Journal of the Civil Engineering Forum, September 2025, 11(3):257-266
DOI 10.22146/jcef.18175
Available Online at https://jurnal.ugm.ac.id/v3/jcef/issue/archive

Sustainable Lightweight Concrete Using Candlenut Shell as Coarse Aggregate: The Impact of Water-Cement Ratios on Strength and Density

Muhammad Reza Hasrul[1,2*], Mohammad Junaedy Rahman[1], Ahnaf Riyandirga Ariyansyah Putra Helmy[1], Taufiq Natsir[1], Ahmad Rifqi Asrib[3]
[1]Department of Civil Engineering and Planning Education, Makassar State University, Makassar, INDONESIA
[2]Graduate School of Environmental, Life, Natural Science and Technology, Okayama University, JAPAN
[3]Department Population and Environmental Education, Graduate School Makassar State University, Makassar, INDONESIA
*Corresponding author: mrezahasrul@unm.ac.id

SUBMITTED 08 December 2024 **REVISED** 23 May 2025 **ACCEPTED** 05 June 2025

ABSTRACT This study explores the promising potential of Candlenut Shell Aggregate (CSA) as a sustainable and innovative alternative for lightweight concrete production. Derived from *Aleurites moluccanus*, CSA is an agricultural by-product characterized by its low density, moderate abrasion resistance, and high water absorption make it suitable for non-structural applications like wall panels and flooring. However, integrating CSA into concrete mixes requires careful management of the water-cement *(w/c)* ratio which significantly affects compressive strength, density, and workability. Concrete mixes were prepared using the absolute volume method, with *w/c* ratios ranging from 0.65 to 0.30, to identify the optimal balance. The absolute volume principle was applied for all mix designs. Our results indicate that an optimal *w/c* ratio of 0.55 yields the most favorable balance, achieving the highest compressive strength of 14.3 MPa and a maximum density of approximately 1850 kg/m^3. This specific ratio strikes an ideal equilibrium between adequate cement hydration and effective void minimization within the concrete matrix. Conversely, higher *w/c* ratios lead to increased porosity, diminishing both strength and density, while lower ratios impair workability, hindering compaction and hydration, ultimately degrading performance. These findings resonate strongly with existing prior research, further emphasizing the crucial need for pre-treatment of CSA, such as soaking or the strategic incorporation of admixtures, to effectively mitigate its inherent high absorption and enhance overall mix performance. In conclusion, this study robustly confirms the feasibility of utilizing CSA as a lightweight aggregate. This represents a significant step towards developing an eco-friendly solution that not only contributes to global sustainability goals by repurposing agricultural waste but also actively reduces reliance on conventional, resource-intensive aggregates. Future research should explore the long-term durability of CSA-based concrete and investigate advanced admixtures to further enhance its properties for broader applications.

KEYWORDS Lightweight concrete; Candlenut shell aggregate; Water-cement ratio; Sustainable construction; Agricultural waste.

1 INTRODUCTION

Lightweight concrete has become increasingly vital in modern construction due to its dual advantages of structural efficiency and environmental sustainability. Typically produced using lightweight or blended aggregates, this type of concrete achieves a maximum density of 1850 kg/m^3 (Mindess et al., 2003). It offers benefits such as reduced dead loads, improved thermal insulation, and lower transportation costs. Studies have further emphasized the need for high-performance lightweight concrete in environmentally challenging settings such as coastal and tropical regions where material degradation is accelerated (Rahman et al., 2024). However, despite these advantages, conventional lightweight concrete often suffers from limitations in mechanical strength and durability, especially when incorporating synthetic or industrial by-product aggregates with inconsistent properties (Sikora et al., 2023). These performance challenges have created a research gap, prompting exploration into alternative aggregate materials that balance structural integrity, cost-effectiveness, and environmental responsibility.

To bridge this gap, researchers are increasingly turning to sustainable aggregates derived from agricultural waste. These materials not only repurpose otherwise discarded biomass but also contribute to a significant reduction in CO_2 emissions associated with aggregate production. For instance, studies have shown that biomass-based concrete can reduce carbon emissions by up to 30% compared to traditional concrete (Jamwal et al., 2024; Navaratnam et al., 2023). Among these alternatives, Candlenut Shell Aggregate (CSA), a by–product of *Aleurites moluccanus*, presents a particularly promising solution. Widely available in countries like Indonesia, CSA is largely underutilized despite its advantageous properties such as low density, moderate hardness, and biodegradability (Putra et al., 2023).

The water-cement (*w/c*) ratio remains a critical factor in determining concrete performance. It directly influences strength, durability, and workability. Higher *w/c* ratios increase porosity, reducing strength and density, while excessively low ratios hinder compaction and hydration (Nawy, 2008; Neville and Brooks, 2010). In lightweight concrete, these challenges are compounded by the variable properties of non-traditional aggregates like CSA, which have high water absorption and organic content. Tailored mix designs, including pre-soaking and the use of water-reducing admixtures, have been recommended to enhance the performance of such materials (Cui et al., 2022; Hilal et al., 2024).

CSA's integration into concrete introduces challenges, particularly related to segregation during mixing due to its lightweight nature. Aggregates may float within the mix when standard *w/c* ratios are applied, leading to nonhomogeneous results. However, research has shown that optimizing the *w/c* ratio and incorporating supplementary cementitious materials (SCMs), such as fly ash or silica fume, can significantly improve hydration, interfacial bonding, and mechanical strength (Carette and Malhotra, 1983; Chindaprasirt et al., 2007). Recent works on foamed concrete and SCMs also support such mix design innovations (Daryono et al., 2023; Patah et al., 2025).

This study investigates the feasibility of CSA as a coarse aggregate for non-structural lightweight concrete applications, including wall panels and flooring. By exploring the effects of varying *w/c* ratios, the research aims to identify the optimal balance between compressive strength and workability. With Indonesia producing over 100 tons of candlenut shells annually, CSA represents a sustainable alternative to conventional aggregates, supporting both waste management and resource conservation goals. The findings contribute to the broader field of sustainable construction by demonstrating the potential of alternative aggregates to meet performance and environmental criteria. Furthermore, the study aligns with global sustainability initiatives, emphasizing material innovation and the reuse of agricultural by-products to reduce environmental impact and promote resource efficiency in the construction sector.

2 MATERIAL AND METHODS

2.1 Material

This study utilized sand as the fine aggregate and Candlenut Shells Aggregate (CSA), sized between 1–2 cm, as the coarse aggregate, as shown in Figure 1. The physical properties of these materials were determined through comprehensive characterization tests. The results, provided in Table 1, demonstrate that CSA exhibits lower specific gravity (1.42) and higher absorption (12.81%) compared to conventional coarse aggregates. These characteristics align with the findings of Natarajan et al. (2022), highlighting the potential of agricultural waste in lightweight concrete applications.

Figure 1 Candlenut Shell Aggregate (CSA)

Table 1. Characteristics of Materials

Testing	Fine Aggregate (Natural Sand (NS))	Candlenut Shell Aggregate (CSA)	Coarse Aggregate (CA)
Specific Gravity SSD Basic	2.44	1.42	2.48
Absorption (%)	7.46	12.81	1.09
Moisture Content (%)	7.42	14.15	0.99
Abrasion (%)	–	9.40	18.83
Silt Content (%)	6.21	7.18	1.04
Unit Weight (gr/L)	1375.80	572.80	1419.08

2.2 Methods

Given the absence of specific guidelines in the Indonesian National Standard (SNI) for lightweight concrete incorporating CSA, the mix design followed the absolute volume principle. The formulations are detailed in Table 2 and 3, presenting mix design data for various *w/c* ratios, with specimens prepared using a mechanical press to ensure consistency. Two compaction techniques were employed: vibration and mechanical pressing. Lower water-cement (*w/c*) ratios (0.35 and 0.30) were compacted exclusively through pressing due to workability constraints, as noted in studies on alternative lightweight aggregates (Alqahtani and Zafar,

Table 2. Volume Absolute Principal Mix Design

Materials Data			
Specific gravity of cement	G_C	=	3.16
Specific gravity of candlenut shell aggregate (CSA)	G_{CSA}	=	1.39
Specific gravity of fine aggregate (Natural Sand (NS))	G_{NS}	=	2.44
Bulk density of candlenut shell aggregate	γ_{CSA}	=	0.57 kg/L
Bulk density of fine aggregate	γ_{NS}	=	1.38 kg/L
Cement Requirements per 1 m^3 of Concrete Mixture			
Determine cement requirements for all mixes	C	=	350.00 kg
Volume of cement	$V_C = C/(G_C \times 1000)$	=	0.11 m
Water Requirements per 1 m^3 of Concrete Mixture			
Water-cement ratio	w/c ratio	=	0.65
Weight of water requirement	$W_w = (w/c\,\text{ratio}) \times C$	=	227.5 kg
	for $G_w = 1$ get $V_w = W_w/(G_w \times 1000)$	=	0.228 m^3
Void			
Assumption of air void content in concrete	v	=	2.0%
	$V_{\text{void}} = 0.01 \times v \times 1$	=	0.02 m^3
Aggregates Requirements per 1 m^3			
If the aggregate content in concrete 60% to 80% by volume	g	=	70.5%
Volume of aggregate in concrete	$V_{Ag} = g \times 1$	=	0.71 m^3
Optimum dry density of combined NS and CSA#	γ_{com}	=	1517.10 kg/m^3
Aggregate compositions by weight	for NS	=	77.00%
	for CSA	=	23.00%
Required weight of NS	$W_{NS} = V_{Ag} \times \gamma_{\text{com}} \times \alpha$	=	823.56 kg
Volume of NS	$V_{NS} = W_{NS}/(G_{NS} \times 1000)$	=	0.34 m^3
Volume of CSA	$V_{CSA} = 1 - (V_C + V_W + V_{NS} + V_v)$	=	0.34 m^3
Required weight of CSA	$W_{CSA} = G_{CSA} \times V_{CSA} \times 1000$	=	417.00 kg
Aggregate-Cement ratio	$A_g/C_{ratio} = (W_{CSA} + W_{NS})/C$	=	3.54

#Note: The aggregate composition was determined by trial and error—filling a flask in layers while tapping with a rubber hammer to allow sand to fill voids between CSA. The mix density was tested using standard methods, and the components were separated by sieving and weighed to determine their proportion.

2023). The compressive strength of the concrete, assessed after 28 days, complied to SNI 1974–2011 standards. The specimens were cured under wet burlap—an approach recognized for minimizing shrinkage and enhancing hydration—consistent with recommendations for lightweight aggregate concretes (Hilal et al., 2024). This methodical approach ensures uniform compaction and evaluates the feasibility of CSA in producing lightweight concrete suitable for both structural and non-structural applications.

3 RESULTS AND DISCUSSION

3.1 Candlenut Shell as Coarse Aggregate

The grain size distribution for Candlenut Shell Aggregate (CSA) and conventional Coarse Aggregate (CA) is shown in Figure 2, with key findings summarized in Table 4. The cumulative passing weight percentages demonstrate CSA's broader particle size distribution compared to CA. This characteristic affects the workability and strength of concrete mixes, and aligns with the findings of Putra et al. (2023), who emphasized

Table 3. Summary of Materials Constituent for Various *W/C* Ratios per 1 m^3 Concrete

Description	**Water-Cement Ratios**				
	0.65	**0.55**	**0.45**	**0.35**	**0.30**
Coarse aggregate	Candlenut Shell Aggregate (CSA)				
Fine aggregate	Natural Sand (NS)				
Maximum aggregate size (mm)	<40	<40	<40	<40	<40
Water requirement in field condition (kg)	235.54	201.57	167.35	133.38	116.14
Cement content (kg/m^3)	350.00	350.00	350.00	350.00	350.00
Water-cement ratio after correction	0.67	0.58	0.48	0.38	0.33
Aggregate requirement in field condition					
- Natural Sand (NS)	823.27	823.27	823.27	823.27	823.27
- Candlenut Shell Aggregate (CSA)	409.25	463.82	504.74	559.31	572.95
Aggregate-cement ratio	3.52	3.68	3.79	3.95	3.99
Unit weight of concrete					
- Design for field condition	1818.06	1838.66	1845.36	1865.96	1862.36
- Actual by trial mixing	1862.43	1794.38	1808.43	1707.84	1788.46

the influence of sand grain size on the compressive strength in cellular lightweight concrete. Similarly, Aboul-Nour et al. (2020) highlighted that the gradation and type of lightweight aggregates significantly influence the strength and density of lightweight aggregate concrete (LWAC).

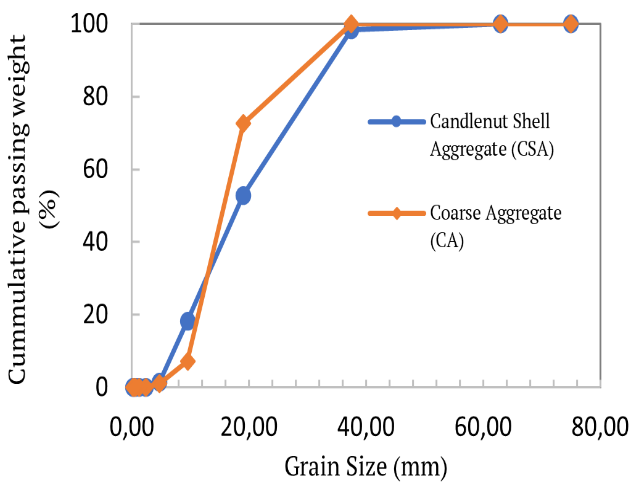

Figure 2 Grain Size Distribution of Candlenut Shell Aggregate (CSA) and Coarse Aggregate (CA)

The properties of CSA underscore its potential as a lightweight aggregate. Its lower specific gravity (1.42) and bulk density (572.80 kg/L) suggest suitability for lightweight concrete applications. However, its higher absorption (12.81%) and moisture content (14.15%) necessitate pre-treatment, such as soaking or the use of water-reducing admixtures, to ensure a stable water-cement ratio (Chandra and Berntsson, 2002; Chindaprasirt et al., 2007).

Table 4. Properties Comparison of Candlenut Shell Aggregate (CSA) and Coarse Aggregate (CA)

Testing	**Candlenut Shell Aggregate (CSA)**	**Coarse Aggregate (CA)**
Specific Gravity SSD Basic	1.42	2.48
Absorption (%)	12.81	1.09
Moisture Content (%)	14.15	0.99
Abrasion (%)	9.40	18.83
Silt Content (%)	7.18	1.04
Bulk Density (kg/L)	572.80	3.66

CSA's lower abrasion resistance (9.40%) compared to conventional coarse aggregates (CA) (18.83%) indicates its superior resistance to wear and mechanical degradation, making it a strong candidate for applications where durability is prioritized. Mannan and Ganapathy (2004) noted that aggregates with high abrasion resistance, such as CSA, can enhance the long-term durability of concrete, particularly in non-structural applications. However, CSA's higher water absorption and lower bulk density require adjustments in mix design, such as increased cement content or the use of supplementary cementitious materials (SCMs), to address potential issues with void content and compaction. Additionally, the higher silt content (7.18%) of CSA compared to CA (1.04%) could weaken the bond strength between the aggregates and cement paste, necessitating cleaning or surface treatment to improve compatibility and bonding performance (Shafigh et al., 2011;

Sivakumar and Santhanam, 2007). The higher silt content observed in CSA is primarily attributed to residual organic matter and fine particles adhered to the shell surface during processing. These impurities are typical of agricultural byproducts and may not be entirely removed without appropriate pre-treatment, such as thorough washing or sieving.

When compared to other innovative replacement materials in concrete, such as coconut shells and palm kernel shells, CSA presents distinct advantages and challenges. Coconut shells, as investigated by Prakash et al. (2021), share similar environmental benefits and lightweight properties with CSA but exhibit lower water absorption and slightly lower abrasion resistance. This makes CSA more resistant to wear over time, though coconut shells may be more suited for applications requiring reduced water-cement ratios. Conversely, CSA's broader particle size distribution enhances its potential to reduce void content in concrete mixes, provided that mix designs are optimized with appropriate admixtures to balance its high water absorption.

Palm kernel shells, commonly used in lightweight concrete, offer comparable abrasion resistance and lower moisture content than CSA (Alengaram et al., 2013). However, their irregular particle shape often complicates mix workability. CSA's more uniform particle shape provides a distinct advantage in achieving better homogeneity and compaction, especially when supplemented with viscosity modifiers (Hilal et al., 2024).

CSA's broader particle size distribution and superior abrasion resistance offer substantial advantages, particularly in reducing voids and enhancing the durability of concrete mixes. However, challenges such as achieving uniform strength and managing high water absorption require advanced mix design strategies. Studies by Alqahtani and Zafar (2023) and Hilal et al. (2024) highlight that incorporating nanomodifications and supplementary cementitious materials (SCMs) can significantly enhance the mechanical properties of lightweight concrete containing alternative aggregates. These enhancements include improved packing density, reduced porosity, and better hydration efficiency. By addressing these challenges, CSA can be effectively utilized in sustainable construction applications, serving as a durable and environmentally friendly solution for a variety of uses.

The potential applications of CSA are particularly notable in non-structural lightweight concrete, such as partition walls and thermal insulation layers, where its lightweight properties and superior abrasion resistance provide significant benefits. These findings emphasize the importance of optimizing mix designs to fully leverage CSA's advantages while addressing its inherent limitations, such as high water absorption and elevated silt content. Mitigation measures, such as pretreatment of aggregates, use of water-reducing admixtures, and incorporation of SCMs, are essential to stabilize the mix and ensure consistent performance.

This approach aligns with broader sustainability goals by repurposing agricultural byproducts like CSA into valuable construction materials, reducing reliance on resource-intensive conventional aggregates. This contributes to environmentally sustainable construction practices, as emphasized in studies by Nawy (2008) and Sivakumar and Santhanam (2007), which advocate for the integration of waste materials into construction to minimize environmental impact while maintaining material performance and durability.

3.2 Compressive Strength

The compressive strength results presented in Table 5 clearly demonstrate the critical influence of the water-cement (*w/c*) ratio on the mechanical performance of concrete mixes incorporating Candlenut Shell Aggregate (CSA). As expected, the compressive strength improves with a reduction in the *w/c* ratio, reflecting the decreased capillary porosity in the concrete matrix due to lower water content (Nawy, 2008). However, the relationship is non-linear, with compressive strength peaking at a *w/c* ratio of 0.55 before declining at lower ratios, highlighting the complex interplay between hydration, compaction, and workability.

Table 5. Compressive Strength Data of Concrete Mix Variations

Mix Variation	Compressive Load (kN)	Age (days)	Cube Compressive Strength (kg/cm²)	Compressive Strength (MPa)
I (0.65)	250	28	99.26	9.7
II (0.55)	370	28	145.93	14.3
III (0.45)	410	28	139.26	13.6
IV (0.35)	245	28	100.74	9.9
V (0.3)	370	28	129.63	12.7

At the highest *w/c* ratio of 0.65, the compressive strength was observed to be the lowest at 9.7 MPa. This reduction is attributed to the excess water content, leading to increased capillary voids, which weaken the bond between the aggregates and the cement paste. This trend is consistent with well-established principles in concrete technology, as higher water content introduces porosity, compromising both strength and durability (Abdelgader et al., 2024; Neville and Brooks, 2010). Similar observations have been made in studies using other lightweight aggregates, such as oil palm shells and coconut shells, which also showed reduced strength at higher *w/c* ratios due to similar porosity issues (Mannan and Ganapathy, 2004; Prakash et al., 2021).

Conversely, the highest compressive strength of 14.3 MPa was achieved at a *w/c* ratio of 0.55 (variation II), indicating optimal hydration conditions. At this ratio, sufficient water is available to fully hydrate the cement without creating excess voids, resulting in a dense and well-compacted matrix. This finding aligns with research by Cui et al. (2022) and Hilal et al. (2024), which identified similar optimal *w/c* ratios for lightweight and sustainable concrete applications. Furthermore, the improved performance at this ratio highlights the compatibility of CSA with concrete mixes when properly balanced, emphasizing its potential for non-structural applications, such as wall panels and flooring.

Interestingly, as the *w/c* ratio decreased further to 0.45 and 0.30, the compressive strength dropped to 13.6 MPa and 12.7 MPa, respectively. This reduction can be attributed to challenges in workability and compaction associated with lower water content. Poor workability leads to incomplete compaction and the formation of microvoids, which reduce the density and strength of the concrete. Similar trends have been observed in studies involving coconut shell aggregates, where excessively low *w/c* ratios resulted in increased microcracking and reduced overall performance due to inadequate hydration (Chindaprasirt et al., 2007; Feldman and Sereda, 1970). However, it is important to note that in mixes with *w/c* ratios of 0.30 and 0.35, despite the initial difficulty in compaction due to low water content, the use of mechanical pressing improved matrix density. This enhanced compaction technique helped offset some of the negative effects of poor workability, contributing to the unexpectedly higher strength observed in the 0.30 mix compared to the 0.35 mix. The initial stress induced during pressing appears to assist in better particle rearrangement and interfacial bonding, thereby increasing the overall strength of the matrix.

The unique properties of CSA, such as high absorption and low density, further complicate *w/c* ratio optimization. CSA's high absorption increases the water demand of the mix, necessitating careful management to avoid underhydration of the cement. Studies have shown that pre-soaking CSA or incorporating water-reducing admixtures can mitigate these challenges, ensuring adequate hydration and improved performance (Hilal et al., 2024; Prakash et al., 2021). Moreover, the inclusion of supplementary cementitious materials (SCMs), like silica fume or fly ash, can enhance packing density and reduce porosity, thereby improving both strength and durability (Hussein et al., 2022). These strategies have been successfully employed in lightweight concrete mixes using other agricultural waste aggregates, further validating their application for CSA-based mixes.

The findings also underscore the importance of a holistic approach to mix design, which considers not only the theoretical benefits of reduced *w/c* ratios but also practical considerations such as workability, compaction, and curing methods. Advanced curing techniques, such as steam curing or extended wet curing, have been shown to mitigate issues related to microcracking and incomplete hydration, particularly in mixes with very low *w/c* ratios (Carette and Malhotra, 1983; Cui et al., 2022). The results of this study are consistent with prior research advocating for an optimal *w/c* ratio range, typically between 0.45 and 0.55, to balance compressive strength and workability while maximizing the performance of lightweight aggregates.

The compressive strength results reaffirm the critical role of the *w/c* ratio in determining the mechanical properties of lightweight concrete. The study highlights the potential of CSA as a viable alternative aggregate, provided that its unique properties are accounted for in the mix design. The optimal *w/c* ratio of 0.55 achieved in this study serves as a benchmark for future research and practical applications, offering a balance between strength and workability while aligning with sustainability objectives. The findings also emphasize the need for continued exploration of admixture technologies and curing techniques to further enhance the performance of CSA-based concrete, ensuring its suitability for a wide range of non-structural applications in sustainable construction.

3.3 Effect of Water-Cement Ratio on Concrete Compressive Strength

The experimental findings illustrated in Figure 3 reveal a clear correlation between water–cement (*w/c*) ratios and the compressive strength of Candlenut Shell Aggregate (CSA)–based lightweight concrete. The compressive strength increased from 9.7 MPa at a high *w/c* ratio of 0.65 to a peak of 14.3 MPa at a *w/c* ratio of 0.55, followed by a decrease to 12.7 MPa at a very low ratio of 0.30. These observations underscore the intricate balance between hydration, porosity, and workability in concrete mixes, particularly when incorporating lightweight aggregates like CSA.

Additionally, the shape of CSA, which is typically flaky and irregular, can contribute to inconsistent compaction and stress distribution in the hardened concrete. This morphology tends to cause particle misalignment and increased void formation under load, leading to fluctuations in compressive strength across specimens. This may partly explain the variations observed in Figure 3, particularly at low *w/c* ratios, where compaction is more critical. Shape modification or blending with angular aggregates could mitigate this issue and improve consistency.

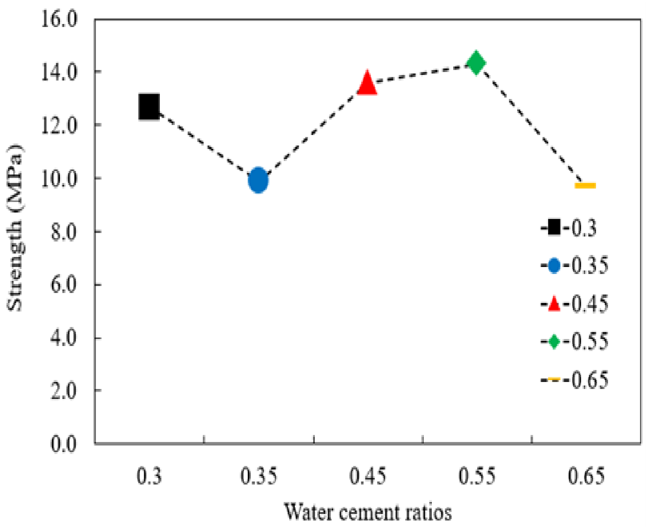

Figure 3 Compressive Strength of Concrete at Different Water-Cement Ratios.

At a *w/c* ratio of 0.65, the excess water increases capillary porosity, leading to lower density and compressive strength. This aligns with established principles in concrete technology, where surplus water weakens the aggregate-cement bond (Nawy, 2008; Neville and Brooks, 2010). As the ratio decreases to 0.55, optimal hydration conditions are achieved, allowing sufficient water for cement hydration while minimizing voids. This results in a peak strength of 14.3 MPa, consistent with previous studies that highlight the ideal range for hydration and compaction (Cui et al., 2022; Putra et al., 2023).

However, at lower *w/c* ratios (e.g., 0.3), a slight reduction in compressive strength to 12.7 MPa is observed, likely due to reduced workability, incomplete compaction, and microvoid formation (Feldman and Sereda, 1970). These findings are corroborated by studies that report similar challenges with low–*w/c* concrete, where admixtures or pre-wetting of aggregates help mitigate workability issues (Aboul-Nour et al., 2020; Hilal et al., 2024). Furthermore, Ortega et al. (2023) emphhasized the importance of optimizing mix design in lightweight concrete containing alternative aggregates to balance strength and workability.

The observed trends confirm that the optimal *w/c* ratio for CSA-based lightweight concrete lies between 0.45 and 0.55. Within this range, compressive strength is maximized without compromising workability, making it suitable for lightweight and non-structural applications. These results support sustainable construction practices by integrating agricultural waste into concrete production while maintaining high-performance properties (Hussein et al., 2022; Sikora et al., 2023).

3.4 Relationship between Strength, Density, and Water-Cement Ratio Using Candlenut Shell

The relationship Between water-cement (*w/c*) ratio, compressive strength, and density of concrete incorporating Candlenut Shell Aggregate (CSA) is presented in Figure 4.

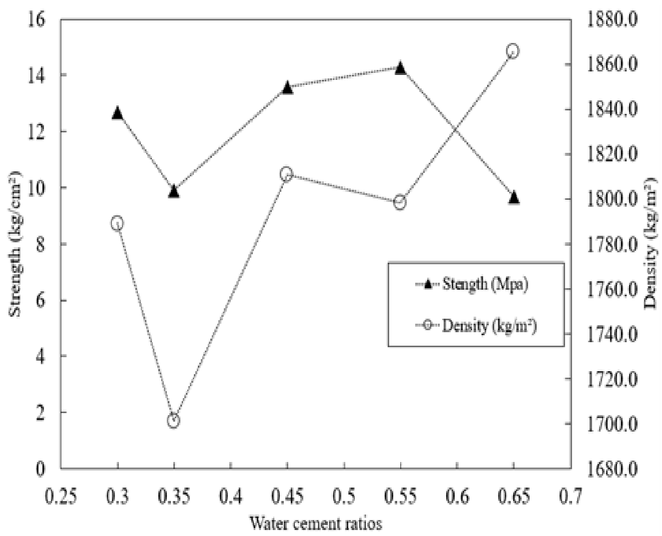

Figure 4 Relationship Between Water-Cement Ratios, Compressive Strength and Density of Concrete

The graph highlights that both compressive strength and density are significantly influenced by the *w/c* ratio, with notable trends across the tested range of 0.65 to 0.30. At a *w/c* ratio of 0.65, the compressive strength and density are at their lowest, approximately 9.7 MPa and 1,600 kg/m^3, respectively. This behavior is consistent with the principles of concrete technology, where excess water in the mix increases porosity, reducing compactness and strength (Nawy, 2008; Neville and Brooks, 2010). Excess water, upon evaporation, leaves voids in the matrix, leading to less dense and weaker concrete.

As the *w/c* ratio decreases to 0.55, the compressive strength peaks at 14.3 MPa, while the density reaches its maximum of approximately 1,850 kg/m^3. This result reflects the optimal balance between water content and cement hydration, ensuring sufficient water is available for the hydration process without introducing excess voids. Research by Putra et al. (2023) and

Cui et al. (2022) similarly identified the 0.50–0.55 range as ideal for achieving maximum strength and density, highlighting the interplay between hydration, porosity reduction, and workability.

Interestingly, as the *w/c* ratio is reduced further to 0.30, both compressive strength and density decrease slightly to 12.7 MPa and approximately 1,700 kg/m^3. While a lower *w/c* ratio theoretically reduces porosity and increases strength, the practical challenges of achieving uniform compaction and adequate hydration at such ratios lead to diminished performance.Feldman and Sereda (1970) and Aboul-Nour et al. (2020) similarly observed that very low *w/c* ratios can result in poor workability and increased void content, negating the benefits of reduced porosity. Furthermore, the low density suggests incomplete cement hydration, a common issue in mixes with insufficient water.

The observed trends confirm that the optimal *w/c* ratio for CSA-based concrete lies around 0.55, where the highest compressive strength and density are achieved. Reductions below this ratio, while reducing theoretical porosity, lead to practical issues that compromise mix performance. Studies by Karimi et al. (2023) and Chandra and Berntsson (2002) emphasize the need for balancing strength and workability, particularly in lightweight concrete, where aggregate properties like high absorption and low bulk density amplify these challenges.

This analysis underscores the importance of optimizing the *w/c* ratio in CSA-based concrete to achieve a balance between strength, density, and workability. An optimal range ensures high performance while mitigating the issues associated with both high and low *w/c* ratios. These findings align with the broader literature and contribute valuable insights into the practical application of lightweight aggregates in sustainable construction.

4 CONCLUSION

Candlenut Shell Aggregate (CSA) has emerged as a promising alternative for lightweight concrete production, offering significant advantages over traditional coarse aggregates. Its substantially lower density enables the creation of lightweight concrete, reducing overall structural load and potentially lowering construction costs. In addition, CSA contributes to environmental sustainability by repurposing agricultural waste, aligning with global sustainability objectives, and reducing dependency on resource-intensive aggregates. These attributes position CSA as a key component in advancing eco-friendly construction practices.

This study highlights the critical influence of the water-cement (*w/c*) ratio on the compressive strength and density of CSA-based concrete. The optimal *w/c* ratio of 0.55 resulted in the highest compressive strength (14.3 MPa) and maximum density (~1850 kg/m^3), reflecting an effective balance between hydration and void minimization. At higher *w/c* ratios, such as 0.65, excess water increase capillary porosity, reducing both strength and density. Conversely, excessively low *w/c* ratios, such as 0.30, impaired workability, leading to inadequate compaction and incomplete hydration, which negatively affected concrete performance.

The findings also underscore CSA's potential for non-structural applications, including wall panels and flooring. While its low density and moderate abrasion resistance are advantageous, CSA's high water absorption and silt content present challenges. Pre-treatment methods, such as pre-soaking and the incorporation of water-reducing admixtures, are recommended to optimize mix performance and ensure consistency in quality. These findings are consistent with prior research advocating for tailored mix designs to enhance the functional performance of alternative aggregates.

In conclusion, CSA offers a sustainable and efficient solution for lightweight concrete applications, particularly where structural weight reduction and environmental conservation are priorities. Future research should focus on long-term durability, thermal insulation properties, and advanced admixture formulations to further enhance the performance of CSA-based concrete. These innovations will pave the way for broader adoption of CSA in sustainable construction, bridging the gap between material innovation and practical application.

DISCLAIMER

The authors declare no conflict of interest.

ACKNOWLEDGMENTS

We would like to acknowledge Tenri Nur Fatimah for her efforts in carrying out the experiments and organizing the data in this study.

REFERENCES

Abdelgader, S. H., Kurpinska, M., Abdelgader, H. S., Omidi Moaf, F. and Amran, M. (2024), 'Study the impact of design method preference on the usefulness of concrete and on co_2 emissions', *International Journal of Building Pathology and Adaptation* .
URL: *https://doi.org/10.1108/IJBPA-12-2023-0185*

Aboul-Nour, L., Zaghlal, M. and Malek, K. (2020), 'Improving compressive strength of lightweight aggregate concrete', *The Egyptian International Journal of Engi-*

neering Sciences and Technology **30**(1), 12–21.
URL: *https://doi.org/10.21608/eijest.2020.104929*

Alengaram, U. J., Muhit, B. A. A. and Jumaat, M. Z. B. (2013), 'Utilization of oil palm kernel shell as lightweight aggregate in concrete – a review.', *Construction and Building Materials* **38**, 161––172.
URL: *https://doi.org/10.1016/j.conbuildmat.2012.08.026*

Alqahtani, F. K. and Zafar, I. (2023), 'Exploring the effect of different waste fillers in manufactured sustainable plastic aggregates matrix on the structural lightweight green concrete', *Sustainability* **15**(3), 2311.
URL: *https://doi.org/10.3390/su15032311*

Carette, G. and Malhotra, V. (1983), 'Mechanical properties, durability, and drying shrinkage of portland cement concrete incorporating silica fume', *Cement, Concrete, and Aggregates* **5**(1), 3–13.
URL: *https://doi.org/10.1520/CCA10244J*

Chandra, S. and Berntsson, L. (2002), *Lightweight Aggregate Concrete: Science, Technology, and Applications*, Noyes Publications: William Andrew Pub.
URL: *https://www.worldcat.org/title/49895577*

Chindaprasirt, P., Homwuttiwong, S. and Jaturapitakkul, C. (2007), 'Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash', *Construction and Building Materials* **21**(7), 1492–1499.
URL: *https://doi.org/10.1016/j.conbuildmat.2006.06.015*

Cui, Y., Wang, L., Liu, J., Liu, R. and Pang, B. (2022), 'Impact of particle size of fly ash on the early compressive strength of concrete: Experimental investigation and modelling', *Construction and Building Materials* **323**, 126444.
URL: *https://doi.org/10.1016/j.conbuildmat.2022.126444*

Daryono, L. R., Aoki, S., Kano, M., Miyanaga, M., Nakashima, K. and Kawasaki, S. (2023), 'Biomineralization grouting for beach sand cemented with micp', *Journal of the Civil Engineering Forum* pp. 31–38.
URL: *https://doi.org/10.22146/jcef.6454*

Feldman, R. F. and Sereda, P. J. (1970), 'Written discussion of "structures and physical properties of cement paste" by george j. verbeck and richard h. helmuth (portland cement association, skokie, ill, u.s.a.)', *Cement and Concrete Research* **3**, 36–44.

Hilal, N., Hamah Sor, N., Hadzima-Nyarko, M., Radu, D. and Tawfik, T. A. (2024), 'The influence of nanosunflower ash and nanowalnut shell ash on sustainable lightweight self-compacting concrete characteristics', *Scientific Reports* **14**(1), 9450.
URL: *https://doi.org/10.1038/s41598-024-60096-5*

Hussein, Y. M., Elrahman, M. A., Elsakhawy, Y., Tayeh, B. A. and Tahwia, A. M. (2022), 'Development and performance of sustainable structural lightweight concrete containing waste clay bricks', *Journal of Materials Research and Technology* **21**, 4344–4359.
URL: *https://doi.org/10.1016/j.jmrt.2022.11.042*

Jamwal, A., Nautiyal, A., Singh, K., Alam, S., Alselami, N. A. and Aati, K. M. (2024), 'Sustainable concrete production: Utilizing cow dung ash and corn stalk ash as eco-friendly alternatives', *Civil Engineering Journal* **10**, 21–36.
URL: *https://doi.org/10.28991/CEJ-SP2024-010-02*

Karimi, H. R., Ebneabbasi, P., Shahni Karamzadeh, N. and Khedri, E. (2023), 'Effect of water to cement (w/c) ratio and age on mechanical behavior of tire–recycled steel fiber reinforced concrete', *Structural Concrete* **24**(2), 2460–2474.
URL: *https://doi.org/10.1002/suco.202200007*

Mannan, M. A. and Ganapathy, C. (2004), 'Concrete from an agricultural waste-oil palm shell (ops)', *Building and Environment* **39**(4), 441–448.
URL: *https://doi.org/10.1016/j.buildenv.2003.10.007*

Mindess, S., Young, J. F. and Darwin, D. (2003), *Concrete*, 2 edn, Prentice Hall.

Natarajan, K. S., Ramalingasekar, D., Palanisamy, S. and Ashokan, M. (2022), 'Effect on mechanical properties of lightweight sustainable concrete with the use of waste coconut shell as replacement for coarse aggregate', *Environmental Science and Pollution Research* **29**(26), 39421–39426.
URL: *https://doi.org/10.1007/s11356-022-18905-9*

Navaratnam, S., Tushar, Q., Jahan, I. and Zhang, G. (2023), 'Environmental sustainability of industrial waste-based cementitious materials: A review, experimental investigation and life-cycle assessment', *Sustainability* **15**(3), 1873.
URL: *https://doi.org/10.3390/su15031873*

Nawy, E. G., ed. (2008), *Concrete Construction Engineering Handbook*, 2 edn, CRC Press.

Neville, A. M. and Brooks, J. J. (2010), *Concrete Technology*, 2 edn, Prentice Hall.

Ortega, J. M., Branco, F. G. and Pereira, L. (2023), 'Long-term behavior related to water ingress in mortars which combine expanded and natural cork lightweight aggregates and eco-friendly cements', *Buildings* **13**(7), 1651.
URL: *https://doi.org/10.3390/buildings13071651*

Patah, D., Dasar, A. and Noor, N. M. (2025), 'The effects of palm oil fuel ash on mechanical and durability properties of sustainable foamed concrete', *Journal of the Civil Engineering Forum* pp. 75–84.
URL: *https://doi.org/10.22146/jcef.13749*

Prakash, R., Thenmozhi, R., Raman, S. N., Subramanian, C. and Divyah, N. (2021), 'Mechanical characterisation of sustainable fibre-reinforced lightweight concrete incorporating waste coconut shell as coarse aggregate and sisal fibre', *International Journal of Environmental Science and Technology* **18**(6), 1579–1590.
URL: *https://doi.org/10.1007/s13762-020-02900-z*

Putra, S. A., Ary Wahyudie, I. and Darta, Y. (2023), 'Pengaruh ukuran butir pasir terhadap kuat tekan cellular lightweight concrete', *Jurnal Inovasi Teknologi Terapan* **1**(2), 428–433.
URL: *https://doi.org/10.33504/jitt.v1i2.88*

Rahman, M. J., Hasrul, M. R., Ashad, H., Yusuf, F. A. and Hasrul, N. R. (2024), 'An assessment of derelict building constructions situated in coastal regions', *Journal of the Civil Engineering Forum* **10**(3), 229––238.
URL: *https://doi.org/10.22146/jcef.10433*

Shafigh, P., Jumaat, M. Z. and Mahmud, H. (2011), 'Oil palm shell as a lightweight aggregate for production high strength lightweight concrete', *Construction and Building Materials* **25**(4), 1848–1853.
URL: *https://doi.org/10.1016/j.conbuildmat.2010.11.075*

Sikora, P., Afsar, L., Rathnarajan, S., Nikravan, M., Chung, S.-Y., Stephan, D. and Abd Elrahman, M. (2023), 'Seawater-mixed lightweight aggregate concretes with dune sand, waste glass and nanosilica: Experimental and life cycle analysis', *International Journal of Concrete Structures and Materials* **17**(1), 47.
URL: *https://doi.org/10.1186/s40069-023-00613-4*

Sivakumar, A. and Santhanam, M. (2007), 'A quantitative study on the plastic shrinkage cracking in high strength hybrid fibre reinforced concrete', *Cement and Concrete Composites* **29**(7), 575–581.
URL: *https://doi.org/10.1016/j.cemconcomp.2007.03.005*