

Reduced-Density Concrete With Non-Expanded Sintered Clay Artificial Aggregate

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This study evaluates reduced-density concrete incorporating non-expanded sintered clay artificial lightweight aggregate (ALWA) produced with coconut fiber ash and rice husk ash. Four coarse-aggregate substitution levels of 0%, 35%, 50%, and 100% by volume were tested for unit weight, compressive strength, and flexural strength at 7, 14, and 28 days. The ALWA exhibited a specific gravity of 1.62 g/cm³ and water absorption of 27.49%, indicating a porous but mechanically viable aggregate. The 50% ALWA mixture achieved the best balance between density and mechanical performance, reaching 24.19 MPa compressive strength and 7.12 MPa flexural strength at 28 days, with a density of 2,210 kg/m³. All ALWA mixtures exceeded the 17.24 MPa compressive-strength criterion used in SNI 03-3449-2002, although their densities remained above the structural lightweight-concrete limit commonly adopted in ACI 213R-14. The measured modulus-of-rupture-to-compressive-strength ratios exceeded ACI 318-19 and SNI 2847:2019 predictions under the ASTM C293 center-point loading configuration used in this study. The results support 50% ALWA replacement as a resource-efficient reduced-density concrete option for applications requiring moderate self-weight reduction, subject to further durability and serviceability verification.

Keywords: Coconut fiber ash; Compressive strength; Flexural strength; Resource efficiency; Rice husk ash; Structural classification

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1. Introduction

Concrete remains one of the most widely used construction materials, but its large material demand and the contribution of cement production to anthropogenic carbon dioxide emissions continue to motivate improvements in concrete constituent materials. In addition, the high self-weight of normal-weight concrete, typically approximately 2,300–2,500 kg/m³, increases gravity load, foundation demand, and member size in many structural systems [1–4].

Structural lightweight concrete is commonly produced by replacing natural aggregate with natural lightweight aggregate or manufactured expanded clay aggregate. Lightweight expanded clay aggregate (LECA) is usually

obtained by thermal expansion at temperatures that may exceed 1,000 °C [5, 6]. Although expanded aggregates can reduce density effectively, the high porosity that gives these materials their low mass may also reduce particle strength and affect concrete mechanical performance [7]. The energy demand of the thermal expansion process is an additional sustainability concern [8].

Non-expanded sintered clay-based artificial lightweight aggregate (ALWA) provides an alternative route because the aggregate is densified and mineralogically transformed without relying primarily on expansive gas formation. The performance of this aggregate type depends on raw-material composition, forming pressure, pore-forming additives, and sintering regime [9, 10]. Agricultural residues

such as rice husk ash (RHA) and coconut fiber ash (CFA) are attractive additives because they are locally abundant in Indonesia and can contribute to pore development during firing [11]. Previous Indonesian studies also show that cold-bonded ALWA, cement type, styrofoam ALWA, steel-fiber ALWA, and ALWA steel-fiber composites can influence the mechanical performance of concrete [12–16].

Several studies have examined the physical and mechanical behavior of clay-based artificial aggregate and the effect of sintering temperature on expanded clay aggregate properties [17, 18]. However, a key structural performance parameter, namely flexural strength or modulus of rupture (f_r), remains insufficiently documented for non-expanded clay-based ALWA incorporating combined CFA and RHA additives. This parameter is important because it governs cracking resistance and serviceability-relevant behavior of slabs, pavements, and beam-type members. Code equations such as ACI 318-19 and SNI 2847:2019 commonly estimate f_r as a function of compressive strength, while SNI 03-3449-2002 provides a strength threshold for structural lightweight concrete classification [19–21]. For porous aggregate systems, however, the interfacial transition zone (ITZ), aggregate surface texture, and absorption characteristics may produce flexural-to-compressive strength ratios that differ from those of conventional normal-weight concrete [22].

Despite the growing literature on manufactured lightweight aggregates, sintered waste-based aggregates, and expanded-clay lightweight concrete [23–27], limited information is available on the simultaneous compressive, flexural, density, and mineralogical performance of reduced-density concrete using this non-expanded clay-based ALWA system. Therefore, this study aims to: (1) evaluate compressive and flexural strength development at 7, 14, and 28 days; (2) compare measured f_r values with ACI 318-19 and SNI 2847:2019 predictions; (3) classify the resulting concrete based on strength and density criteria; and (4) identify the substitution level that offers the most favorable balance between mechanical performance and density reduction. The contribution of this work is therefore the integrated evaluation of an Indonesian CFA-RHA clay ALWA from aggregate properties to concrete-level flexural response and code-based structural classification, providing a direct basis for material selection in reduced-density concrete applications. This distinguishes the present study from prior Indonesian ALWA research, which reported compressive, split-tensile, or steel-fiber-modified behavior without flexural strength or code-based classification [12–16]; from expanded-clay systems, which rely on gas-expansion sintering above 1,000 °C with a different den-

sification mechanism [5, 8, 17, 18]; and from other waste-derived sintered aggregates, which use different precursor chemistries without a combined CFA-RHA clay matrix [23–27].

2. Theory and formula

The mechanical evaluation focused on compressive strength, flexural strength, and the relationship between these two parameters. Flexural strength was expressed as the modulus of rupture, determined using simple-beam center-point loading. For a rectangular beam specimen, the modulus of rupture is calculated as:

$$f_r = \frac{3PL}{2bh^2} \quad (1)$$

where P is the maximum applied load (N), L is the span length (300 mm), b is the beam width (100 mm), and h is the beam depth (100 mm). The 28-day f_r / f'_c ratio was used as an index of flexural efficiency relative to compressive strength.

The measured modulus of rupture was compared with the ACI 318-19 expression $f_r = 0.62\lambda(f'_c)^{0.5}$, where λ is the lightweight-concrete modification factor [19]. For this comparison, $\lambda = 1.0$ was used as a normal-weight reference benchmark rather than as a formal reclassification of the ALWA mixtures. Because $\lambda < 1.0$ would reduce the predicted modulus of rupture, $\lambda = 1.0$ provides the higher code benchmark. The same expression was used as the SNI 2847:2019 benchmark [20]. Structural classification was evaluated separately using the strength and density criteria discussed below [3, 21].

3. Experimental setup

3.1. Raw Materials

Ordinary Portland Cement (OPC) Type I was used as the primary binder, with a specific gravity of 3.10 g/cm³, an initial setting time of 133 min, and a final setting time of 242 min, conforming to SNI 2049-1:2020 [28]. Natural fine aggregate was Lumajang sand with a fineness modulus of 3.04, specific gravity of 2.701, and saturated surface-dry (SSD) water absorption of 1.695%. Natural coarse aggregate was crushed gravel with a nominal size of 5-10 mm, specific gravity of 2.687, and SSD absorption of 1.752%.

The ALWA raw materials comprise clay from Tulungagung, East Java, coconut fiber ash, and rice husk ash. The clay had a plasticity index of 21.95%. The specific gravities of CFA and RHA were 1.90 and 1.93 g/cm³, respectively. X-ray fluorescence testing indicated silica- and alumina-rich compositions: RHA contained 54.13% SiO₂; CFA contained 36.61% SiO₂ and 17.12% K₂O; and clay contained 40.13%

SiO₂ and 26.55% Al₂O₃. These oxide compositions support aluminosilicate phase formation during sintering.

3.2. ALWA Production

ALWA was produced using a non-expanded sintering method. Two compositions were initially evaluated: C1, consisting of 97% clay, 2% CFA, and 1% RHA; and C2, consisting of 95% clay, 3% CFA, and 2% RHA. The dry materials were blended until homogeneous, compacted into cylindrical molds of 20 mm diameter and 40 mm height under static hydraulic loading, and then sintered in two stages. The first stage was conducted at 500 °C for 1 h to remove bound water and organic matter. The second stage was conducted at 900 °C for 20 min to promote mineral transformation and densification. Based on single-particle compressive strength, C1 was selected for all concrete mixtures.

3.3. Concrete Mixtures and Specimen Preparation

Concrete mixtures were designed for a target compressive strength of 25 MPa using the SNI mix-design method and a constant water-to-cement ratio of 0.51 (Table 1). Four ALWA coarse-aggregate substitution levels were applied by volume: 0% (control, V0), 35% (V1), 50% (V2), and 100% (V3). Cylindrical specimens of 100 mm diameter and 200 mm height were cast for compressive-strength and density testing, while prismatic beam specimens of 100 mm × 100 mm × 400 mm were cast for flexural-strength testing. Three replicate specimens were prepared for each mixture and test age. All specimens were demolded after 24 h and water-cured until testing at 7, 14, or 28 days. Slump testing in accordance with SNI 1972:2022 confirmed that all mixtures satisfied the target slump of 10 ± 2 cm [29]. Prior to batching, the ALWA was pre-soaked in water for 24 h and then air-dried for 6 h to obtain a saturated-surface-dry (SSD) condition; under this condition, the ALWA was assumed not to absorb additional mixing water, and the batch water was determined from the design water-to-cement ratio, with no separate absorption correction applied.

3.4. Mechanical Testing and Data Treatment

Compressive strength was determined using a Universal Testing Machine in accordance with SNI 1974:2011 [30]. Flexural strength was measured using simple-beam center-point loading with a 300 mm span in accordance with ASTM C293/C293M-16 [31]. The results are reported as the mean $\pm$ standard deviation of three specimens. Results with a coefficient of variation above 15% were checked using the outlier treatment principles in ASTM E178-21 [32].

4. Results and discussion

4.1. Physical and Mineralogical Properties of ALWA

The selected C1 ALWA exhibited a specific gravity of 1.62 g/cm³ and water absorption of 27.49%, as summarized in Table 2. Compared with the natural coarse aggregate specific gravity of 2.687, the ALWA specific gravity was approximately 40% lower, confirming effective aggregate-level density reduction. The high absorption value indicates the presence of internal pores generated by organic-matter removal and sintering. Such pores can retain moisture and may contribute to later-age hydration, as reported for porous lightweight aggregate systems [33, 34]; however, internal curing was not directly quantified in the present study.

X-ray diffraction analysis of the sintered ALWA indicated dominant quartz (SiO₂) with a prominent diffraction peak at $2\theta = 26 - 27^\circ$ and secondary peaks at $2\theta = 34 - 36^\circ$ associated with stable aluminosilicate phases. Previous work on sintered ash-based lightweight aggregate shows that high-temperature sintering can develop microstructures that control particle performance [27]. In the present ALWA, the stable quartz and aluminosilicate phases support aggregate integrity and contribute to load transfer across the paste-aggregate interface.

4.2. Compressive Strength Development

V0, V2, and V3 exhibited an overall increase in compressive strength with curing age, whereas V1 showed a non-monotonic response, decreasing between 7 and 14 days before recovering at 28 days (Table 3). The control mixture reached a 28-day compressive strength of 35.38 MPa, exceeding the 25 MPa target. Among the ALWA mixtures, V2 with 50% substitution showed the most balanced strength development, increasing from 21.93 MPa at 7 days to 24.19 MPa at 28 days.

The V2 response may reflect a favorable balance between natural aggregate stiffness and the porous ALWA. The SSD-conditioned ALWA may retain internal moisture, but internal curing was not directly quantified; therefore, it remains a plausible rather than demonstrated mechanism [33, 34]. The 35% mixture showed a temporary strength decrease at 14 days. Because the standard deviation at this age was low, the result appears to represent a consistent measured response rather than a single-specimen anomaly. Its recovery at 28 days confirms continued strength development, although the cause of the non-monotonic response cannot be established from the present data alone.

To verify that the 14-day response of V1 was not a specimen-level artifact, the individual V1 compressive-strength values were checked. The 7-day values were

Table 1. Concrete mix proportions per cubic meter

Mixture	Cement (kg)	Water (kg)	Fine aggregate (kg)	Natural coarse aggregate (kg)	ALWA (kg)
V0 (0%)	402	205	660	1000	0
V1 (35%)	402	205	660	652	205
V2 (50%)	402	205	660	500	315
V3 (100%)	402	205	660	0	600

Water-to-cement ratio = 0.51 (205/402 kg), held constant across all mixtures. Prior to batching, ALWA was brought to SSD condition (24 h soak, 6 h air-dry); no additional absorption water correction was applied.

Table 2. Physical properties of ALWA

Property	Value	Unit	Remark
Specific gravity	1.62	g/cm ³	~40% lower than natural coarse aggregate
Water absorption	27.49	%	High internal porosity
Particle compressive strength (C1)	16.29	MPa	Optimum mixture
Particle compressive strength (C2)	11.69	MPa	Non-optimum mixture

C1 = 97% clay, 2% CFA, and 1% RHA; C2 = 95% clay, 3% CFA, and 2% RHA. CFA = coconut fiber ash; RHA = rice husk ash.

Table 3. Compressive strength development and density

ALWA substitution (%)	7 days (MPa)	14 days (MPa)	28 days (MPa)	Density (kg/m ³)	Strength gain 7–28 days (%)
0 (V0)	23.96 ± 2.90	29.84 ± 3.69	35.38 ± 2.88	2,330	47.66
35 (V1)	22.13 ± 0.81	17.61 ± 0.43	23.02 ± 3.76	2,300	4.02
50 (V2)	21.93 ± 2.63	22.47 ± 1.52	24.19 ± 3.29	2,210	10.31
100 (V3)	17.63 ± 2.09	17.80 ± 1.03	20.12 ± 1.12	2,170	14.12

Values are means ± standard deviations of three specimens. ALWA = artificial lightweight aggregate.

22.079, 21.356, and 22.969 MPa; the 14-day values were 17.926, 17.787, and 17.126 MPa; and the 28-day values were 24.111, 26.110, and 18.838 MPa. The corresponding coefficients of variation (CoV) were 3.7%, 2.4%, and 16.3%, respectively. The 14-day result, which shows the apparent dip, in fact has the lowest CoV of the three ages, confirming a consistent measured response rather than a single-specimen artifact. The 28-day CoV slightly exceeded 15% because one specimen was lower than the other two; however, ASTM E178-21 checking did not statistically justify excluding this value for $n = 3$, and no specimen was excluded from any reported result [32].

4.3. Flexural Strength Development

The control mixture achieved the highest flexural strength at all ages, reaching 9.26 MPa at 28 days (Table 4). Among ALWA mixtures, V2 showed the highest 28-day flexural strength of 7.12 MPa, corresponding to 76.9% retention relative to the control. The reduction in flexural strength with increasing ALWA content is consistent with the influence of porous lightweight aggregate on concrete stiffness and

tensile cracking resistance [35].

The comparatively high flexural strength of V2 indicates that partial replacement may provide a more favorable stress distribution than full replacement. At 100% ALWA, the continuous porous-aggregate skeleton may increase deformability and reduce peak rupture stress. This interpretation agrees with earlier observations that lightweight aggregate properties influence the mechanical response and brittleness of lightweight aggregate concrete [36].

4.4. Code Comparison and Structural Classification

The 28-day mechanical summary and code comparison are presented in Table 5. All measured f_r / f'_c ratios were higher than the values implied by the ACI 318-19 and SNI 2847:2019 modulus-of-rupture equations [19, 20]. The measured ratios ranged from 0.262 to 0.357, whereas the corresponding code-predicted ratios ranged from 0.104 to 0.138. This difference suggests that the code equations are conservative for the tested non-expanded ALWA concrete under the present ASTM C293 center-point loading configuration. It should not be generalized to third-point loading or

Table 4. Flexural strength development

ALWA substitution (%)	f_r at 7 days (MPa)	f_r at 14 days (MPa)	f_r at 28 days (MPa)	Strength gain 7–28 days (%)
0 (V0)	5.86 ± 0.05	9.05 ± 0.19	9.26 ± 0.49	58.02
35 (V1)	5.89 ± 0.03	7.21 ± 0.40	8.23 ± 0.31	39.73
50 (V2)	5.83 ± 0.04	6.61 ± 0.09	7.12 ± 0.41	22.13
100 (V3)	5.84 ± 0.03	6.02 ± 0.03	6.78 ± 0.42	16.10

Values are means $\pm$ standard deviations of three specimens. f_r = modulus of rupture.

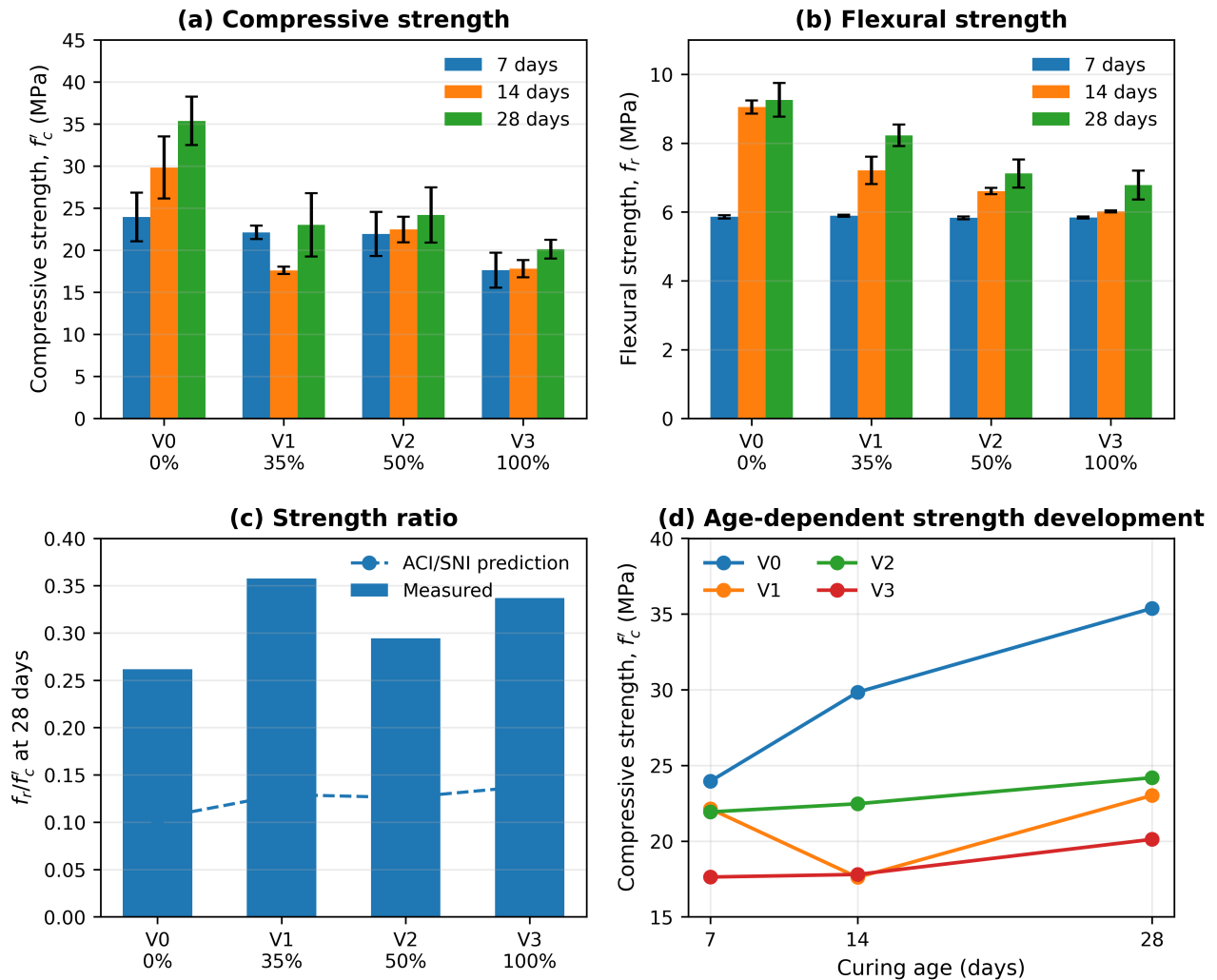


Fig. 1. Multi-mechanical performance of reduced-density concrete with non-expanded clay-based ALWA. (a) Compressive strength at 7, 14, and 28 days. (b) Flexural strength at 7, 14, and 28 days. (c) Measured f_r/f_c ratios at 28 days compared with ACI/SNI predicted ratios. (d) Compressive strength development with curing age. Values represent the mean of three specimens; error bars denote ± 1 standard deviation.

broader structural applications without additional verification.

Several factors may explain the elevated measured f_r values. First, the rougher surface texture of non-expanded

ALWA can improve mechanical interlocking at the ITZ compared with smoother vitrified expanded aggregates [22, 36]. Second, the angular and clean Lumajang sand may improve the paste-fine aggregate contact zone [26].

Table 5. Mechanical performance, code comparison, and classification at 28 days

ALWA (%)	f'_c (MPa)	Density (kg/m ³)	f_r (MPa)	f_r / f'_c	Predicted f_r (MPa)	Classification
0	35.38	2,330	9.26	0.262	3.69	Normal weight
35	23.02	2,300	8.23	0.357	2.97	Reduced-density
50	24.19	2,210	7.12	0.294	3.05	Reduced-density
100	20.12	2,170	6.78	0.337	2.78	Reduced-density

Predicted f_r values were calculated using $f_r = 0.62\lambda(f'_c)^{0.5}$ with $\lambda = 1.0$ as a common normal-weight reference benchmark. This assumption was used for comparative purposes and does not constitute a formal reclassification of the ALWA mixtures as normal-weight concrete. Density-based classification was evaluated separately.

Third, the center-point loading configuration used in ASTM C293/C293M generally produces higher modulus-of-rupture values than third-point loading because the maximum moment occurs at a single central section rather than over a constant-moment region. Therefore, the deviation from code prediction should be interpreted as a conservative code comparison rather than direct evidence that the code equation is invalid.

All ALWA mixtures exceeded the 17.24 MPa compressive-strength threshold used in SNI 03-3449-2002 [21]. However, none of the ALWA mixtures met the 1,850 kg/m³ density limit commonly used for structural lightweight concrete classification in ACI 213R-14 [3]. The mixtures are therefore more appropriately described as reduced-density or semi-lightweight concrete rather than fully structural lightweight concrete. The current limitation is primarily related to the specific gravity of the non-expanded ALWA, which remains higher than that of many expanded aggregates such as LECA [5, 17].

The combined strength development, flexural response, f_r / f'_c ratio, and age-dependent compressive-strength trend are summarized in Fig. 1.

4.5. Engineering Significance, Sustainability, and Limitations

The 50% ALWA mixture provided the most practical balance among the investigated mixtures. It achieved 68.4% compressive-strength retention relative to the control, the highest flexural strength among ALWA concretes, and a density reduction of approximately 5.2%. This trade-off is practically meaningful for applications where moderate self-weight reduction is useful but full structural lightweight classification is not required, such as selected secondary precast components, architectural panels, and non-primary concrete elements. It is less compelling for primary strength-to-weight-optimized members because the compressive-strength reduction is substantially larger than the density reduction. Therefore, any use in load-bearing structural members should be supported by project-specific

verification of elastic modulus, shrinkage, durability, and member-level serviceability.

The sustainability contribution of this material should be read as the use of waste-derived ingredients rather than as a proven low-carbon outcome, since no life-cycle assessment was performed in this study; the incorporation of CFA and RHA provides a resource-efficiency advantage by diverting agricultural by-products into aggregate production [25, 37]. The maximum sintering temperature of 900 °C is lower than the temperature commonly associated with LECA production, which is often above 1,000 °C [5, 18]. However, the environmental benefit should not be overstated without a life-cycle assessment that includes drying, grinding, firing, transport, rejected particles, and curing energy. Therefore, the material is best described at this stage as a resource-efficient reduced-density aggregate system rather than a fully quantified low-carbon material. Related studies on self-compacting and fiber-reinforced lightweight concrete also show that aggregate type, matrix design, and reinforcement strategy strongly affect fresh and hardened-state behavior [38].

The principal limitations of this study are the use of one clay source, one selected ash combination, one sintering schedule, and three specimens for each mixture-age condition. The center-point flexural test gives consistent internal comparison but should not be generalized to all flexural-loading configurations. Future work should quantify elastic modulus, drying shrinkage, absorption kinetics, chloride penetration, carbonation resistance, life-cycle impacts, and member-level performance under service and ultimate limit states.

5. Conclusions

This study evaluated reduced-density concrete incorporating non-expanded sintered clay ALWA produced with CFA and RHA. The ALWA had a specific gravity of 1.62 g/cm³, approximately 40% lower than natural coarse aggregate, and water absorption of 27.49%. XRD results indicated

quartz and aluminosilicate phases that support aggregate integrity after sintering.

All ALWA mixtures achieved 28-day compressive strengths above 17.24 MPa. The 50% substitution mixture reached 24.19 MPa at 28 days with a density of 2,210 kg/m³, providing the best compromise between density reduction and compressive-strength retention.

Flexural strength decreased with increasing ALWA content, but the 50% substitution mixture still reached 7.12 MPa at 28 days, corresponding to 76.9% retention relative to the control mixture. The measured f_r/f'_c ratios exceeded ACI 318-19 and SNI 2847:2019 predictions under the adopted center-point loading configuration, suggesting conservative code estimates only for the tested configuration and sample size. This conclusion is limited to the ASTM C293 center-point loading configuration and three-specimen sample size used in this study and should not be generalized to third-point loading or larger sample sizes without further verification.

The investigated concrete should be classified as reduced-density concrete rather than structural lightweight concrete because the densities remained above 1,850 kg/m³. Additional optimization of aggregate composition, pre-wetting, matrix design, and sintering parameters is required before the material can meet full structural lightweight density requirements.

Overall, 50% ALWA replacement is recommended as the most promising mixture among those tested for applications requiring moderate self-weight reduction with acceptable compressive and flexural performance. Before structural specification, durability, shrinkage, elastic modulus, and member-level behavior must be verified.

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