

Sintering-controlled clay-based artificial lightweight aggregate with coconut fiber ash and rice husk ash for reduced-density concrete

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Article Info	Abstract
Article History: Received 29 June 2026 Accepted 29 Aug 2026 Keywords: Artificial lightweight aggregate; Clay-based aggregate; Coconut fiber ash; Reduced-density concrete; Resource efficiency; Sintering	A 50% volume replacement of natural coarse aggregate with the selected clay-based artificial lightweight aggregate (ALWA) produced the best strength-density balance within the tested matrix, reaching 24.19 MPa compressive strength, 7.12 MPa flexural strength, and 2210 kg/m³ concrete density at 28 days, corresponding to a 5.1% density reduction relative to the control. The ALWA was produced from 97% clay, 2% coconut fiber ash (CFA), and 1% rice husk ash (RHA) and evaluated under three thermal regimes: 500 °C, 900 °C, and two-stage sintering at 500 °C followed by 900 °C. Aggregate characterization included visual observation, oven-dry bulk specific gravity, water absorption, single-particle crushing strength, and qualitative X-ray diffraction (XRD). The two-stage C1-S3 aggregate showed fewer visible macroscopic defects than direct 900 °C firing and the highest mean C1 single-particle crushing strength (16.29 MPa), with an oven-dry bulk specific gravity of 1.62 and water absorption of 27.49%. Concrete containing 0%, 35%, 50%, and 100% ALWA was evaluated for density, compressive strength, and flexural strength. Although all ALWA mixtures exceeded the cited Indonesian compressive-strength threshold for structural lightweight concrete, their densities remained above 1850 kg/m³; the tested mixtures are therefore classified consistently as reduced-density concrete. The XRD interpretation is qualitative, and no SEM, quantitative phase analysis, or pore-size data are available. The high ALWA absorption is consequently treated as a principal constraint requiring controlled moisture conditioning, workability-retention verification, durability testing, and field-scale batch-water correction.

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1. Introduction

Concrete remains the dominant material for buildings and infrastructure, but its high density, normally about 2300-2500 kg/m³, imposes large dead loads on structural systems and increases foundation demand. Reduced-density concrete is therefore attractive because moderate weight reduction can improve construction efficiency, decrease member self-weight, and support more resource-efficient structural design without necessarily changing the basic concrete production route [1–3].

Lightweight concrete is commonly obtained by replacing natural aggregate with natural porous aggregate or manufactured expanded clay aggregate. Expanded clay aggregate can substantially reduce density, but the high-temperature expansion process is energy intensive, and the resulting high porosity may reduce particle strength, elastic stiffness, and concrete compressive strength [4–

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6]. For many regional applications, especially where local clay and agricultural residues are available, non-expanded artificial lightweight aggregate (ALWA) offers a practical alternative because aggregate properties can be adjusted through composition, pelletization, and sintering control [6–8]. In clay-based ALWA, firing temperature governs water release, organic decomposition, gas evolution, mineral transformation, and the balance between particle porosity and mechanical resistance [6,8–10]. Agricultural residues can modify the feedstock oxide balance, but their influence depends on dosage and thermal history rather than on ash origin alone. In the present raw materials, RHA is silica-rich whereas CFA has a comparatively high K_2O content. Because K_2O is one of several fluxing oxides that can contribute to lower-temperature softening in sintered ceramic systems [6], its presence provides a plausible chemical context for sintering; however, the present XRF data do not quantify a liquid phase, vitrification temperature, or pore morphology.

Recent studies further illustrate the processing sensitivity of waste-derived artificial aggregates. Islam et al. [7] produced clay-based artificial aggregate containing RHA and waste glass and evaluated the resulting lightweight concrete, including durability-related properties. Lim et al. [8] showed for rice-husk/sediment aggregates that increasing rice-husk addition can lower particle density while increasing water absorption and reducing crushing strength, whereas higher sintering temperature can improve crushing resistance and reduce absorption. Earlier Indonesian ALWA investigations also showed that aggregate-production route, ALWA incorporation, and binder/replacement choices influence concrete mechanical response [11–13]. More recent work has reported substantial variation in density, absorption, porosity, and crushing resistance among waste-based artificial aggregates depending on feed composition and processing route [14–15], while a 2024 review emphasizes that aggregate properties and the resulting interfacial response jointly control concrete mechanical performance [16]. These studies sharpen the present gap: the combined effect of low CFA-RHA additions and a staged 500 °C-to-900 °C treatment on a non-expanded clay aggregate, followed through to reduced-density concrete performance, has not been established for the material system investigated here.

This study therefore evaluates clay-based ALWA incorporating CFA and RHA with emphasis on the relationship between the applied thermal regime, measured aggregate properties, and the density-strength response of reduced-density concrete. The experimental program includes visual assessment, oven-dry bulk specific gravity, water absorption, single-particle crushing strength, qualitative XRD, concrete density, compressive strength, and flexural strength. The specific contribution is an integrated process-property-performance assessment that distinguishes direct observations from literature-supported hypotheses and explicitly avoids treating unmeasured microstructure or durability as experimentally demonstrated.

2. Materials and Methods

2.1 Materials

The materials used in this study were Ordinary Portland Cement (OPC), natural fine aggregate, natural coarse aggregate, clay, coconut fiber ash, rice husk ash, and water. OPC was obtained from PT Semen Tiga Roda. The raw clay was collected from a pottery production area in Tulungagung, East Java, Indonesia. Natural fine aggregate was obtained from Lumajang, Indonesia, and natural crushed stone with a nominal size of 5–10 mm was used as the normal coarse aggregate. Tables 1–3 summarize the main properties of the cement, fine aggregate, and coarse aggregate.

CFA and RHA were used as mineral and pore-forming additives in ALWA production. Two composition codes were evaluated: C1, comprising 97% clay, 2% CFA, and 1% RHA by mass, and C2, comprising 95% clay, 3% CFA, and 2% RHA by mass. C1 was selected on the basis of preliminary workability and particle stability observations and was used to produce the ALWA for the subsequent concrete mixtures. The raw materials are shown in Fig. 1, and their chemical compositions are subsequently used to interpret the roles of silica, alumina, and alkali oxides during sintering.

Table 1. Cement characteristics

Parameter	Result	Unit	Requirement
Specific gravity	3.10	g/cm ³	-
Initial setting time	133	min	>= 45 min
Final setting time	242	min	<= 375 min

Table 2. Physical properties of fine aggregate

Parameter	Value
Fineness modulus	3.04
Gradation zone	Zone 1
Bulk density	1.662 g/cm ³
Mud content	1.64%
Specific gravity	2.701
Water absorption (SSD)	1.695%

Table 3. Physical properties of natural coarse aggregate

Parameter	Value
Fineness modulus	5.83
Aggregate size	5-10 mm
Bulk density	1.528 g/cm ³
Mud content	0.33%
Specific gravity	2.687
Water absorption (SSD)	1.752%



CLAY



COCONUT FIBER ASH



RICE HUSK ASH

Fig. 1. Raw materials used for ALWA production

2.2 ALWA Preparation and Sintering

The preparation procedure consisted of dry mixing, water addition, mechanical pressing, pre-pellet cutting, pelletization, drying, and sintering. The complete workflow is summarized in Fig. 2. Clay, CFA, and RHA were dry-mixed until visually homogeneous. Water was then added gradually to obtain a plastic consistency suitable for particle formation. The mixture was pressed using a hydraulic jack-assisted molding system under a constant applied load corresponding to a 20 kg mass, as illustrated in Fig. 3.

The pressed material was cut into approximately 20 mm × 20 mm pre-pellets, as shown in Fig. 4. The pre-pellets were rotated in a mixer at an inclination angle of about 45° for 4-5 min to reduce sharp edges and obtain rounded aggregate particles, as shown in Fig. 5. The particles were dried at room temperature for 48 h before sintering. Three sintering regimes were evaluated (Table 4). In the two-stage process, heating at 500 °C was intended to remove bound water and volatile material before the final 900 °C stage, thereby reducing sudden internal expansion and cracking. The electric furnace used for sintering is shown in Fig. 6.

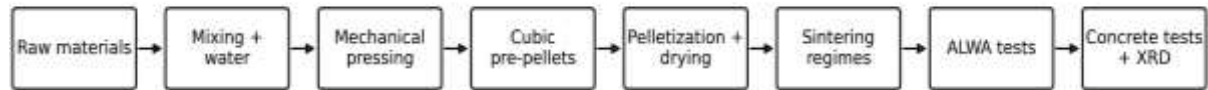


Fig. 2. Experimental workflow for ALWA production and concrete evaluation

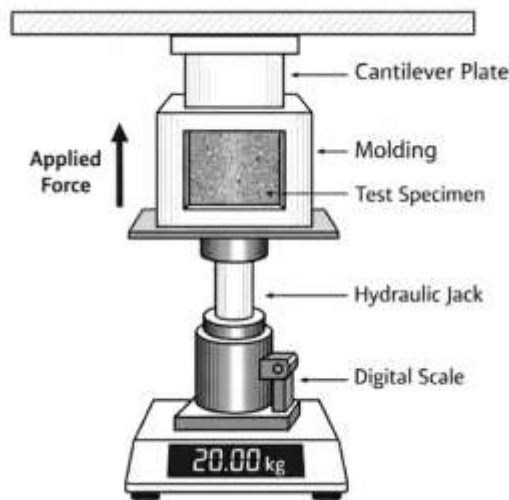


Fig. 3. Schematic illustration of the ALWA pressing system



Fig. 4. Cubic pre-pellets before pelletization



Fig. 5. Pelletization process using mixer rotation

Table 4. Sintering variations

Code	Temperature (°C)	Heating process	Heating duration
S1	500	Single-stage	1 h
S2	900	Single-stage	1 h
S3	500 + 900	Two-stage	1 h + 20 min

**500 °C for 1 h****900 °C for 20 min**

Fig. 6. Sintering process using an electric furnace

2.3 Aggregate and Concrete Testing

The produced aggregate was evaluated using visual inspection, oven-dry bulk specific gravity, water absorption, single-particle crushing strength, and X-ray diffraction (XRD). The oven-dry bulk specific gravity was calculated from the oven-dry particle mass and the displaced particle volume obtained by water immersion; water absorption was calculated from the mass difference between the oven-dry and saturated surface-dry (SSD) states. Single-particle crushing tests were performed using a Universal Testing Machine, and only particles without visible defects were selected. Before concrete batching, the selected C1-S3 ALWA was pre-soaked in water for 24 h and then air-dried for 6 h to obtain a reproducible SSD condition. The test setup is shown in Fig. 7. According to the experimental record confirmed by the first author, the XRD specimen was a C1 ALWA subjected to the two-stage S3 regime (500 °C for 1 h followed by 900 °C for 20 min); the laboratory file name retained “900” because 900 °C was the final firing stage.



Fig. 7. Single-particle crushing test of ALWA using a Universal Testing Machine

Concrete mixtures were prepared by volume-based replacement of natural coarse aggregate with ALWA. Four replacement levels were used: 0%, 35%, 50%, and 100%, identified as V0, V1, V2, and

V3, respectively. The replacement masses were calculated using the oven-dry bulk specific gravities of the natural coarse aggregate (2.687) and the selected C1-S3 ALWA (1.62), rather than loose bulk densities. Cylindrical specimens of 100 mm × 200 mm were prepared for compressive-strength and density tests, with three specimens tested for each mixture and age. Compressive strength was measured at 7, 14, and 28 days. Flexural strength was evaluated using 100 mm × 100 mm × 400 mm prisms under center-point loading, and the modulus of rupture f_r was calculated from Eq. (1) [17–19]. The concrete mix proportions are summarized in Table 5.

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

where P is the maximum applied load, L is the span, b is the beam width, and h is the beam depth. The concrete compression setup is shown in Fig. 8. The 28-day flexural-to-compressive strength ratios were compared with the ACI 318-19 expression for modulus of rupture and the corresponding Indonesian concrete-code expression [17–18]. Potential outliers were evaluated using ASTM E178-21; no observation was deleted solely because it interrupted an age-related trend [20].



Fig. 8. Concrete compressive strength testing setup

Table 5. Concrete mix proportions

Variation	Description	Cement (kg)	Water (kg)	Sand (kg)	Gravel (kg)	ALWA (kg)
V0	0% ALWA	402	205	660	1000	0
V1	35% ALWA	402	205	660	652	205
V2	50% ALWA	402	205	660	500	315
V3	100% ALWA	402	205	660	0	600

3. Results

3.1 Chemical, Physical, and Mineralogical Characteristics of ALWA

An X-ray fluorescence (XRF) analysis showed that RHA had the highest SiO_2 content (54.13%), while CFA contained 36.61% SiO_2 and a comparatively high K_2O content of 17.12%; the clay contained 40.13% SiO_2 and 26.55% Al_2O_3 (Table 6). These measured oxides provide a basis for a bounded sintering interpretation. K_2O can act as a fluxing oxide in clay-derived sintered systems [6,21–22], but the present results do not support a simple monotonic claim that more CFA or more K_2O necessarily increases particle strength: C2 actually contains more CFA (3%) and more RHA (2%) than C1 (2% CFA and 1% RHA), yet C1 was stronger than C2 under all three thermal regimes in the crushing-strength results reported below. The difference therefore reflects the combined feed composition and thermal history rather than a single-oxide effect. The 500 °C pre-stage can plausibly separate part of the dehydration/devolatilization process from the final 900 °C sintering

stage, which is consistent with the fewer visible macroscopic cracks and higher C1 crushing strength after S3. This remains a mechanism-consistent hypothesis, not direct proof of liquid-phase formation, pore stabilization, or microscopic densification, because thermogravimetry, dilatometry, SEM, quantitative phase analysis, and pore-size distribution were not measured.

Table 6. Oxide composition of CFA, RHA, and clay used to support the bounded chemistry-based sintering interpretation

Oxide Compound	CFA (%)	RHA (%)	Clay (%)
SiO ₂	36.61	54.13	40.13
Al ₂ O ₃	3.28	3.09	26.55
Fe ₂ O ₃	3.36	4.89	16.25
CaO	7.96	3.83	0.86
K ₂ O	17.12	8.02	0.35
MgO	3.17	1.86	0.49

Visual observations confirmed that the applied thermal regime affected the macroscopic condition of the particles. Aggregates fired at 500 °C retained their general shape but showed limited apparent sintering. Direct firing at 900 °C showed visible cracking and pore openings. Under the two-stage S3 regime, the illustrated particles showed fewer visible macroscopic defects and C1 reached the highest measured mean single-particle crushing strength (16.29 ± 3.78 MPa), compared with 10.60 ± 2.03 MPa at 500 °C and 10.55 ± 5.10 MPa at 900 °C. These measured values and the corresponding macroscopic comparison are summarized in Fig. 9. These observations are macroscopic and do not quantify pore size, pore connectivity, or microscopic compactness.

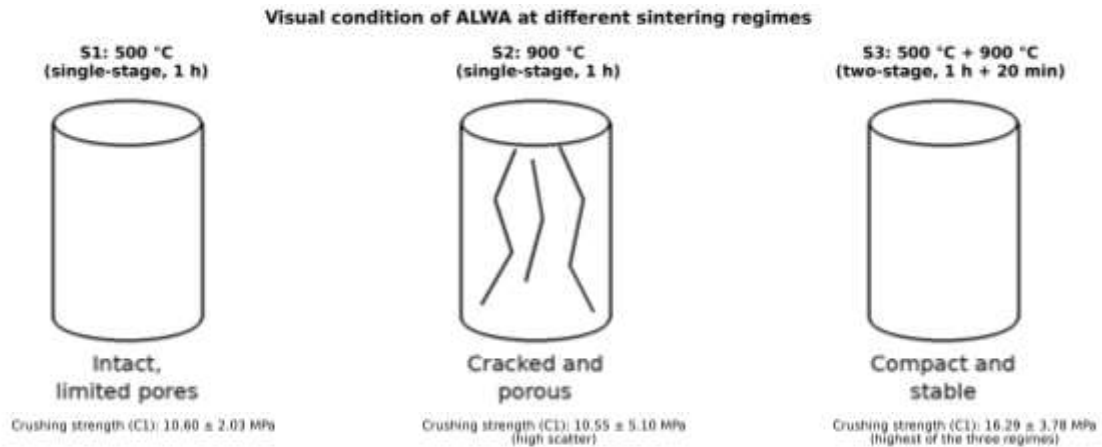


Fig. 9. Macroscopic comparison of ALWA under the three sintering regimes, annotated with the corresponding C1 single-particle crushing strengths; the schematic descriptors do not represent pore-size or microscopic measurements

The selected C1-S3 ALWA had an oven-dry bulk specific gravity of 1.62 and water absorption of 27.49% (Table 7). The specific gravity was substantially lower than that of the natural coarse aggregate (2.687), confirming its density-reduction function. The high absorption demonstrates substantial water-accessible porosity, but it does not by itself establish pore-size distribution or pore-network connectivity. Practically, such absorption can make the effective mixing-water condition and workability sensitive to the aggregate moisture state and may influence transport-related durability; these implications are addressed explicitly in Sections 4.1 and 4.4 [23–26].

Table 7. Physical properties of the selected C1-S3 ALWA used in concrete, highlighting low oven-dry bulk specific gravity and high-water absorption

Parameter	Value
Oven-dry bulk specific gravity	1.62
Water absorption	27.49%

Single-particle crushing results showed that two-stage sintering produced the highest particle resistance (Table 8). C1 and C2 are composition codes rather than replicate-series identifiers: C1 contains 97% clay, 2% CFA, and 1% RHA, whereas C2 contains 95% clay, 3% CFA, and 2% RHA. Under the S3 two-stage regime, C1 reached 16.29 MPa and C2 reached 11.69 MPa. Direct single-stage firing generally produced lower strength or greater scatter. C1-S3 was selected for all subsequent concrete batches. The observed temperature sensitivity is consistent with previous studies showing that firing regime and clay-based phase development govern lightweight-aggregate porosity and particle resistance [21–22].

Table 8. Effect of composition and sintering regime on single-particle crushing strength; S3 gives the highest mean strength for both C1 and C2

Composition	Temperature (°C)	<i>n</i>	Average strength (MPa)	s.d. (MPa)
C1	500	7	10.60	2.03
C2	500	6	8.54	1.55
C1	900	6	10.55	5.10
C2	900	4	6.98	1.53
C1	500 + 900	3	16.29	3.78
C2	500 + 900	3	11.69	0.41

For context, the selected C1-S3 aggregate combines a relatively low oven-dry bulk specific gravity (1.62) with high water absorption (27.49%). The absorption is comparable to the approximately 27% value reported for a recent recycled-concrete-fines artificial aggregate [14] but is higher than the below-20% values reported for optimized binary clay-based artificial aggregates in recent work [15]. The measured single-particle crushing strengths (11.69–16.29 MPa for the S3 compositions) provide a direct particle-level resistance metric, while the high absorption remains a clear practical limitation. Because aggregate degradation during full-scale handling, mixing, pumping, or repeated transport was not separately quantified, the present results are not used to claim field-scale abrasion or handling adequacy. The aggregate is therefore benchmarked as a reduced-density product requiring moisture and durability control rather than as a direct equivalent to a low-absorption commercial expanded-clay aggregate. The qualitative XRD pattern used for mineralogical screening is presented in Fig. 10.

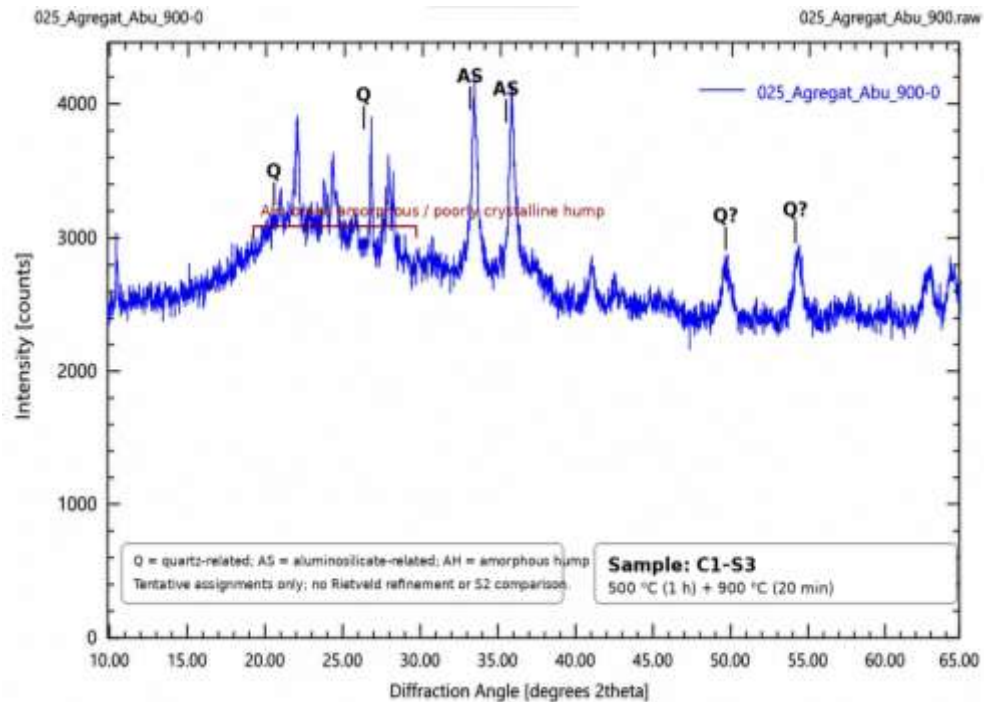


Fig. 10. XRD pattern of C1 ALWA after the S3 two-stage treatment (500 °C for 1 h followed by 900 °C for 20 min). Q = tentative quartz-related peak; AS = tentative aluminosilicate-related feature; AH = broad amorphous hump. Assignments are qualitative

The C1-S3 scan contains prominent features tentatively associated with quartz and aluminosilicate phases, together with a broad hump in the 2θ range of approximately 20° – 30° , which is consistent with an amorphous or poorly crystalline fraction. These annotations are qualitative because the available laboratory output did not include Rietveld refinement or reference-pattern matching statistics, and no comparative S2 scan was available. No scanning electron microscopy (SEM) images were collected. Consequently, the interpretation is restricted to qualitative mineralogical screening, macroscopic defect observations, and measured particle strength; microscopic compactness is not claimed.

3.2 Compressive Strength and Density

Compressive strength and density results are shown in Table 9. The control mixture achieved 35.38 MPa at 28 days. Among ALWA mixtures, the 50% replacement mixture (V2) showed the most balanced development, increasing from 21.93 MPa at 7 days to 24.19 MPa at 28 days. The 100% ALWA mixture reached the largest density reduction but also the lowest strength, indicating that excessive replacement creates a more deformable aggregate skeleton and weaker load path.

Table 9. Compressive-strength development and density of ALWA concrete; V2 provides the best 28-day strength-density balance among the ALWA mixtures

ALWA replacement (%)	7 days (MPa)	14 days (MPa)	28 days (MPa)	Density (kg/m ³)	Density reduction (%)
0	23.96 ± 2.90	29.84 ± 3.69	35.38 ± 2.88	2330	-
35	22.13 ± 0.81	17.61 ± 0.43	23.02 ± 3.76	2300	1.3
50	21.93 ± 2.63	22.47 ± 1.52	24.19 ± 3.29	2210	5.1
100	17.63 ± 2.09	17.80 ± 1.03	20.12 ± 1.12	2170	6.9

Note: Values are means ± standard deviation, where replicate data were available. ALWA, artificial lightweight aggregate. Comparative takeaway: V2 (50% ALWA) provides the best combined 28-day strength-density response among the ALWA mixtures (24.19 MPa and 2210 kg/m³, a 5.1% density reduction); V3 gives the largest density reduction (6.9%) but the lowest 28-day compressive strength, while V1 contains the unresolved 14-day anomaly discussed below.

The 35% ALWA mixture showed non-monotonic between-specimen strength results: 22.13 ± 0.81 MPa at 7 days, 17.61 ± 0.43 MPa at 14 days, and 23.02 ± 3.76 MPa at 28 days. The 14-day coefficient of variation was 2.4%, indicating that the lower mean was shared by the three specimens rather than being caused by one isolated outlier. Because different cylinders were tested at each age, the sequence must not be interpreted as strength loss followed by recovery within the same specimen. Porous lightweight aggregates can alter effective water availability and paste-aggregate interfacial conditions depending on initial moisture state and absorption kinetics [6,16,23], but the present program did not measure internal relative humidity, absorption-time response, SEM morphology, or leaching. The mechanism therefore remains unresolved, and no internal-curing, leaching, or moisture-driven strength-recovery mechanism is claimed. The observations were retained because ASTM E178-21 did not justify deletion based solely on trend inconsistency. A rigorous follow-up should use independently prepared replicate batches, a larger replicate number selected through an a priori precision or power criterion, randomized specimen allocation to test ages, and a controlled/logged ALWA moisture-conditioning protocol. Companion measurements of absorption kinetics and, where feasible, internal relative humidity would allow any recurrence of the pattern to be tested against measured moisture variables rather than inferred retrospectively.

3.3 Flexural Strength and Density-Based Classification

Flexural strength results are presented in Table 10. The control mixture achieved the highest 28-day modulus of rupture of 9.26 MPa. Among ALWA mixtures, V2 again gave the best balance, reaching 7.12 MPa at 28 days. Although flexural strength generally decreased with increasing ALWA content, all mixtures retained measurable post-casting strength development. The 50% mixture retained 76.9% of the control flexural strength while reducing density by about 5.1%. Table 11 compares the 28-day mechanical performance and density-based classification. All mixtures exceeded the 17.24 MPa minimum compressive-strength threshold cited in the Indonesian lightweight-concrete guidance [27]. However, the densities of all ALWA mixtures remained above 1850 kg/m³. The present V1-V3 mixtures are therefore described consistently as

reduced-density concrete rather than structural lightweight concrete. This terminology aligns the engineering claim with both measured strength and measured density.

Table 10. Flexural-strength development of ALWA concrete; V2 reaches 7.12 MPa at 28 days while reducing density by 5.1%

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

Note: Values are means ± standard deviation for $n = 3$ specimens. f_r , modulus of rupture.

Table 11. Mechanical performance and density-based classification at 28 days; all ALWA mixtures remain above 1850 kg/m³ and are designated reduced-density concrete

ALWA (%)	f_c' (MPa)	Density (kg/m ³)	f_r (MPa)	f_r/f_c'	ACI f_r pred. (MPa)	SNI f_r pred. (MPa)	Classification
0	35.38	2330	9.26	0.262	3.69	3.69	Normal weight
35	23.02	2300	8.23	0.357	2.97	2.97	Reduced-density
50	24.19	2210	7.12	0.294	3.05	3.05	Reduced-density
100	20.12	2170	6.78	0.337	2.78	2.78	Reduced-density

Note: ACI 318-19 and SNI 2847:2019 predictions are based on $f_r = 0.62\lambda\sqrt{f_c'}$. All mixtures have density above 1850 kg/m³; therefore, $\lambda = 1.0$ is applied in this comparison. Comparative takeaway: measured f_r values are approximately 2.3-2.8 times the corresponding code estimates for all four mixtures, including the normal-weight control; therefore, the excess is not uniquely attributable to ALWA replacement.

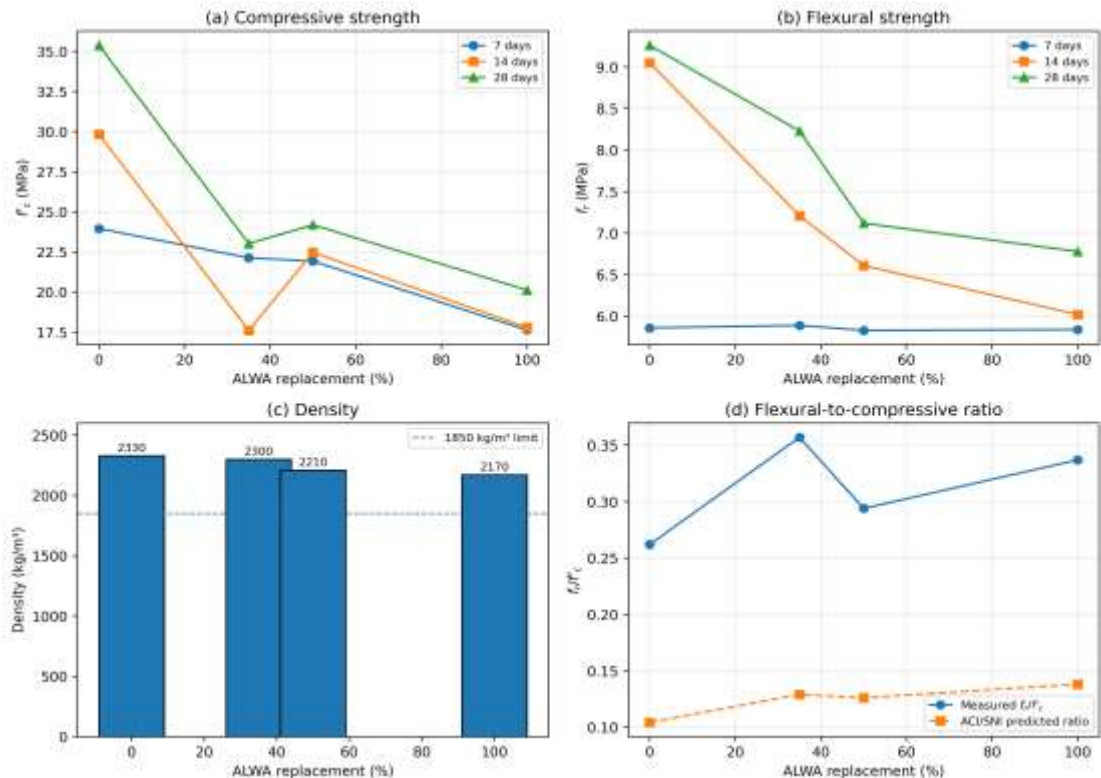


Fig. 11. Coupled performance of non-expanded ALWA concrete: (a) compressive-strength development, (b) flexural-strength development, (c) density, and (d) measured f_r/f_c' ratio compared with the ACI prediction

All three ALWA mixtures exceed the cited Indonesian compressive-strength threshold on strength alone but do not satisfy the cited 1850 kg/m³ density limit. Density is therefore the classification-

limiting property, and the term reduced-density concrete is used throughout for V1-V3. The measured f_r/f_c' ratios ranged from 0.262 to 0.357 and exceeded the corresponding code-predicted ratios. This does not imply that the code expression is invalid. Center-point loading can give higher modulus-of-rupture values than third-point loading, and the normal-weight control also shows a comparably large margin over the prediction (Table 11). The observed excess is therefore discussed primarily as a test-configuration/material-system effect rather than as evidence of an ALWA-specific surface mechanism. Figure 11 summarizes the coupled compressive-strength, flexural-strength, density, and ratio results.

4. Discussion

4.1 Effect of Two-Stage Sintering on Aggregate Quality

The measured results show that the two-stage S3 regime produced the most favorable macroscopic/mechanical response for the tested clay-CFA-RHA formulation: fewer visible macroscopic defects and the highest C1 single-particle crushing strength. A plausible process explanation is that the 500 °C hold permits part of the dehydration and volatile release to occur before the final 900 °C sintering stage, thereby reducing the coincidence of rapid gas evolution with high-temperature softening. The measured oxide composition is consistent with a fluxing contribution from CFA because K_2O is a recognized fluxing oxide in sintered clay systems [6,21–22]; however, C2 contains more CFA and RHA than C1 and nevertheless gives lower crushing strength at every regime. The results therefore do not support attributing C1 superiority to K_2O alone. The overall response is more reasonably interpreted as the combined effect of clay fraction, ash dosage, oxide balance, gas evolution, and thermal history. Because SEM, thermogravimetry/dilatometry, quantitative phase analysis, and pore-size measurements were not available, no microscopic densification, liquid-phase fraction, or pore-stabilization mechanism is claimed as experimentally demonstrated.

The 27.49% water absorption is a critical implementation constraint rather than a secondary material property. In the present experiment, the selected ALWA was pre-soaked for 24 h and air-dried for 6 h before batching as the laboratory moisture-conditioning procedure. If a highly absorptive aggregate enters the mixer below its intended moisture state, part of the batch water may be withdrawn during mixing and early placement; if free surface water is present, the effective water addition can increase locally. Either condition can affect workability and strength repeatability. Because an absorption-time curve and fresh-concrete slump-retention series were not measured here, the manuscript does not claim a measured slump-loss rate. For field implementation, the following controls are recommended: (i) determine absorption kinetics at short and long intervals; (ii) define a mass-based target moisture range rather than relying on conditioning time alone; (iii) measure stockpile moisture and correct batch water for absorbed and free surface water; (iv) verify slump immediately after mixing and at relevant placement times such as 30 and 60 min; and (v) use a compatible water-reducing admixture rather than uncontrolled additional water. If absorption remains excessive, revised sintering or a validated surface-treatment approach may be considered. The large water-accessible porosity implied by the absorption result also makes direct durability testing necessary; it should not be treated as proof of a specific connected pore network. Durability implications and appropriate follow-up tests are discussed in Section 4.4.

4.2 Density-Strength Trade-Off and Engineering Relevance

The 50% ALWA replacement mixture is the most defensible optimum within the tested matrix because it balances density, compressive strength, and flexural strength rather than maximizing one response. The 100% mixture produced the lowest density but the greatest strength reduction. The 35% mixture retained higher 28-day flexural strength than the 50% mixture, but its compressive-strength dataset contained the unresolved 14-day anomaly. Accordingly, V2 provides the most consistent combined performance for applications requiring moderate self-weight reduction with adequate mechanical resistance. This balanced outcome is consistent with earlier ALWA studies showing that aggregate-production route, replacement level, and binder system jointly influence density, compressive strength, and tensile/flexural response [11–13].

Nevertheless, the cold-bonded and polystyrene-based aggregates examined previously are not directly equivalent to the present sintered clay-CFA-RHA system.

From a structural-engineering perspective, the present mixtures should be considered reduced-density concrete until a broader performance database is available. Potential applications may include selected precast or architectural components and other elements where moderate self-weight reduction is useful, but the current study does not establish design suitability for major structural members. Such use requires evaluation of elastic modulus, drying shrinkage, creep, reinforcement bond, durability, and member-level stiffness and strength, together with project-specific code checks.

4.3 Sustainability Implications and Limitations

The use of CFA and RHA provides a resource-efficiency rationale because both are agricultural by-products. The two-stage process also used a peak temperature of 900 °C, below the bloating temperatures commonly associated with expanded-clay manufacture [5–6]. These observations indicate potential environmental benefit only. They do not establish a lower environmental footprint because drying, grinding, rejected particles, furnace efficiency, transport, service life, and end-of-life treatment were not quantified. A cradle-to-gate or cradle-to-grave life-cycle assessment is therefore a prerequisite before the material is described as green, low-carbon, or environmentally superior. This study used one clay source, two CFA-RHA compositions for particle-level comparison, one selected C1-S3 aggregate for concrete production, one principal concrete mix design, and three specimens per variation and test age. The XRD scan represented C1-S3 and was interpreted qualitatively; no comparative S2 scan, SEM, quantitative phase analysis, pore-size distribution, thermogravimetry/dilatometry, absorption-time curve, or internal-moisture measurements were available. The flexural test used center-point loading, which can yield higher modulus-of-rupture values than third-point loading, so comparisons with other loading configurations should be made cautiously. These analytical and replication limits constrain mechanistic interpretation. Future work should add direct microstructural/thermal characterization, durability and serviceability testing, independent replicate batches, and formal life-cycle assessment [28].

4.4 Durability Considerations

Durability was not evaluated experimentally in this study and is therefore treated as a priority limitation. The 27.49% absorption demonstrates substantial water-accessible porosity in the selected aggregate, but absorption alone cannot quantify sulfate resistance, carbonation rate, chloride transport, or freeze-thaw performance of the resulting concrete. Transport and deterioration depend on the combined cement-paste matrix, interfacial transition zone, aggregate moisture state, and any accessible aggregate porosity. Accordingly, the present mechanical results should not be extrapolated to long-term or aggressive-exposure performance. A standards-based follow-up program is recommended. ASTM C1012/C1012M-24a [29] can be used as a binder/mortar-level sulfate-susceptibility screening method, but because its scope is hydraulic-cement mortar rather than concrete, it should be supplemented by a defined concrete-level sulfate-exposure program with expansion and residual mass/strength measurements. For reinforced applications, apparent chloride diffusion can be evaluated using ASTM C1556-25 [30]. Accelerated carbonation resistance can be compared using ISO 1920-12:2015 [31], which remains current, and freeze-thaw resistance of concrete can be evaluated using ASTM C666/C666M-26 [32] where freezing exposure is relevant. These tests should be paired with sorptivity/water-absorption measurements and SEM/porosimetry so that transport-related performance can be related to measured material characteristics rather than inferred from absorption alone.

5. Conclusions

This study investigated thermal-regime control of a clay-based artificial lightweight aggregate incorporating coconut fiber ash and rice husk ash and evaluated the selected aggregate in reduced-density concrete. The clearest aggregate-level result is that the two-stage S3 sequence (500 °C followed by 900 °C) produced fewer visible macroscopic defects and the highest measured C1 mean

single-particle crushing strength (16.29 ± 3.78 MPa) among the tested thermal regimes. C1 contained 97% clay, 2% CFA, and 1% RHA and was selected for concrete production. Its oven-dry bulk specific gravity was 1.62 and its water absorption was 27.49%. XRF showed that RHA was silica-rich and CFA contained a comparatively high K_2O fraction. Although K_2O can contribute to fluxing during sintering, C2 contained more CFA and RHA than C1 yet remained weaker under each thermal regime; consequently, the results do not support a single-oxide explanation for C1 performance. The combined feed composition and staged thermal history provide a plausible process interpretation, but the qualitative C1-S3 XRD pattern, without SEM, quantitative phase analysis, thermal analysis, or pore-size measurements, does not establish microscopic densification, liquid-phase fraction, or pore topology. ALWA incorporation reduced concrete density at every replacement level. The 50% mixture (V2) provided the best combined response within the tested matrix, reaching 24.19 MPa compressive strength, 7.12 MPa flexural strength, and 2210 kg/m^3 density at 28 days. It retained 68.4% of the control compressive strength and 76.9% of the control flexural strength while reducing density by 5.1%. The 100% replacement mixture achieved the largest density reduction (6.9%) but the lowest 28-day compressive strength. Although all ALWA mixtures exceeded the cited Indonesian compressive-strength threshold for structural lightweight concrete, their measured densities remained above 1850 kg/m^3 . V1-V3 are therefore classified consistently as reduced-density concrete. The non-monotonic V1 age results, including the 17.61 ± 0.43 MPa mean at 14 days, are retained as an unresolved between-age/between-specimen anomaly and are not interpreted as evidence of internal curing, leaching, or strength recovery. The high ALWA absorption is the principal implementation limitation. The laboratory used 24 h pre-soaking followed by 6 h air-drying, but future mixture design should determine absorption kinetics, define a mass-based aggregate moisture target, correct batch water for absorbed and free surface water, and verify workability retention rather than compensate with uncontrolled water addition. Durability was not measured, so the 27.49% absorption should be treated as a reason for testing rather than as proof of poor durability. Future validation should include concrete-level sulfate exposure, carbonation, chloride transport for reinforced applications, and freeze-thaw testing where relevant, together with sorptivity, shrinkage, elastic modulus, creep, reinforcement bond, and member-level serviceability. The center-point flexural results should also be interpreted with the known limitation that this loading configuration can yield higher modulus-of-rupture values than third-point loading. Finally, CFA and RHA provide a resource-efficiency rationale, but the study does not establish environmental superiority; formal life-cycle assessment remains necessary before green or low-carbon claims are made.

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