

Preliminary Development of Lightweight Concrete through the Integration of Waste-Derived Materials

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Abstract : *The increasing demand for natural resources and the accumulation of agricultural and construction waste have encouraged the development of alternative materials for concrete production. This study presents a preliminary investigation of lightweight concrete incorporating pumice and coconut shell as components of the coarse aggregate system, roof-tile waste as a partial replacement for natural fine aggregate, and eggshell powder and quicklime as components of the binder system. The developed mixture was evaluated in terms of density and 7-day compressive strength using three cylindrical specimens. The average density was 1,600 kg/m³, with a standard deviation of 11.14 kg/m³, while the average compressive strength was 14.00 MPa, with a standard deviation of 0.26 MPa. The coefficients of variation were 0.70% for density and 1.89% for compressive strength. These results provide an initial characterization of the developed mixture and indicate the feasibility of combining lightweight and waste-derived materials in a single concrete mixture. However, the findings are limited to one mixture composition and a 7-day testing age. Further investigation involving direct 28-day strength testing, additional mixture proportions, and durability evaluation is required to establish the engineering performance of the developed concrete.*

Kata Kunci : *Lightweight Concrete; Waste-Derived Materials; Pumice; Coconut Shell; Roof-Tile Waste; Eggshell Powder; Quicklime*

INTRODUCTION

The construction industry consumes substantial quantities of natural resources and contributes to environmental impacts through the extraction, processing, and production of construction materials. Concrete, one of the most widely used construction materials, relies heavily on Portland cement and natural aggregates. The continued demand for these conventional constituents has increased interest in alternative materials that can reduce dependence on virgin resources and provide beneficial applications for waste materials (Collivignarelli et al., 2020; Sandanayake et al., 2020; Zamora-Castro et al., 2021). The incorporation of waste-derived materials into concrete

provides an opportunity to address both resource consumption and waste accumulation. Agricultural, food-related, and construction wastes have been investigated as potential alternative materials for concrete, either as aggregate replacements or as partial replacements within cementitious systems. However, waste-derived materials possess different physical and chemical characteristics from conventional concrete constituents. Their density, porosity, particle characteristics, water absorption, and interaction with the cementitious matrix can consequently influence the fresh and hardened properties of concrete (Collivignarelli et al., 2020; Sandanayake et al., 2020).

Lightweight concrete provides a particular opportunity for incorporating low-density alternative aggregate materials. Pumice is a porous volcanic material with relatively low density and has been used as a lightweight aggregate in concrete. Coconut shell, as an agricultural waste material, also has potential as a lightweight aggregate because of its relatively low density. Nevertheless, the porous characteristics of lightweight aggregates can affect water absorption, workability, stress transfer, and compressive strength. The development of lightweight concrete therefore requires an appropriate balance between density reduction and mechanical performance (Dwarampudi & Venkateshwari, 2024; Mutnbak, 2026). Construction-derived waste can also be incorporated into the fine aggregate system. Recycled roof-tile waste, after appropriate processing and particle-size classification, can be used as an alternative aggregate material. Previous research has demonstrated the potential of recycled roof-tile aggregate in concrete while also highlighting the importance of its characteristics for strength development and durability (Ceesay & Miyazawa, 2019). In addition, eggshell waste has been investigated as a calcium-rich material for partial replacement or modification of cementitious constituents. Previous studies have examined the use of eggshell powder in cement-based materials, with its performance depending on factors such as processing, particle size, and replacement level (Sagar et al., 2023; Chong et al., 2024).

Although individual waste-derived and lightweight materials have been investigated in concrete, the simultaneous integration of materials with different functions presents a different materials-engineering problem. In an integrated mixture, lightweight aggregates influence density and moisture behavior, recycled fine aggregates influence particle packing and water demand, while eggshell powder and quicklime form part of the binder system and may influence matrix development. The combined effects of these materials cannot necessarily be predicted from the behavior of each material when used independently. Therefore, experimental evaluation of the integrated mixture is required to determine whether density reduction can be achieved while retaining measurable mechanical performance.

Accordingly, this study presents a preliminary development of lightweight concrete through the integration of various waste-derived and lightweight materials. Pumice and coconut shell were incorporated as components of the coarse aggregate system, roof-tile waste was used as a partial replacement for natural fine aggregate, and eggshell powder and quicklime were incorporated as components of the binder system. The developed mixture was preliminarily evaluated based on density and compressive strength. The study aims to assess the feasibility of integrating these materials within a single lightweight concrete mixture and to provide an initial basis for further investigation of its mechanical and durability performance.

RESEARCH METHODS

Material

Portland cement was used as the primary cementitious material in the concrete mixture. It served as the principal binder responsible for binding the aggregate particles and contributing to strength development through hydration. The Portland cement used in the mixture had a density of $3,150 \text{ kg/m}^3$. Clean water was used for concrete mixing. Water was required for the hydration of the cementitious binder and for producing a workable fresh concrete mixture. The water content was determined according to the predetermined mix-design procedure. The density of water was taken as $1,000 \text{ kg/m}^3$. Merapi sand was used as the primary natural fine aggregate. The sand contributed to the fine aggregate fraction and particle packing within the concrete mixture. A portion of the natural sand was replaced with processed roof-tile waste according to the predetermined mixture proportions. The density of the Merapi sand used in the mix-design calculation was $2,550 \text{ kg/m}^3$. Pumice was incorporated as a lightweight component of the coarse aggregate system. Its relatively low density was utilized to reduce the overall density of the concrete mixture. The density adopted for the mix-design calculation was 850 kg/m^3 .

Coconut shell was incorporated as another lightweight component of the coarse aggregate system. The material was processed into aggregate particles suitable for concrete production and incorporated according to the predetermined mixture proportions. A density of 700 kg/m^3 was adopted for the mix-design calculation. Discarded roof tiles were processed and incorporated as a partial replacement for natural fine aggregate. The roof-tile waste was subjected to size reduction and particle-size classification before being incorporated into the concrete mixture. The density adopted for the mix-design calculation was $2,250 \text{ kg/m}^3$. Eggshell waste was processed into eggshell powder (ESP) and incorporated as a partial component of the binder system. The eggshells were cleaned, dried, ground, and sieved before use. A density of $2,450 \text{ kg/m}^3$ was adopted for the mix-design calculation. Quicklime was incorporated as a component of the binder system together with Portland cement and eggshell powder. The density adopted for quicklime in the mix-design calculation was $3,350 \text{ kg/m}^3$. A superplasticizer was incorporated as a chemical admixture to improve the workability of the fresh concrete mixture while limiting the need for additional mixing water. Its dosage was determined according to the predetermined mix-design procedure. All constituent materials are presented in Figure 1.



Figure 1. Constituent Materials

Material Preparation

Prior to concrete production, the constituent materials were prepared according to their respective functions and proportions in the mix design. Pumice and coconut shell were prepared for incorporation into the coarse aggregate fraction. Coconut shells were cleaned to remove adhering impurities and processed into particles of suitable size. Roof-tile waste was cleaned and subjected to crushing and particle-size classification to obtain particles suitable for use as a partial replacement of the natural fine aggregate. The processing of recycled roof-tile material was intended to provide a consistent aggregate fraction for incorporation into the mixture. Eggshell waste was cleaned to remove residual impurities, dried, ground into powder, and sieved before incorporation into the binder system. The prepared materials were subsequently stored and batched according to the predetermined mixture proportions.

Mix Design

The concrete mixture was developed as a preliminary mixture intended to combine conventional, lightweight, and waste-derived materials within a single concrete system. The mix-design procedure considered the target compressive strength, water requirement, water-to-binder ratio, binder composition, aggregate proportions, and superplasticizer dosage. The initial target compressive strength was determined according to the design procedure adopted in the original mix design. The calculation resulted in an initial compressive strength of 21.16 MPa. A strength margin of 8.5 MPa was subsequently incorporated to establish the target strength used in the mixture design. The water requirement was determined based on a target slump of 100 mm and a maximum aggregate size of 20 mm. The initial water requirement was subsequently reduced according to the assumed water-reducing contribution of the superplasticizer. The resulting mixing-water content used in the mixture was 169.3333 kg/m³. The water-to-binder ratio adopted in the mixture was approximately 0.555. The total binder content was 305.20 kg/m³, consisting of Portland cement, eggshell powder, and quicklime.

The binder composition consisted of 88% Portland cement, 2% eggshell powder, and 10% quicklime. Accordingly, the quantities used per cubic metre were 268.5722 kg of Portland cement, 6.1039 kg of eggshell powder, and 30.5196 kg of quicklime. The coarse aggregate system consisted of pumice, coconut shell, and conventional crushed stone. The proportions were established as 65% pumice, 5% coconut shell, and 30% crushed stone, respectively. The total coarse aggregate content adopted in the mix design was 697.00 kg/m³. The fine aggregate system consisted of Merapi sand and roof-tile waste at proportions of 85% and 15%, respectively. The total fine aggregate content adopted in the mix design was 725.58 kg/m³. The superplasticizer dosage was specified in the original mix-design procedure as 0.4% of the Portland cement mass. The dosage should therefore be reported according to the actual laboratory dosage used in concrete production.

The final mixture proportions on a unit-volume basis are presented in Table 3.1. The table follows the predetermined mix design and includes Portland cement, water, eggshell powder, quicklime, pumice, coconut shell, Merapi sand, roof-tile waste, and the conventional coarse aggregate component. Sample preparations and curing process is presented in Figure 2.



Figure 2. Sample Preparations and Curing Process

Table 1. Mix Proportions of the Developed Lightweight Concrete

Material	Quantity (kg/m ³)	Density (kg/m ³)
Portland cement	268.5722	3150
Water	169.3333	1000
Eggshell powder	6.1039	2450
Quicklime	30.5196	3350
Pumice	453.0527	850
Coconut shell	34.8502	700
Merapi sand	616.7462	2550
Roof-tile waste	108.8376	2250

Testing Procedures

The workability of the fresh concrete mixture was assessed using the slump test. The target slump adopted during the mix-design procedure was 100 mm. The test was conducted to evaluate the consistency and workability of the fresh mixture prior to specimen casting. The density of the hardened concrete was determined at 7 days. The density was obtained from the measured mass and volume of the concrete specimen. The measured density was used to evaluate the effectiveness of the lightweight aggregate system in reducing the unit weight of the developed concrete mixture. The compressive strength of the concrete was experimentally determined at 7 days using cylindrical specimens measuring 150 mm in diameter and 300 mm in height. The compressive load was applied until failure, and the compressive strength was determined from the maximum applied load divided by the cross-sectional area of the specimen.

For a specimen diameter of 150 mm, the nominal cross-sectional area is approximately 17,671 mm². The resulting 7-day compressive-strength value was used as the primary measured mechanical-performance indicator of the preliminary mixture. The experimental results were analyzed primarily in terms of density and compressive strength. The density result was interpreted in relation to the incorporation of pumice and coconut shell as lightweight aggregate components, while the compressive-strength result was evaluated in relation to the overall integrated mixture composition.

The measured 7-day compressive strength was also compared with the estimated 28-day strength obtained from the strength-development relationship adopted in the study. The estimated 28-day value was treated as a calculated value rather than a direct

experimental measurement. The slump test and concrete sample appearance after compression test is shown in Figure 3.

Three cylindrical concrete specimens were tested at the age of 7 days to determine compressive strength. The measured compressive strength of each specimen was calculated by dividing the maximum applied load by its measured cross-sectional area. The compressive strength results were then summarized using the arithmetic mean, standard deviation, and coefficient of variation to describe the central tendency and variability of the measurements.

Concrete density was determined from the measured mass and calculated specimen volume. Three specimens were evaluated, and the density results were summarized using the arithmetic mean, standard deviation, and coefficient of variation. These statistical measures were used to describe the variation among the tested specimens. The compressive strength and density measurements were used as the primary indicators for the preliminary evaluation of the developed lightweight concrete mixture.



Figure 3. Slump Test and Concrete Sample Appearance after Compression Test

RESULTS AND DISCUSSION

Density

The density of the developed concrete mixture was evaluated using three cylindrical specimens. The measured densities were 1,588, 1,602, and 1,610 kg/m³ for Specimens 1, 2, and 3, respectively. The average density was 1,600 kg/m³, with a standard deviation of 11.14 kg/m³ and a coefficient of variation of 0.70%. The relatively low coefficient of variation indicates limited variation in density among the three tested specimens. The measured average density provides an initial indication of the lightweight characteristics of the developed mixture. The incorporation of pumice and coconut shell was intended to reduce the density of the concrete mixture because these materials have relatively low densities compared with conventional mineral aggregates.

Table 2. Density Test Results of the Developed Lightweight Concrete

Specimen	Mass (kg)	Volume (m ³)	Density (kg/m ³)
Specimen 1	8.385	0.005280	1,588

Specimen	Mass (kg)	Volume (m ³)	Density (kg/m ³)
Specimen 2	8.524	0.005321	1,602
Specimen 3	8.524	0.005294	1,610
Average	8.478	0.005298	1,600
Standard deviation (SD)	0.080	0.000021	11.14
Coefficient of variation (CV)	0.95%	0.39%	0.70%

Source: Experimental test results.

Nevertheless, the measured density alone does not establish the overall engineering performance of the concrete. Density should be evaluated together with compressive strength and other relevant properties. Further testing involving additional specimens and curing ages would provide a stronger basis for characterizing the density and performance of the developed mixture.

Compressive Strength

The compressive strength of the developed concrete was evaluated using three cylindrical specimens at the age of 7 days. The measured compressive strengths were 14.2, 13.7, and 14.1 MPa, respectively, with an average of 14.00 MPa. The standard deviation was 0.26 MPa, while the coefficient of variation was 1.89%.

Table 3. Compressive Strength Test Results at 7 Days

Specimen	Diameter (mm)	Cross-sectional area (mm ²)	Maximum load (kN)	Compressive strength (MPa)
Specimen 1	149.8	17,624.37	250.27	14.2
Specimen 2	150.2	17,718.61	242.75	13.7
Specimen 3	149.9	17,647.90	248.84	14.1
Average	149.97	17,663.63	247.28	14.00
Standard deviation (SD)	0.21	49.05	3.99	0.26
Coefficient of variation (CV)	0.14%	0.28%	1.61%	1.89%

Source: Experimental test results.

The relatively low coefficient of variation indicates limited variation in compressive strength among the three tested specimens. However, the results represent only the preliminary performance of the investigated mixture and should not be interpreted as evidence of compliance with a particular concrete strength class without reference to the applicable requirements.

The measured compressive strength reflects the combined behavior of the binder and aggregate systems, including Portland cement, eggshell powder, quicklime, pumice, coconut shell, roof-tile waste, and the other mixture constituents. Because the study evaluated a single integrated mixture, the individual contribution of each constituent to compressive strength cannot be isolated from the available results. The 7-day results provide an initial characterization of the developed concrete. Further testing at 28 days and later curing ages is necessary to establish the actual strength development of the mixture.

Relationship Between Density and Compressive Strength

The developed concrete mixture achieved an average density of 1,600 kg/m³ and an average 7-day compressive strength of 14.00 MPa. The corresponding coefficients of variation were 0.70% for density and 1.89% for compressive strength, indicating limited variation among the three tested specimens for both properties.

These results provide an initial characterization of the relationship between density and compressive strength for the investigated mixture. The measured density indicates that the mixture has relatively low unit weight, while the compressive strength results demonstrate that the specimens developed measurable mechanical strength at 7 days.

However, because only one mixture composition was evaluated, the results do not establish a general relationship between density and compressive strength or identify the individual effects of the constituent materials. A more systematic investigation involving different mixture proportions and multiple curing ages is required to determine how changes in material composition affect both properties.

Sustainability Perspective

The preliminary mixture incorporates several waste-derived materials, including coconut shell, roof-tile waste, and eggshell powder, originating from agricultural, construction, and household waste streams. Their incorporation provides an opportunity to utilize materials that would otherwise require disposal while reducing the use of selected conventional concrete constituents. The use of coconut shell as a component of the coarse aggregate system provides a potential alternative to a portion of conventional natural aggregate and contributes to the reduction in concrete density. Similarly, roof-tile waste is used as a partial replacement for natural fine aggregate, providing an application for construction-derived waste while reducing the corresponding demand for virgin fine aggregate.

Eggshell powder is incorporated as a partial component of the binder system. Its use demonstrates the possibility of integrating a calcium-rich biowaste material into a Portland-cement-based concrete mixture. Together, these materials illustrate an integrated approach in which waste-derived materials from different sources perform different functions within the same concrete mixture.

Nevertheless, the incorporation of waste materials does not automatically establish an environmental advantage. Collection, cleaning, crushing, drying, grinding, and particle-size classification require additional materials, energy, and processing. Therefore, the sustainability performance of the developed mixture cannot be quantified solely from the quantity of waste incorporated. A comprehensive assessment involving material consumption, processing energy, embodied carbon, and economic considerations would be required to establish its overall sustainability performance. Overall, the results demonstrate the preliminary feasibility of integrating lightweight and waste-derived materials within a single concrete mixture, while also highlighting the need for further experimental investigation. Direct 28-day and longer-term strength testing, water absorption, durability assessment, and systematic variation of material proportions would provide a stronger basis for evaluating the engineering and sustainability performance of the developed mixture.

CONCLUSION

This study presents a preliminary investigation of lightweight concrete incorporating pumice, coconut shell, roof-tile waste, eggshell powder, and quicklime. The developed mixture achieved an average density of 1,600 kg/m³ and an average 7-day compressive strength of 14.00 MPa based on three tested specimens. The coefficients of variation were 0.70% for density and 1.89% for compressive strength. These results provide an initial characterization of the mixture and indicate the feasibility of integrating lightweight and waste-derived materials within a single concrete system.

The findings remain preliminary because only one mixture composition and one compressive-strength testing age were evaluated. Further studies should include direct 28-day and longer-term strength testing, systematic variation of mixture proportions, and additional performance assessments, including water absorption and durability. These investigations are necessary to establish the engineering suitability and potential sustainability benefits of the developed concrete.

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