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Development of lightweight foamed concrete using surface-modified oil palm kernel shell

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ABSTRACT

Growing environmental concerns and seismic safety requirements have intensified the need for innovative building materials in the construction industry. This challenge is particularly acute in seismically active regions like Indonesia, where the convergence of the Indo-Australian, Pacific, and Eurasian tectonic plates creates unique structural demands for buildings and infrastructure. This study investigates the development of lightweight foamed concrete incorporating oil palm kernel shell (OPKS) as a sustainable aggregate for earthquake-resistant construction applications. The research comprehensively examines the effects of surface modification using silane-siloxane nanocoating and optimizes cement-to-OPKS ratios (2.5:1, 2.7:1, and 3.3:1) across different target specific gravities (1.0, 1.2, and 1.4). The experimental program involved preparing OPKS specimens with both uncoated and coated treatments, followed by characterization of their physical and mechanical properties. Density stability, compressive strength, and tensile strength development were monitored over a 28-day curing period. Microscopic analysis revealed significant morphological modifications resulting from surface treatment, contributing to enhanced aggregate-matrix bonding. Results demonstrate that higher s.g. mixtures (1.4) achieved superior stability and strength performance, reaching 8 MPa for specimens with CT aggregates. Surface treatment significantly enhanced concrete workability and reduced moisture absorption, particularly evident in specimens with higher cement content. The study establishes that OPKS-based lightweight foamed concrete represents a viable solution for non-structural building elements in seismically active regions, particularly for applications requiring compressive strengths below 3 Mpa (residential wall applications). This research contributes to sustainable construction practices by effectively utilizing agricultural waste while meeting structural safety requirements for residential applications.

Keywords: light weight foam concrete, foam agent, oil palm kernel shell, surface coating.

INTRODUCTION

The construction industry faces mounting pressure to develop sustainable and earthquake-resistant building materials, particularly crucial in seismically active regions [Murtagh et al., 2020]. This challenge is especially relevant in Indonesia, situated at the intersection of three major tectonic plates: Indo-Australian, Pacific, and Eurasian [MSN, 2016]. This geological complexity drives the need for innovative construction materials, leading to increased interest in lightweight foamed concrete (LWFC). This material offers promising seismic resistance characteristics through its reduced mass and unique mechanical properties while addressing environmental considerations [Ramamurthy et al., 2009].

LWFC has attracted significant attention in seismic-resistant construction due to its ability to reduce inertial forces during earthquakes. The lower density of lightweight concrete leads to decreased structural weight, potentially improving building response to seismic activity, making it particularly valuable in earthquake-prone regions [Ngui, 2023]. Amran et al. [2015] highlight LWFC's versatility in construction applications, noting that its controlled density, typically ranging from 300 to 1600 kg/m³, enables customization for various structural elements. This adaptability, combined with reduced mass, makes LWFC an attractive option for seismic-resistant construction.

The incorporation of agricultural waste into lightweight concrete has emerged as a sustainable construction solution. Research has demonstrated the potential of oil palm kernel shell (OPKS) and other agricultural waste materials as lightweight aggregates, showing improved mechanical properties [Mo et al., 2016]. OPKS concrete can achieve structural-grade compressive strengths while maintaining significantly reduced density [Alengaram et al., 2013]. Studies confirm that OPKS-based concrete can attain high strength with low density, making it suitable for seismic zone applications while providing environmental benefits through agricultural waste utilization [Shafigh et al., 2014]. This dual advantage addresses both structural and sustainability requirements in modern construction.

Recent innovations in LWFC technology have focused on enhancing both mechanical properties and sustainability. Research has shown that foaming agent selection significantly influences concrete strength and stability [Panesar, 2013]. The addition of fibers to LWFC has demonstrated notable improvements in both compressive and flexural strength characteristics [Falliano et al., 2019]. Further advancement in the field includes the incorporation of superhydrophobic foam into cement composites, presenting new opportunities for developing sustainable, multi-functional building materials [Xu et al., 2024]. These developments represent significant progress in optimizing LWFC performance for construction applications.

The incorporation of agricultural waste and industrial by-products in lightweight concrete demonstrates alignment with circular economy principles in construction. Research has shown that palm oil fuel ash can effectively serve as a supplementary cementitious material, reducing cement consumption and CO_2 emissions while enhancing concrete properties [Khankhaje et al., 2016]. Studies on waste material utilization in construction, including rubber aggregate replacement, suggest broader applications for seismic-resistant lightweight concrete [Rashad, 2016]. Further investigations reveal that palm oil fuel ash as a filler in lightweight foamed concrete can improve strength and durability, offering sustainable solutions for seismic regions [Lim et al., 2013].

The integration of OPKS as a lightweight aggregate in concrete offers significant density reduction potential, though technical challenges require careful consideration. Pre-treatment of OPKS is crucial for optimizing its performance, with surface modification demonstrating substantial improvements in concrete workability, showing up to 41% enhancement compared to untreated aggregates [Yew et al., 2023]. Treatment significantly reduces OPKS's naturally high water absorption tendency, which typically compromises concrete strength and durability [Krishnamurthy et al., 2019]. Various treatment methods, particularly hot water treatment, have demonstrated notable improvements in mechanical properties, including enhanced flexural and tensile strengths [Lee et al., 2019; Sofyani et al., 2019].

This research investigates the development of sustainable LWFC incorporating OPKS as an alternative aggregate. The study focuses on evaluating the effectiveness of nanomaterial surface treatment on OPKS and optimizing cement-to-OPKS ratios across various concrete densities, as specified by target specific gravity (s.g.) values. A key objective is developing LWFC specifically engineered for residential wall applications in accordance with Indonesian standards (SNI 0300349, 1989), which specify compressive strength requirements below 3 MPa for non-structural elements. This target strength aligns with non-load-bearing building components while maintaining adequate seismic resistance properties.

MATERIALS AND METHODS

Cement and foam agent

The primary binder used in this study was ordinary Portland cement conforming to Standard B (2004) specifications, obtained in 50-kg bags from commercial sources. To make foam, sodium dodecyl sulfate was dissolved in propylene glycol to make a surfactant solution as a foam agent. This foam agent was then diluted with water at a 1:20 volume ratio. The foam was produced using a foam generator that created uniform, fine bubbles. The target s.g. of the LWFC was achieved by carefully controlling the proportions of foam and water in the mixture.

OPKS preparation and coating process

OPKS was obtained from a palm oil processing facility located in Aceh Jaya District, Aceh, Indonesia. The material is subject a systematic preparation process, beginning with thorough washing using clean tap water to remove debris and separate any residual kernel material. The cleaned shells were then subjected to a three-day air-drying period under ambient conditions to ensure proper moisture content.

The OPKS were subsequently treated using a nanocoating solution comprising silane and siloxane in a 1:1 ratio at 5% concentration. The treatment process involved immersing the shells in the solution for 10 minutes, followed by a two-hour drying period. Physical characterization of the shells revealed irregular shapes and varied particle size distribution, as documented in Figure 1. To evaluate the effectiveness of the surface treatment, both optical microscopy and scanning electron microscopy (SEM) analyses were conducted.

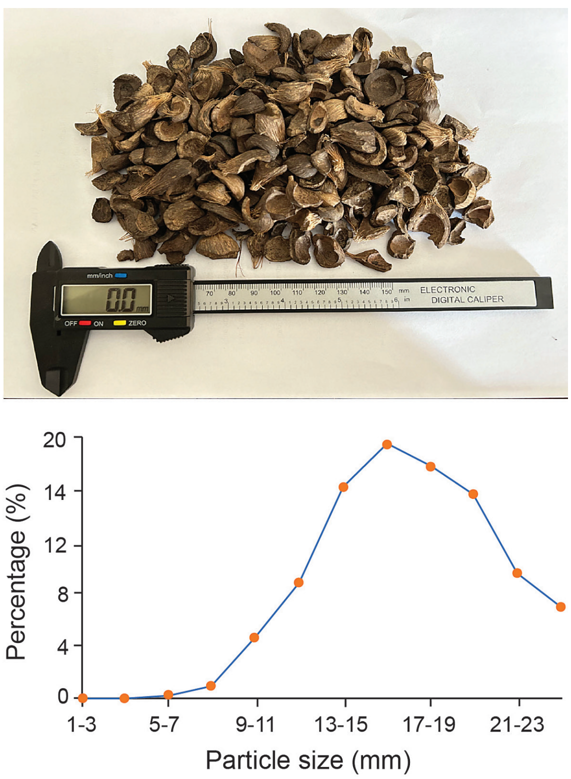

Figure 1. Physical characterization of OPKS aggregates

Mix design

Eighteen distinct concrete mixtures were prepared for this investigation. The mix design proportions were developed to achieve target s.g. values of 1.0, 1.2, and 1.4 for the LWFC. Throughout all mixtures, the OPKS content was maintained at 20% of the total weight, using both uncoated (UC) and coated (CT) OPKS specimens. The cement-to-OPKS ratios were varied at 2.5:1, 2.7:1, and 3.3:1. Water content was adjusted according to the target s.g., with foam volume percentages ranging from 10% to 40%.

Curing process and testing

The fresh LWFC mixtures were cast into standard cylindrical molds measuring 100 mm in diameter and 200 mm in height. After an initial setting period of 24 hours, the specimens were carefully demolded and transferred to a controlled curing environment. The samples underwent water curing at room temperature for designated periods of 7, 14, and 28 days to evaluate strength development in accordance with The British Standards Institution [2002], specifications for compressive and tensile strength determination.

RESULTS AND DISCUSSION

Nanocoated OPKS observation

Microscopic examination of OPKS surfaces revealed significant morphological modifications resulting from silane-siloxane surface treatment. The analysis, conducted using both SEM and optical microscopy, demonstrated distinct differences between UC and CT specimens.The SEM micrographs of UC specimens (Figure 2a) exhibited characteristic surface features including pronounced parallel ridges and systematic arrangement of microporous structures. These natural surface characteristics reflect the biological origin of OPKS, with the ridged patterns likely corresponding to the shell's original cellular structure. The microporous features, uniformly distributed across the surface, suggest potential areas for mechanical interlocking with cement paste.

Following treatment with 5% silane-siloxane solution, the CT specimens (Figure 2b) displayed markedly different surface characteristics. The coating formed a continuous network over the substrate, effectively modifying the surface

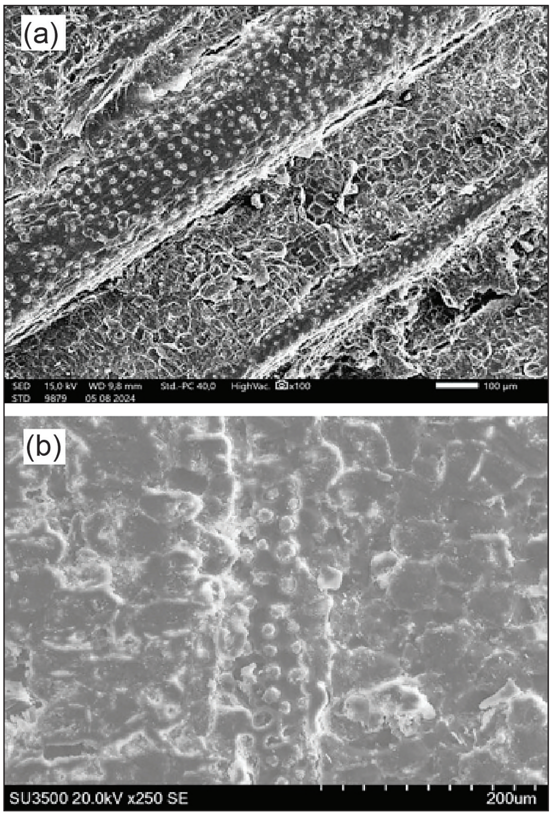

Figure 2. Surface characterization of OPKS using SEM: (a) uncoated and (b) silane-siloxane (5%) coated specimens at 200 µm magnification

topography. This surface modification resulted in partial filling of the inherent surface irregularities, creating a more homogeneous texture while maintaining the fundamental ridge pattern. The uniform distribution of the coating, clearly visible at 200 µm magnification, indicates successful surface modification.

Complementary optical microscopy observations (Figure 3) provided additional insight into the surface modification process. The treatment appeared to create a more uniform surface texture without completely obscuring the underlying OPKS structure. This modified surface morphology suggests potential enhancement of interfacial bonding characteristics between the OPKS and cement matrix in LWFC. The observed microstructural modifications indicate that silane-siloxane treatment effectively alters OPKS surface properties, potentially improving its performance as an aggregate in LWFC through enhanced bonding characteristics and reduced moisture absorption tendencies.

LWFC density

Table 1 presents comprehensive density data for LWFC incorporating OPKS across three s.g.

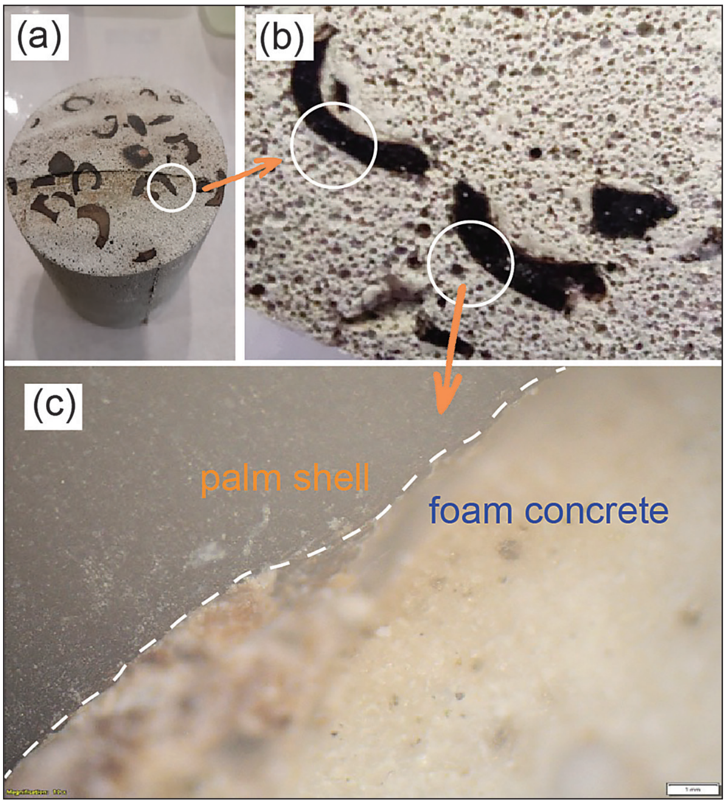

Figure 3. Optical microscopy characterization: (a) internal structure of LWFC, (b) embedded OPKS aggregate morphology, and (c) interface bonding at the OPKS-cement matrix boundary zone

levels, examining both UC and CT specimens with varying cement-to-OPKS ratios. The results demonstrate distinct patterns of density evolution and stability depending on the target density and surface treatment of the aggregates.

For mixtures with s.g. 1.0, specimens exhibited initial demolded densities ranging from 1081 to 1188 kg/m³. After 28 days of curing, significant variations in density reduction were observed, ranging from 11 to 40 kg/m³. This behavior suggests more pronounced density changes at lower target densities, likely due to the higher void content and resulting microstructural instability. Notably, CT specimens showed varying stability patterns, with CT-2.5:1 exhibiting an 18 kg/m³ reduction while CT-2.7:1 showed a larger 38 kg/m³ decrease.

The intermediate density mixtures (s.g. 1.2) demonstrated more consistent behavior, with initial densities spanning 1228 to 1289 kg/m³. Most specimens in this category showed uniform density reductions between 37 and 46 kg/m³, indicating more predictable density evolution. However, CT-3.3:1 exhibited exceptional stability with only a 13 kg/m³ reduction, suggesting potential optimization of coating effects at this density level.

The highest density specimens (s.g. 1.4) showed superior stability characteristics. Initial densities ranged from 1318 to 1395 kg/m³, with final values settling between 1306 and 1383 kg/m³. Density reductions were minimal, ranging from 10 to 33 kg/m³, indicating enhanced microstructural stability. This improved performance aligns with findings by Amran et al. [2015] regarding enhanced structural integrity in higher density foamed concrete. The results are also comparable to observations by Ünal et al., [2024] in studies of lightweight concrete incorporating treated agricultural wastes (Table 1).

Compressive strength

Figure 4 illustrates the compressive strength evolution of lightweight foamed concrete (LWFC) specimens monitored over a 28-day curing period at s.g. of 1.0, 1.2, and 1.4. The research compared both UC and CT oil palm kernel shell aggregates at varying cement-to-OPKS ratios, with a target strength benchmark of 3.0 MPa indicated by a horizontal dashed line in the graph.

For specimens with s.g. 1.0, the cement-to-OPKS ratio emerged as a critical factor influencing strength development. Specimens containing the highest cement content (3.3:1 ratio) consistently demonstrated superior performance, achieving approximately 2.5 MPa at 28 days for both UC and CT samples. This behavior aligns with findings from Alengaram et al. [2013], who documented enhanced interfacial transition zone characteristics with increased cement content. The improvement in bonding mechanics between aggregate and cement paste directly contributed to higher strength values.

Surface treatment effects were evident when comparing UC and CT specimens. The CT OPKS

Table 1. Density of OPKS-based LWFC: comparison between UC and CT specimens at varying s.g. (1.0, 1.2, and 1.4) and cement-to-OPKS ratios (2.5:1, 2.7:1, and 3.3:1)

Sample	Density (kg/m³)		Reduction (kg/m³)	Sample	Density (kg/m³)		Reduction (kg/m³)
	Demolded	28-day			Demolded	28-day	
s.g. (1.0)				s.g. 1.2			
UC-2.5:1	1111	1076	35	UC-2.5:1	1282	1245	37
UC-2.7:1	1081	1070	11	UC-2.7:1	1240	1200	40
UC-3.3:1	1112	1170	40	UC-3.3:1	1270	1230	40
CT-2.5:1	1188	997	18	CT-2.5:1	1228	1182	46
CT-2.7:1	1115	1077	38	CT-2.7:1	1253	1207	46
CT-3.3:1	1135	1101	34	CT-3.3:1	1289	1276	13
s.g. 1.4							
UC-2.5:1	1395	1383	12				
UC-2.7:1	1318	1306	12				
UC-3.3:1	1356	1323	33				
CT-2.5:1	1383	1370	13				
CT-2.7:1	1391	1363	28				
CT-3.3:1	1360	1350	10				

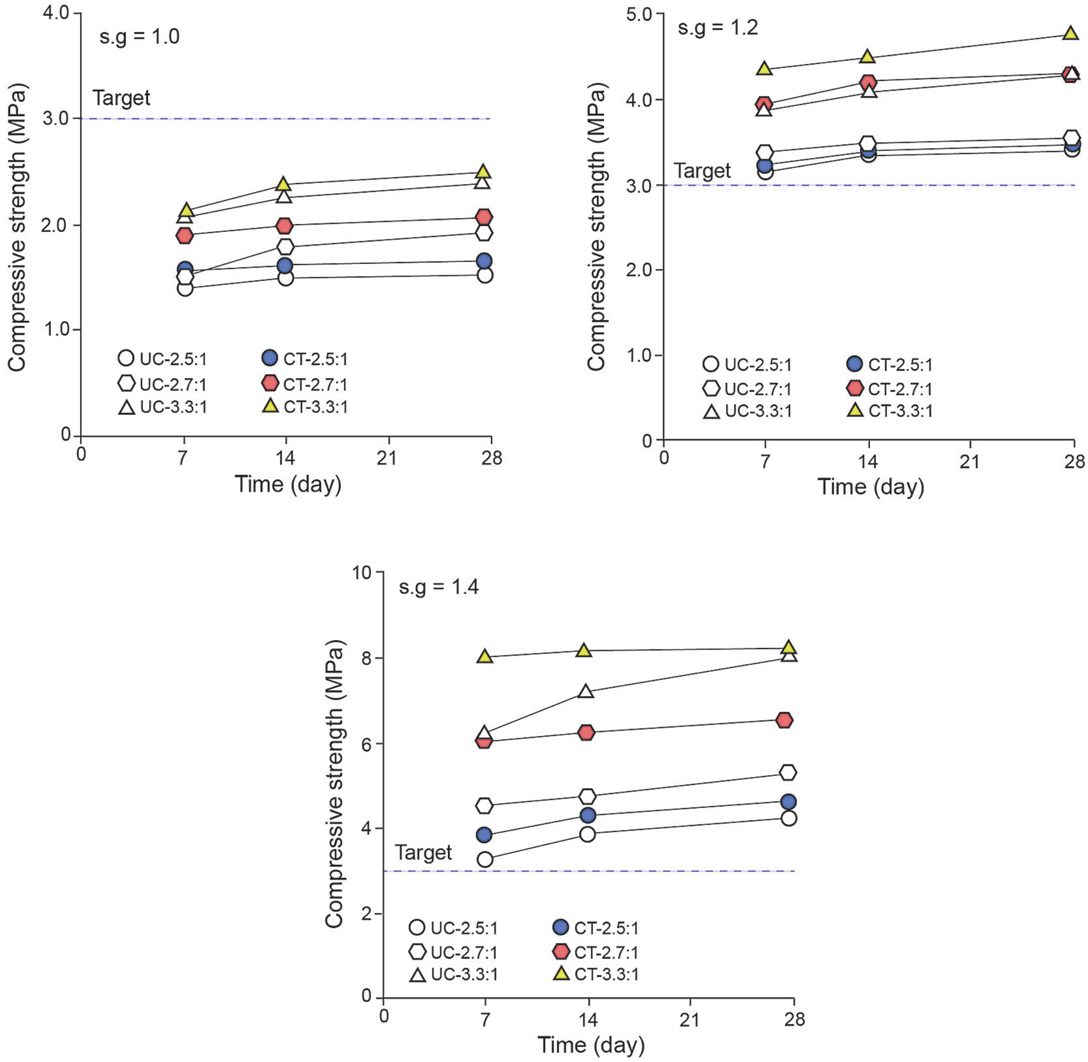

Figure 4. Compressive strength development of OPKS-based LWFC over 28-day curing period at s.g. of 1.0, 1.2, and 1.4: comparison between UC and CT at varying cement-to-OPKS ratios

specimens generally exhibited marginally higher strength values compared to their UC counterparts at identical cement-to-OPKS ratios. This enhancement can be attributed to improved bonding characteristics between the treated aggregate surface and cement paste matrix, supporting observations by Mo et al. [2016] regarding the positive influence of surface treatment on mechanical properties. The strength development pattern followed typical cement hydration behavior, as described by Bullard et al. [2011], with rapid strength gain during the initial 14 days, followed by more gradual increases through 28 days. However, it's noteworthy that none of the mixtures reached the target strength of 3.0 MPa, suggesting the need for either increased cement content or additional strengthening measures for structural applications.

Specimens with lower cement-to-OPKS ratios (2.5:1 and 2.7:1) achieved compressive strengths between 1.5 and 2.0 MPa. These values align with Ramamurthy et al. [2009] classification of foamed concrete, indicating suitability for non-structural applications. The results suggest that while OPKS foamed concrete at s.g. 1.0 may not meet structural requirements, it offers viable solutions for non-load-bearing applications where reduced density is advantageous, particularly in seismic-resistant construction.

For specimens with s.g. 1.2, all mixtures demonstrated progressive strength development throughout the curing duration, with varying rates of strength gain influenced by both cement content and surface treatment. The strength development pattern followed characteristic cement hydration behavior, with most significant increases occurring during the first 14 days of curing, followed by more moderate gains through day 28. This pattern aligns with fundamental cement hydration mechanisms described in literature, where early-age strength development is dominated by rapid calcium silicates hydration. The cement-to-OPKS ratio emerged as a crucial factor influencing strength development. Specimens incorporating higher cement content (3.3:1 ratio) consistently demonstrated superior performance, with CT OPKS specimens achieving approximately 4.8 MPa at 28 days. The effect of surface treatment was particularly evident when comparing CT and UC specimens at identical cement ratios, with CT-3.3:1 reaching 4.8 MPa compared to 4.3 MPa for UC-3.3:1 at 28 days.

Notably, all mixtures at this s.g. exceeded the target strength of 3.0 MPa, including those with lower cement-to-OPKS ratios (2.5:1). This achievement suggests that s..g. 1.2 represents an optimal balance between density and strength requirements, making it suitable for various construction applications. The enhanced performance of CT specimens indicates successful modification of aggregate-paste interfacial properties through surface treatment.

For specimens with s.g. 1..4, revealing superior performance characteristics across all mix variations. The results showcase exceptional strength achievement, with all specimens significantly exceeding the target strength of 3.0 MPa throughout the testing period. The most remarkable performance was observed in specimens combining CT aggregates with the highest cement-to-OPKS ratio (CT-3.3:1), achieving approximately 8 MPa at 28 days. This notable strength development validates the potential of OPKS foamed concrete for structural applications. The effectiveness of surface treatment becomes particularly pronounced at this density level, with CT specimens consistently outperforming their UC counterparts. The cement-to-OPKS ratio proved to be a decisive factor in strength development. While specimens with lower ratios (2.5:1 and 2.7:1) achieved substantial strengths ranging from 4 to 6.5 MPa, the higher ratio (3.3:1) demonstrated markedly superior performance. This trend suggests a strong correlation between cement content and mechanical properties at higher densities. The strength development pattern followed the characteristic hydration behavior, with rapid initial strength gain followed by more gradual development. Notably, even at early ages (7 days), specimens achieved significant strength values, indicating efficient hydration and strength development mechanisms. The enhanced performance at this density level can be attributed to improved particle packing, reduced void content, and stronger interfacial bonding between the treated aggregate surface and cement matrix, particularly evident in specimens with higher cement content.

Tensile strength

The relationship between tensile strength and cement:OPKS ratio demonstrates complex interactions influenced by surface treatment and s.g. in LWFC. Figure 5 presents comprehensive data across three s.g. levels, revealing significant insights into material behavior and performance.

In specimens with s.g. 1.0, tensile strength values range from 0.27 to 0.44 MPa, showing moderate but consistent improvement with increasing cement content. Surface-treated specimens consistently outperform their UC counterparts, particularly at higher cement:OPKS ratios. At the optimal 3.3:1 ratio, CT specimens achieve a tensile strength of 0.44 MPa, representing a significant improvement over the 0.33 MPa recorded for UC specimens. This enhancement can be attributed to improved interfacial bonding between the modified aggregate surface and cement matrix, as documented in previous research by Mo et al. [2014].

The transition to s.g. 1.2 reveals a substantial improvement in overall tensile strength performance, with values ranging from 0.46 to 0.68 MPa. At this density level, the benefits of surface treatment become more pronounced, with CT specimens consistently demonstrating 15–20% higher strength compared to UC variants. This performance enhancement aligns with established research on interfacial transition zone properties in LWFC. The combination of higher matrix density and improved aggregate-paste interaction appears to create optimal conditions for strength development, particularly evident in specimens with higher cement content.

Specimens with s.g. 1.4 demonstrate the highest tensile strength values in the study, ranging from 0.58 to 1.0 MPa. At this density level, the influence of cement content becomes increasingly significant, as evidenced by the steeper progression of strength development with increasing cement:OPKS ratios. While surface-treated specimens maintain their performance advantage, the relative difference between CT and UC specimens becomes less pronounced. This observation suggests that at higher matrix densities, the

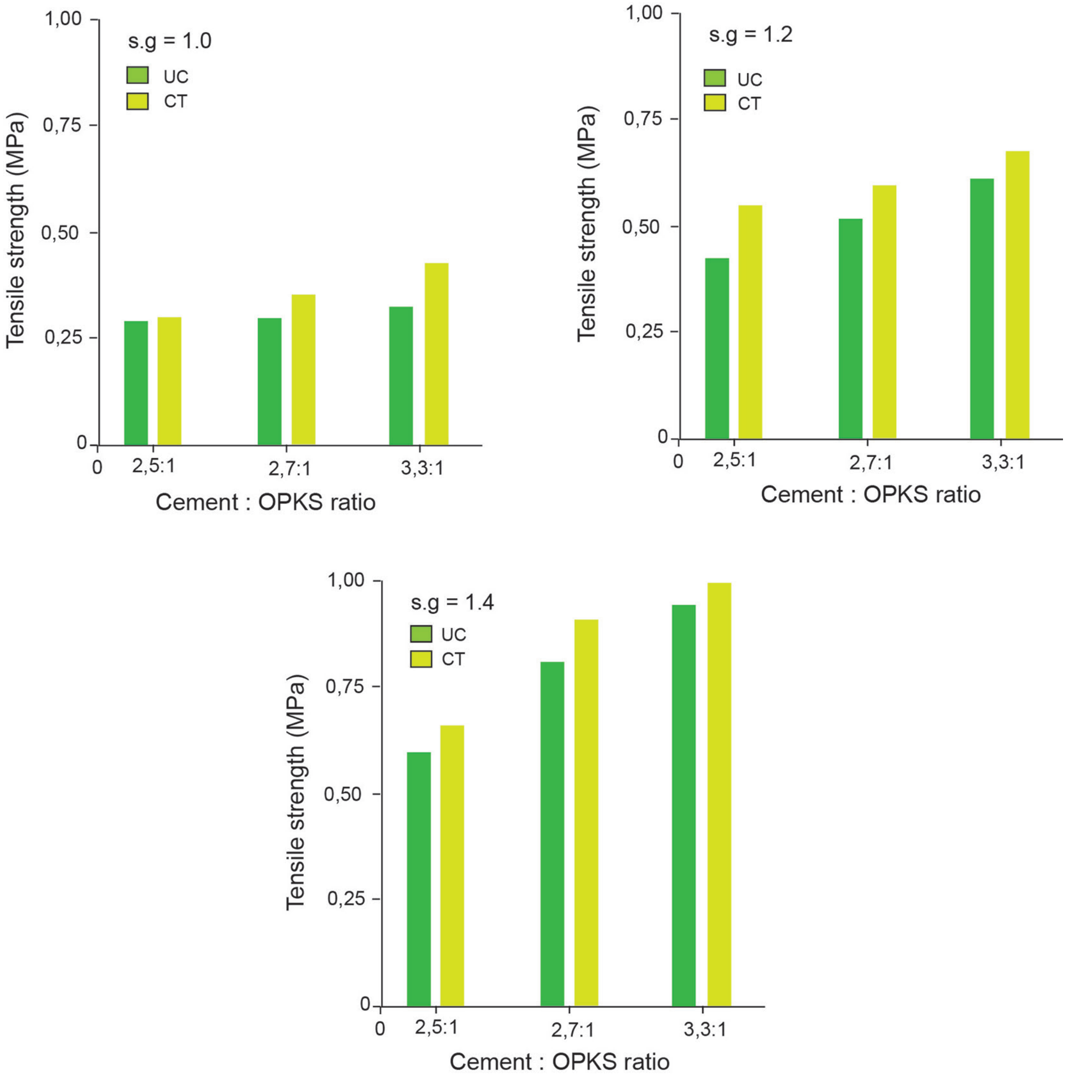

Figure 5. Tensile strength development of OPKS-based LWFC over 28-day curing period at s.g. of 1.0, 1.2, and 1.4: comparison between UC and CT at varying cement-to-OPKS ratios

overall composite behavior becomes increasingly dominated by matrix properties rather than interfacial characteristics.

The influence of surface treatment on tensile strength development appears most effective at intermediate density levels (s.g. 1.2), where the balance between matrix density and aggregate-paste interaction reaches an optimal point. This phenomenon could be attributed to the competing effects of matrix densification and interfacial bond strength. At lower densities, the relatively weak matrix limits overall strength development, while at higher densities, the enhanced matrix properties begin to overshadow the benefits of surface treatment.

Cement content consistently emerges as a critical factor in strength development across all s.g. levels. The relationship between cement:OPKS ratio and tensile strength demonstrates a generally linear trend, with higher cement content contributing to improved strength values. This correlation becomes more pronounced at higher s.g., suggesting synergistic effects between matrix density and binder content. The 3.3:1 cement:OPKS ratio consistently produces the highest strength values within each density category, indicating an optimal balance between aggregate content and paste volume.

The comprehensive analysis of tensile strength development provides valuable insights for material optimization in practical applications. For non-structural applications requiring moderate strength, compositions with s.g. 1.2 and surface-treated aggregates offer an optimal balance between performance and material efficiency. Applications demanding higher strength capabilities would benefit from compositions with s.g. 1.4, particularly when incorporating surface-treated aggregates and higher cement content. These findings have significant implications for the development of lightweight construction materials, particularly in seismic-prone regions where the combination of reduced mass and adequate tensile strength is crucial. The demonstrated improvements in tensile strength through surface treatment and optimal mix proportioning provide a foundation for developing more efficient and sustainable construction materials utilizing agricultural waste products.

CONCLUSIONS

The investigation of LWFC incorporating OPKS has yielded significant insights into its potential as a sustainable construction material. The research demonstrates that through careful control of s.g. and surface treatment, OPKS-based foamed concrete can achieve properties suitable for building applications, particularly in seismic-prone regions.

The most promising results were observed in higher density mixtures with s.g. 1.4, which exhibited exceptional stability and achieved compressive strengths up to 8 MPa when using coated aggregates. The application of silane-siloxane nanocoating proved particularly effective, enhancing both workability and mechanical properties while reducing moisture absorption issues commonly associated with agricultural waste aggregates.

The study reveals a clear relationship between cement content and performance, with higher cement-to-OPKS ratios consistently producing superior results across all density ranges. This finding provides valuable guidance for mix design optimization in practical applications. Notably, the material's performance characteristics align well with requirements for non-structural building elements, particularly in residential construction where compressive strengths below 3 MPa are specified.

Beyond technical performance, this research contributes to sustainable construction practices by demonstrating the viable utilization of agricultural waste in building materials. The successful development of OPKS-based foamed concrete represents a significant step toward more environmentally conscious construction practices, particularly relevant in regions with abundant palm oil production.

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REFERENCES

1. Alengaram U.J., Al Muhit B.A. bin Jumaat, M.Z. (2013). Utilization of oil palm kernel shell as lightweight aggregate in concrete–A review. *Constr. Build. Mater., 38*, 161–172. https://doi.org/10.1016/j.conbuildmat.2012.08.026
2. Amran Y.M., Farzadnia N., Ali, A.A. (2015). Properties and applications of foamed concrete; a review. *Constr. Build. Mater., 101*, 990–1005. https://doi.org/10.1016/j.conbuildmat.2015.10.112
3. Bullard J.W., Jennings H.M., Livingston, R.A., Nonat A., Scherer G.W., Schweitzer J.S., Scrivener K.L. Thomas, J.J. (2011). Mechanisms of cement hydration. *Cem. Concr. Res., 41*(12), 1208–1223. https://doi.org/10.1016/j.cemconres.2010.09.011
4. Falliano D., De Domenico D., Ricciardi G. Gugliandolo E. (2019). Compressive and flexural strength of fiber-reinforced foamed concrete: Effect of fiber content, curing conditions and dry density. *Constr. Build. Mater., 198*, 479–493. https://doi.org/10.1016/j.conbuildmat.2018.11.197
5. Khankhaje E., Hussin M.W., Mirza J., Rafieizonooz M., Salim M.R., Siong H.C. Warid, M.N.M. (2016). On blended cement and geopolymer concretes containing palm oil fuel ash. *Mater. Des., 89*, 385–398. https://doi.org/10.1016/j.matdes.2015.09.140
6. Lee S.T., Handika N., Tjahjono E. Arijoeni E. (2019). Study on the effect of pre-treatment of Oil Palm Shell (OPS) as coarse aggregate using hot water 50- °C and room temperature water 28- °C to lightweight concrete strength. *In MATEC Web of Conf. 276*, 01023. EDP Sciences. https://doi.org/10.1051/matecconf/201927601023
7. Lim S.K., Tan C.S., Lim O.Y. Lee Y.L. (2013). Fresh

and hardened properties of lightweight foamed concrete with palm oil fuel ash as filler. *Constr. Build. Mater., 46*, 39–47. https://doi.org/10.1016/j.conbuildmat.2013.04.015

8. Mo K.H., Alengaram U.J., Jumaat, M.Z. (2014). A review on the use of agriculture waste material as lightweight aggregate for reinforced concrete structural members. *Adv. Mater. Sci. Eng., 1*,1–9. http://dx.doi.org/10.1155/2014/365197
9. Mo K.H., Alengaram U.J., Jumaat M.Z., Yap S.P. Lee S.C. (2016). Green concrete partially comprised of farming waste residues: a review. *J. Clean. Prod., 117*, 122–138. https://doi.org/10.1016/j.jclepro.2016.01.022
10. MSN. (2016). *Encarca Encyclopedia. Volcano and Tectonic Earthquake of Indonesia*. http://encyclopedia2.thefreedictionary.com/volcanic+indonesia
11. Murtagh N., Scott L. Fan J. (2020). Sustainable and resilient construction: Current status and future challenges. *J. Clean. Prod., 268*,122264. https://doi.org/10.1016/j.jclepro.2020.122264
12. Ngui, J.K. (2023). *Compressive strength forecasting of rubberised lightweight foamed concrete with fresh density of 1350 kg/m³ during the hardening process utilising elastic wave method (Doctoral dissertation, UTAR)*. http://eprints.utar.edu.my/id/eprint/5930
13. Ramamurthy K., Nambiar E.K. Ranjani G.I.S. (2009). A classification of studies on properties of foam concrete. *Cem. Concr. Compos., 31*(6), 388–396. https://doi.org/10.1016/j.cemconcomp.2009.04.006
14. Panesar D.K. (2013). Cellular concrete properties and the effect of synthetic and protein foaming agents. *Constr. Build. Mater., 44*, 575–584. https://doi.org/10.1016/j.conbuildmat.2013.03.024
15. Ramamurthy K., Nambiar E.K. Ranjani G.I.S. (2009). A classification of studies on properties of foam concrete. *Cem. Concr. Compos., 31*(6), 388–396. https://doi.org/10.1016/j.cemconcomp.2009.04.006
16. Rashad, A.M. (2014). A comprehensive overview about the influence of different admixtures and additives on the properties of alkali-activated fly ash. *Mater. Des., 53*, 1005–1025. https://doi.org/10.1016/j.matdes.2013.07.074
17. Shafigh P., Mahmud H.B., Jumaat M.Z.B., Ahmmad, R. Bahri, S. (2014). Structural lightweight aggregate concrete using two types of waste from the palm oil industry as aggregate. *J. Clean. Prod., 80*, 187–196. https://doi.org/10.1016/j.jclepro.2014.05.051
18. SNI 03-0349. (1989). Indonesia national standard for concrete brick for wall masonry, in Bahasa. Badan Standardisasi Nasional Indonesia.
19. Sofyani F.D., Handika N., Tjahjono E. Arijoeni E. (2019). Flexural behaviour of reinforced lightweight concrete beam using hot water pre-treated oil palm shell coarse aggregate. In *MATEC Web of Conferences 276*, 01032. EDP Sciences. https://doi.org/10.1051/matecconf/201927601032
20. Standard, B. (2004). Cement. Composition, specifications and conformity criteria for common cements.
21. The British Standards Institution, (2002), BSI - BS EN 12390-3:2002, Testing hardened concrete – Part 3: Compressive strength of test specimens, The British Standards Institution (BSI), London.
22. Ünal M.T., Hashim H., Gökçe H.S., Ayough P., Köksal F.U.A.T., El-Shafi A. Salman, A.M. (2024). Physical and mechanical properties of pre-treated plant-based lightweight aggregate concretes: A review. *Constr. Build. Mater., 444*, 137728. https://doi.org/10.1016/j.conbuildmat.2024.137728
23. Yew M.K., Yew M.C., Beh J.H., Lee F.W., Lim S.K., Lee Y.L., Lim J.H. Kabeer K.S.A. (2023). Effect of pre-soaking treatment method of plant-based aggregate on the properties of lightweight concrete—preliminary study. *Coatings, 13*(5), 864. https://doi.org/10.3390/coatings13050864
24. Xu Y., Mao J., Jiang J., Chu H., Li W., Kang X., Tong S. Jiang L. (2024). Research on the performance of foamed concrete based on superhydrophobic bulk modification. *Constr. Build. Mater., 438*, 137231. https://doi.org/10.1016/j.conbuildmat.2024.137231