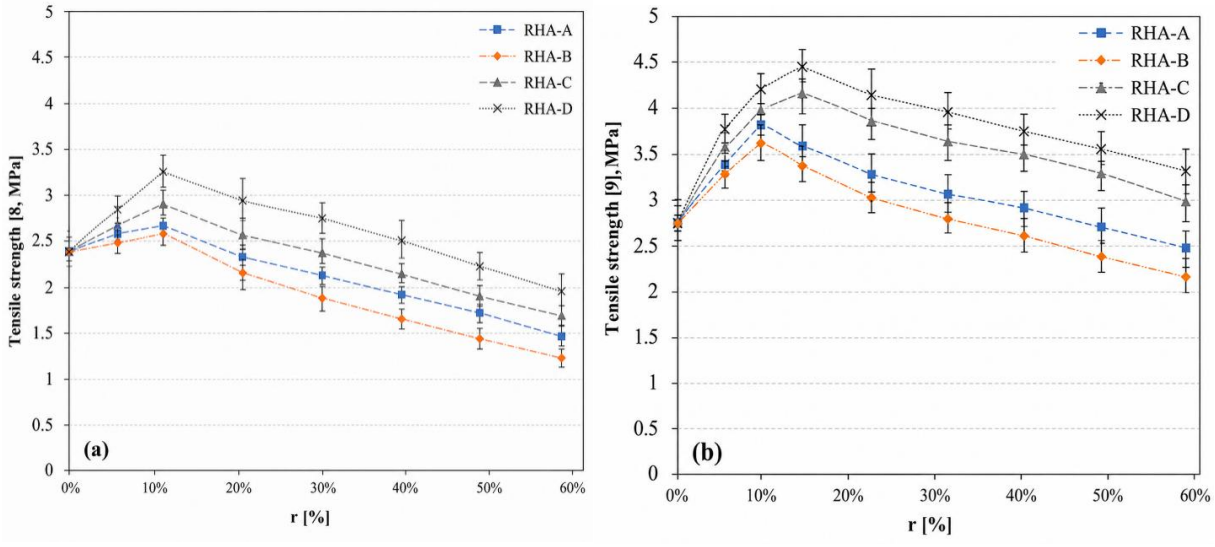

Fig. 5. Tensile strength trends of RHA mortar at age of 28, and 91-days.

Average of five specimens was taken as the representative tensile strength of the specimen. Tensile strength test was conducted at the ages of 28 and 91 day. Relationship developed between percentages of rice husk ash added to tensile strength with implementation of cement type CEM II/A-LL 32.5R are shown in **Fig 5**. For all mortar of cement type CEM II/A-LL 32.5R as the compressive strength increases

the tensile strength also increases. Where, tensile strength was affected by each of RHA replacement ratio, and the type of cement used. From the observation results, there was increase in tensile strength in all RHA mixes up to 15%RHA, 10%RHA-B, 20%RHA-C and 40%RHA- D at 28 days age compared to control mixture.

The amount of increase was varied, where RHA-A and B presented maximum improvement strength at 5% replacement ratio about 13.84% and 11.07% compared to PLC control sample. On the other hand, RHA-C and D presented maximum strength at 10%, where the values of strength improvement reached 18.36% and 25.23% respectively.

6.3.2. Cement properties affect the tensile strength of RHA mortars

The change in tensile strength of all RHA mixtures with cement type PLC vs. OPC comparisons at varying replacement rates (0%, 5%, 10%, 15%, 20%, 30%, 40%, 50%, and 60%) are presented in **Table 7**. The Figure illustrates tensile strength differences between RHA replacement rates on test days of 28, and 91 days. According to the results, there are clearly different trends when similar replacement rates are compared. In RHA mortar mixtures results of, 10% RHA-A and B, 30%RHA-C and 20%RHA-D replacement produced the greatest tensile strength (ft) values of OPC compared to 10% RHA mixtures of PLC mortar at 28 days. As replacement levels increased, tensile strength of PLC to OPC decreased. After 91 days, a maximum tensile strength of 3.87MPa and 4.49MPa were achieved for the Portland limestone cement with RHA A and B mortar of 10% replacement level with an increase of 26.1%, and 36.30% higher than the control mortar. However, at 50% and 60% RHA-A and 40%, 50% and 60% replacement ratio, mortar provides a decrease in strength about 5.94% and 13.43% to 5.94%, 17.83% and 23.78% respectively. On the other hand, with OPC cement mortar blended RHA achieved 4.46MPa, 4.33MPa, 4.86MPa and 5.14MPa at 30% RHA-A and B, and 20% RHA-C and D with an increase of 32.51%, 30.48%, 38.07% and 41.44% higher than OPC control mortar. Even at 50%, and 60% RHA-A, C and D with OPC cement (CEM I 52.5N) mortar showed higher tensile strength of 3.22%, 21.61% and 25.86% respectively than OPC mortar. While it was same value with 60% RHA-B.

Furthermore, a comparison of RHA blended PLC mortar to RHA OPC mortar relative to their control mixture at 28 days age, shows an average increase with replacement ratio up to 15%RHA-A, 10%RHA- B, 20%RHA-C and 40%RHA-D compared to 30%RHA-A, 20%RHA-B and 60%RHA-C and D, respectively. In contrast to the results of compressive strength, the performance of RHA tensile strength with cement type CEM I 52.5N is much better than that of cement CEM II/A-LL 32.5R. Generally, tensile strength of RHA mortar with PLC decreased with increasing replacement ratio over 15% RHA-A, 10%RHA-B, 20%RHA-C and 30% RHA-D compared to control sample. While, with cement CEM I 52.5N, tensile strength increased up to 30%RHA-A, 20%RHA-B and 60% RHA-C and D, respectively. In addition to the high amount of silica availability in mixture, which is not reacted, because of Insufficient CH of hydration cement to react, producing second gel. Also, the reduction in strength can be attributed to the clinker dilution effect.

Table 7. Tensile strength of RHA mortar with cement type CEM II/A-LL 32.5R

RHA (%) of cement	RHA-A	RHA-B	RHA-C	RHA-D	RHA-A	RHA-B	RHA-C	RHA-D
	28 days				91days			
5%	2.71	2.58	2.93	3.17	3.48	3.39	3.77	3.98
10%	2.89	2.8	3.05	3.33	3.87	3.71	4.01	4.21
15%	2.57	2.45	2.74	3.02	3.64	3.45	4.12	4.49
20%	2.31	2.21	2.59	2.9	3.31	3.14	3.86	4.13
30%	2.16	1.97	2.43	2.79	3.09	2.9	3.75	3.96
40%	2.03	1.74	2.29	2.64	2.87	2.69	3.63	3.77
50%	1.76	1.55	2.07	2.47	2.69	2.35	3.38	3.64
60%	1.47	1.29	1.93	2.36	2.50	2.18	3.09	3.31
PLC control	2.49				2.86			

6 Conclusions

Based on the experimental results and discussion, the following conclusions can be drawn:

i. The use of Portland limestone cement (CEM II/A-LL 32.5R) partially replaced with RHA increases the water demand of the mixtures. In addition to the effect of the RHA particles themselves, this reduction in flowability may also be attributed to the fineness of the limestone particles, combined with the inherently high-water demand of RHA due to its large specific surface area
ii. The specific surface area and amorphous structure of each RHA type have a direct impact on the development of mortar strength. The results indicate that the maximum effective replacement levels differ among the RHA types. For RHA-A, the optimum replacement ratio was found to be 40%, while for RHA-B it was 30%. In contrast, RHA-C and RHA-D demonstrated significant improvements at higher replacement levels, where using 60% RHA-C and RHA-D increased the compressive strength of the mortar by approximately 5.11% and 11.76%, respectively, compared to the control specimens.
iii. The results show that increasing the fineness of the re-processed rice husk ash (RHA-D) directly enhances its pozzolanic effectiveness (reducing the mean particle size from 15.804 μm in RHA-C to 12.64 μm in RHA-D), which in turn leads to an improvement in the strength of the RHA-blended mortar.
iv. The combination of the two supplementary cementitious materials can, in some cases, reduce the strength of the mixtures. This reduction occurs because the total amount of reactive SiO_2 exceeds the available calcium hydroxide ($Ca(OH)_2$) produced during cement hydration. When the $Ca(OH)_2$ is insufficient, the silica in both the RHA and the limestone does not fully participate in pozzolanic reactions and instead behaves primarily as an inert filler. Consequently, the effective binder content in the system decreases. This effect is similar to increasing the aggregate-to-cement ratio, leading to a noticeable reduction in strength particularly evident in mixtures containing RHA-A and RHA-B.
v. Since the limestone content in CEM II/A-LL 32.5R does not exceed 12.4% of the total cement, the reduction in limestone at high cement-replacement levels becomes minimal. Even at a 60% replacement of cement with rice husk ash (RHA-Cand D), the remaining limestone accounts for only about 4.96% of the original cement volume. Therefore, the high replacement ratio of burnt rice husk ash does not significantly affect mortar strength through limestone dilution, because the limestone content becomes too low to influence the overall reaction mechanisms.
vi. Loss on ignition (LOI) has a direct impact on the strength of mortars. This effect is clearly observed when re-burning RHA-C to produce RHA-D, where the LOI decreased significantly from 11.35% (RHA-C) to 1.65% (RHA-D). This reduction in LOI enhances the quality and purity of the ash, resulting in an increase in the amorphous silica content from 84.30% to 93.49%, thereby improving its pozzolanic effectiveness.
vii. The incorporation of highly pozzolanic RHA types (RHA-C and RHA-D) enhances the degree of hydration of Portland limestone cement (PLC) at later ages. This beneficial effect is likely attributed to the pozzolanic reactivity of the ash and the additional water retained within its porous structure, which becomes available for continued hydration.

Abbreviations

Abbreviation	Meaning
RHA	Rice Husk Ash
OPC	Ordinary Portland Cement
LOI	loss on ignition
SP	superplasticizer
SCM	Supplementary Cementitious Materials
C-S-H	Calcium–Silicate–Hydrate
w/c	Water-to-Cement Ratio

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CRediT authorship contribution statement

Binyamien Ibrahim Rasoul: Author designed the study, developed the methodology, performed the experiments, collected the data, contributed to data analysis, statistical analysis, prepared the figures, and drafted the manuscript.

Competing interests

The author declares that there are no competing interests.

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are not publicly available due to confidentiality and institutional restrictions but are available from the corresponding author on reasonable request.

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