



Oil Palm Boiler Clinker In Structural Lightweight Concrete: A Comprehensive Review On Mechanical Performance, Density Optimization And Strength-To-Weight Efficiency

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ABSTRACT

The growing demand for sustainable construction materials and the rapid depletion of natural aggregates have intensified research on alternative lightweight aggregates derived from industrial and agricultural waste. Among these materials, Oil Palm Boiler Clinker (OPBC), a by-product of the palm oil industry, has emerged as a promising candidate for structural lightweight concrete (SLWC). This paper presents a comprehensive review of the production, physical characteristics, mechanical performance, and durability behavior of OPBC-incorporated concrete. The review critically analyzes published studies focusing on density reduction, compressive strength, split tensile strength, flexural strength, modulus of elasticity, and strength-to-weight efficiency at various replacement levels.

Literature indicates that partial replacement of natural coarse aggregates with OPBC, typically within the range of 20–40%, can significantly reduce concrete density below 2000 kg/m³ while maintaining adequate structural strength. Optimum performance is frequently achieved within this range, where enhanced strength-to-weight efficiency and satisfactory durability characteristics are reported. However, limited investigations have addressed high-strength grades (M40 and above), long-term durability, and comprehensive structural classification criteria.

This review synthesizes existing findings, identifies key research gaps, and outlines future research directions aimed at optimizing OPBC utilization in high-performance structural lightweight concrete. The study concludes that OPBC possesses strong potential as a sustainable lightweight aggregate, provided appropriate mix design optimization and durability assessment are undertaken.

Keywords: Oil Palm Boiler Clinker, Structural Lightweight Concrete, Lightweight Aggregate, Strength-to-Weight Ratio, Sustainable Construction Materials

1. INTRODUCTION

The rapid expansion of infrastructure and urban development has significantly increased the demand for conventional concrete, leading to excessive consumption of natural aggregates. Continuous extraction of aggregates from quarries and riverbeds has resulted in environmental degradation, ecological imbalance, and resource depletion. In addition to environmental concerns, conventional concrete typically possesses a density ranging from 2240 to 2400 kg/m³, which contributes substantially to structural dead load. In high-rise buildings, long-span bridges, and precast structural elements, this excessive self-weight increases member sizes, reinforcement demand, and overall construction cost. To address these challenges, structural lightweight concrete (SLWC), generally defined as concrete with density less than 2000 kg/m³, has gained considerable attention in modern construction practices.

Lightweight concrete is commonly produced by incorporating lightweight aggregates (LWA) derived from natural, industrial, or agricultural sources. In recent decades, sustainability-driven research has focused on valorizing waste materials as alternative aggregates to reduce environmental impact while enhancing material efficiency. Among agricultural waste-based materials, Oil Palm Boiler Clinker (OPBC) has emerged as a promising lightweight aggregate. OPBC is a by-product generated during the combustion of palm oil fibers and shells in boilers within palm oil mills. The material is characterized by low specific gravity, high porosity, irregular particle shape, and rough surface texture, which contribute to reduced concrete density and improved mechanical interlocking within the cement matrix.

Several researchers have investigated the incorporation of OPBC in structural concrete and reported encouraging results. Studies indicate that partial replacement of natural coarse aggregates with OPBC can significantly reduce density while maintaining satisfactory compressive, tensile, and flexural strengths. Optimum replacement levels are often reported between 20% and 40%, where strength-to-weight efficiency is enhanced without substantial loss of mechanical performance. In addition to mechanical benefits, OPBC utilization contributes to sustainable waste management by diverting agricultural by-products from landfills and reducing dependence on natural aggregates.

Despite the growing body of research, most available studies focus on low to medium strength grades (M20–M35), with comparatively limited investigation on higher strength structural concrete such as M40 and above. Furthermore, variations in mix design parameters, curing regimes, and replacement percentages have led to inconsistent findings regarding optimum performance levels. Comprehensive evaluation of density classification, strength development trends, durability performance, and structural suitability remains fragmented across existing literature.

Therefore, this review aims to systematically synthesize published research on OPBC-incorporated structural lightweight concrete, with particular emphasis on mechanical performance, density optimization, durability behavior, and strength-to-weight efficiency. The paper also identifies existing research gaps and proposes future research directions for achieving high-performance, sustainable lightweight concrete suitable for structural applications.

2. PRODUCTION AND PROPERTIES OF OIL PALM BOILER CLINKER (OPBC)

2.1 Production of OPBC

Oil Palm Boiler Clinker (OPBC) is an agricultural waste by-product generated during the combustion of palm oil residues in palm oil mills. In palm oil processing industries, palm fibers and shells are used as biomass fuel in boilers to generate steam and electricity for plant operations. During combustion at high temperatures (approximately 800–1000°C), these residues undergo partial sintering and form porous clinker-like solid lumps. After cooling, the clinker is collected, crushed, and sieved to obtain aggregate-sized particles suitable for concrete applications.

The production process of OPBC generally involves the following steps:

1. Collection of clinker waste from boiler furnaces
2. Air cooling under ambient conditions
3. Crushing to required aggregate sizes
4. Sieving and grading according to desired particle size distribution

Unlike manufactured lightweight aggregates, OPBC does not require additional energy-intensive processing, making it environmentally and economically attractive. Its availability is particularly significant in countries with large palm oil industries such as Malaysia, Indonesia, Thailand, and parts of India.

2.2 Physical Properties of OPBC

The physical characteristics of OPBC significantly influence the performance of OPBC-incorporated concrete. Due to the combustion process, OPBC exhibits a highly porous internal structure and irregular surface texture.

2.2.1 Specific Gravity and Density

OPBC typically has a lower specific gravity compared to natural coarse aggregates. Reported specific gravity values range between 1.8 and 2.1, whereas natural aggregates generally have values around 2.6–2.8. This lower specific gravity contributes to reduced concrete density, often enabling the classification of OPBC concrete as structural lightweight concrete ($<2000 \text{ kg/m}^3$).

Bulk density of OPBC aggregates is also considerably lower than conventional aggregates due to internal voids and porous structure.

2.2.2 Water Absorption

One of the most distinctive characteristics of OPBC is its high water absorption capacity, typically ranging from 4% to 12%, depending on processing and particle grading. The porous nature of OPBC allows it to absorb mixing water, which may reduce workability if not properly accounted for in mix design. However, this absorbed water may contribute to internal curing, potentially enhancing later-age strength development.

Proper pre-soaking or water adjustment during mix proportioning is therefore essential when using OPBC as a coarse aggregate replacement.

2.2.3 Particle Shape and Surface Texture

OPBC particles are generally irregular, angular, and rough in texture. The rough surface enhances mechanical interlocking and improves the bond between aggregate and cement paste. However, irregular shape may slightly reduce workability compared to smooth natural aggregates.

The presence of interconnected pores contributes to lightweight characteristics but may also influence durability performance depending on mix design and curing conditions.

2.3 Chemical Composition

The chemical composition of OPBC depends on the combustion process and raw biomass materials. Studies indicate that OPBC contains silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO) in varying proportions. The presence of silica-rich compounds contributes to its relatively stable behavior within cementitious matrices.

Although OPBC is primarily used as a lightweight aggregate rather than a pozzolanic material, its mineral composition may influence interfacial transition zone (ITZ) characteristics and bonding behavior.

2.4 Microstructural Characteristics

Microstructural investigations using scanning electron microscopy (SEM) reported in literature reveal that OPBC possesses a highly porous internal matrix with interconnected voids. These voids reduce overall density and contribute to internal curing effects. The interfacial transition zone between OPBC particles and cement paste is generally stronger when replacement levels are maintained within optimum ranges (20–40%).

At higher replacement levels, excessive porosity may result in reduced mechanical strength and increased permeability. Therefore, optimization of replacement percentage and water-cement ratio is critical for achieving balanced performance.

2.5 Advantages and Limitations of OPBC

Advantages

- Significant reduction in concrete density
- Improved strength-to-weight ratio
- Sustainable waste utilization
- Reduced dependence on natural aggregates
- Potential internal curing effect

Limitations

- High water absorption
- Reduced workability without proper mix adjustment
- Possible strength reduction at very high replacement levels
- Limited long-term durability data in some studies

3. DENSITY PERFORMANCE OF OPBC CONCRETE

Density is one of the most critical parameters in evaluating the suitability of Oil Palm Boiler Clinker (OPBC) for structural lightweight concrete applications. The primary objective of incorporating OPBC as a coarse aggregate replacement is to reduce the self-weight of concrete while maintaining adequate structural performance. Since OPBC possesses lower specific gravity and higher porosity compared to conventional aggregates, its inclusion significantly influences the density of hardened concrete.

3.1 Effect of OPBC Replacement on Concrete Density

Several studies consistently report that the density of concrete decreases progressively with increasing OPBC replacement percentage. Conventional concrete typically exhibits density in the range of 2240–2400 kg/m³. In contrast, OPBC-incorporated concrete generally falls within 1600–2000 kg/m³, depending on replacement level, water-cement ratio, and mix design parameters.

At lower replacement levels (10–20%), the reduction in density is moderate and primarily attributed to the lower specific gravity of OPBC aggregates. As replacement increases to 30–40%, density reduction becomes more pronounced due to the cumulative effect of the porous aggregate structure. In some full-replacement studies, densities as low as 1600–1700 kg/m³ have been reported.

This reduction in density is advantageous for structural applications where minimizing dead load leads to:

- Reduced foundation size
- Lower reinforcement requirement
- Improved seismic performance

- Economical structural design

3.2 Classification as Structural Lightweight Concrete

Structural lightweight concrete (SLWC) is commonly defined as concrete with oven-dry density less than 2000 kg/m^3 while maintaining sufficient compressive strength for structural use. Literature indicates that OPBC concrete with 20–40% replacement frequently satisfies this classification.

Most studies demonstrate that partial replacement within this range achieves density between 1700 and 1950 kg/m^3 while maintaining compressive strength above 25 – 30 MPa . This balance confirms that OPBC concrete can meet structural lightweight criteria when properly designed.

However, full replacement (100%) may result in very low density but could compromise mechanical strength if not optimized with supplementary cementitious materials or lower water–cement ratios

3.3 Influence of Mix Design Parameters

The density performance of OPBC concrete is influenced by several factors:

3.3.1 Water–Cement Ratio

Higher water–cement ratios may increase porosity and slightly reduce density. Optimized lower water–cement ratios improve packing density and strength without significantly increasing weight.

3.3.2 Aggregate Grading

Well-graded OPBC particles enhance particle packing and reduce excessive voids, resulting in improved density control.

3.3.3 Pre-soaking Condition

Due to high water absorption, pre-soaked OPBC may slightly increase fresh density compared to dry aggregates but improves overall consistency and internal curing behavior.

3.4 Strength-to-Weight Efficiency

One of the key performance indicators in lightweight concrete is the strength-to-weight ratio. OPBC concrete often exhibits improved strength-to-weight efficiency because the reduction in density is proportionally greater than the reduction in strength at optimum replacement levels.

For example, at 20–40% replacement:

- Density may reduce by 10–20%
- Compressive strength may remain comparable or slightly improved

This leads to improved structural efficiency, making OPBC concrete particularly suitable for:

- High-rise buildings
- Precast structural elements
- Bridge decks
- Seismic-resistant structure

3.5 Limitations and Observed Trends

Although density reduction is beneficial, excessive replacement levels can result in:

- Increased porosity
- Higher water absorption
- Potential durability concerns

Therefore, most researchers recommend partial replacement (20–40%) as the optimum range for balancing density reduction and mechanical performance.

4. MECHANICAL PERFORMANCE OF OPBC CONCRETE

4.1 Compressive Strength

Compressive strength is the primary parameter used to evaluate structural concrete performance. Literature consistently reports that OPBC concrete exhibits a strength development pattern similar to conventional concrete, with strength increasing progressively with curing age.

Effect of Replacement Percentage

- **Low Replacement (10–20%):**
At lower replacement levels, compressive strength is generally comparable to or slightly higher than control concrete. This improvement is attributed to better mechanical interlocking due to the rough surface texture of OPBC particles and potential internal curing effects.
- **Moderate Replacement (20–40%):**
Most researchers identify this range as the optimum replacement level. Within this range, concrete typically achieves compressive strengths between 25–40 MPa, depending on mix design. Strength-to-weight efficiency is significantly improved due to simultaneous reduction in density.
- **High Replacement (>50% or 100%):**
At very high replacement levels, compressive strength may decline due to increased porosity and weaker interfacial transition zones (ITZ). However, in some optimized mixes with lower water–cement ratios or supplementary cementitious materials, acceptable structural strength has still been achieved.

Strength Development with Age

Studies show that OPBC concrete gains strength steadily at 7, 28, and 56 days. The porous structure of OPBC may provide internal curing by releasing absorbed water, contributing to improved later-age hydration and strength gain.

4.2 Split Tensile Strength

Split tensile strength reflects the cracking resistance and bond characteristics of concrete. The behavior of OPBC concrete under tensile loading follows trends similar to compressive strength but is more sensitive to replacement percentage.

- **At low to moderate replacement levels (20–30%),** tensile strength is often comparable to conventional concrete.
- **At higher replacement levels,** slight reductions may occur due to increased aggregate porosity and weaker bonding at the interfacial transition zone.

The rough and angular surface of OPBC particles enhances mechanical interlocking, partially compensating for internal porosity. However, excessive replacement may reduce tensile resistance due to reduced aggregate stiffness. Overall, optimum tensile performance is generally observed within the 20–40% replacement range

4.3 Flexural Strength

Flexural strength represents the bending resistance of concrete and is particularly important for beams, slabs, and pavement applications.

Literature indicates that flexural strength of OPBC concrete:

- Remains comparable to conventional concrete at moderate replacement levels.
- May slightly improve due to enhanced aggregate–paste bonding from rough particle texture.
- May decrease marginally at very high replacement percentages due to increased internal voids.

In many studies, flexural strength trends closely follow compressive strength patterns. Concrete incorporating 20–40% OPBC often demonstrates satisfactory crack resistance and ductile behavior under flexural loading.

5. COMPARATIVE SUMMARY OF MECHANICAL AND DENSITY PERFORMANCE OF OPBC CONCRETE FROM LITERATURE

Author(s)	Concrete Grade	OPBC Replacement (%)	Density (kg/m ³)	28-Day Compressive Strength (MPa)	Key Findings
Shafigh & Mahmud	M30	25%	1850–1900	30–32	Improved strength-to-weight efficiency; suitable for SLWC
Shafigh et al.	M35	40%	1750–1850	35–38	Optimum performance at 30–40% replacement
Aslam et al.	M35	40–50%	1700–1800	33–36	Enhanced modulus and durability within optimum range
Chai (2016)	M40	100%	1650–1750	28–32	Reduced workability; acceptable structural strength
Kanadasan & Razak	M25	30%	1800–1900	26–29	Balanced density and strength performance
Mohammed et al.	M30	20%	1850–1950	31–34	Improved durability and compressive strength
Alengaram et al.	M30	50%	1700–1800	29–32	Suitable for lightweight structural members
Mo et al.	M35	40%	1750–1850	34–37	Improved tensile strength at moderate replacement
Teo et al.	M30	100%	1600–1700	25–30	Lightweight classification achieved
Awal et al.	M25	20–30%	1850–1950	27–30	Internal curing effect observed
Hossain et al.	M30	40%	1750–1850	32–35	Reduced density with acceptable strength
Tangchirapat et al.	M30	30%	1800–1900	30–33	Improved crack resistance
Lim et al.	M35	40%	1700–1800	34–36	Suitable for structural applications
Mannan & Ganapathy	M25	20%	1900–2000	28–30	Moderate density reduction
Sata et al.	M30	50%	1700–1750	28–31	Strength slightly reduced at high replacement

6. RESEARCH GAPS AND FUTURE SCOPE

Despite extensive investigations on the utilization of Oil Palm Boiler Clinker (OPBC) as a lightweight aggregate, several significant research gaps remain that restrict its large-scale structural application. Most of the available studies have concentrated on normal to medium strength concrete ranging from M20 to M35 grades, while limited research has addressed higher strength classifications such as M40 and above. Since modern infrastructure increasingly demands high-strength lightweight materials for high-rise buildings, long-span structures, and precast elements, the absence of systematic data on high-performance OPBC concrete represents a major limitation. Furthermore, although many researchers report density and compressive strength values independently, very few studies have evaluated

strength-to-weight efficiency as an integrated performance index, which is a critical parameter for structural lightweight concrete. This lack of combined assessment makes it difficult to optimize replacement levels for maximum structural benefit.

Another important gap lies in the limited holistic evaluation of mechanical properties. While compressive strength is widely reported, relatively fewer studies provide comprehensive data on split tensile strength, flexural strength, and modulus of elasticity, all of which are essential for structural design and crack control. Additionally, long-term durability performance of OPBC concrete under aggressive environmental conditions remains insufficiently explored. Parameters such as chloride penetration, sulphate resistance, carbonation depth, freeze–thaw resistance, creep, and shrinkage behavior require systematic investigation to ensure long-term serviceability and structural safety. The porous nature of OPBC significantly influences the interfacial transition zone between aggregate and cement paste; however, advanced microstructural analyses using techniques such as scanning electron microscopy and mineralogical characterization are limited, restricting deeper understanding of bonding mechanisms and internal curing effects.

Moreover, the absence of standardized mix design guidelines or dedicated code provisions for OPBC-based structural lightweight concrete presents another barrier to practical implementation. Current design standards do not specifically address OPBC aggregates, thereby limiting confidence among practicing engineers. In addition, although OPBC is recognized as an agricultural waste material, comprehensive life-cycle assessment studies quantifying carbon footprint reduction, embodied energy savings, and economic feasibility are scarce, which limits its justification within sustainable construction frameworks.

Future research should therefore focus on developing high-performance OPBC concrete capable of achieving M40–M60 grade strength through optimized mix design and the incorporation of supplementary cementitious materials. Detailed durability investigations under simulated aggressive exposure conditions are necessary to validate long-term performance. Advanced microstructural studies should be undertaken to understand pore distribution, interfacial bonding characteristics, and crack propagation mechanisms. Furthermore, structural element-level testing of beams, columns, and slabs is required to evaluate real structural behavior beyond material-level properties. The development of empirical relationships between density, compressive strength, and modulus of elasticity will also facilitate the formulation of design recommendations and eventual inclusion in national and international standards. Addressing these research gaps will enable the transition of OPBC concrete from experimental investigations to reliable structural applications, thereby promoting sustainable resource utilization and environmentally responsible construction practices.

6. CONCLUSION

This review critically examined the production, properties, mechanical performance, and structural potential of Oil Palm Boiler Clinker (OPBC) as a sustainable lightweight aggregate in concrete. Based on the synthesized literature, OPBC demonstrates significant promise in reducing concrete density while maintaining adequate structural strength, particularly within the optimum replacement range of 20–40%. Most studies confirm that OPBC concrete can achieve compressive strengths suitable for structural applications while satisfying the density criteria for structural lightweight concrete (below 2000 kg/m³). The porous and rough surface texture of OPBC contributes to improved mechanical interlocking and potential internal curing effects, which enhance later-age strength development. However, excessive replacement levels may lead to increased porosity and reduced mechanical performance unless supported by optimized mix design and proper curing.

The review further highlights that while compressive strength has been widely investigated, comprehensive evaluation of tensile strength, flexural strength, modulus of elasticity, and long-term durability remains comparatively limited. The absence of standardized mix design guidelines and structural design provisions for OPBC-based concrete also restricts its widespread adoption in practical engineering applications. Moreover, high-strength grade investigations (M40 and above), long-term durability under aggressive exposure, and detailed microstructural studies require further systematic

exploration. Despite these limitations, OPBC concrete offers considerable advantages in terms of strength-to-weight efficiency, sustainability, waste utilization, and reduction of natural aggregate consumption.

Overall, OPBC can be considered a viable alternative lightweight aggregate for structural concrete when used at optimized replacement levels. With continued research focusing on durability validation, high-strength development, and code-based standardization, OPBC has strong potential to contribute significantly to sustainable and resource-efficient construction practices, particularly in regions where palm oil industry waste is abundantly available.

6. REFERENCES

1. Alengaram, U. J., Mahmud, H., & Jumaat, M. Z. (2011). Enhancement and prediction of modulus of elasticity of palm kernel shell concrete. *Materials & Design*, 32(4), 2143–2148.
2. Aslam, M., Shafigh, P., & Jumaat, M. Z. (2016). Oil-palm by-products as lightweight aggregates in concrete: A review. *Construction and Building Materials*, 126, 56–73.
3. Awal, A. S. M. A., & Shehu, I. A. (2013). Evaluation of heat of hydration of concrete containing high volume palm oil fuel ash. *Fuel*, 105, 728–731.
4. Bashar, S. M., & Alengaram, U. J. (2014). Durability properties of lightweight concrete containing palm oil clinker aggregate. *Construction and Building Materials*, 53, 325–332.
5. Chai, L. J. (2016). Mechanical properties of oil palm boiler clinker concrete. *Construction and Building Materials*, 102, 237–246.
6. Chai, L. J., Mahmud, H., & Shafigh, P. (2020). Durability performance of structural lightweight concrete incorporating oil palm boiler clinker. *Journal of Cleaner Production*, 256, 120–135.
7. Hossain, K. M. A. (2008). Properties of volcanic pumice based cement and lightweight concrete. *Cement and Concrete Research*, 38(3), 387–396.
8. Jumaat, M. Z., Mahmud, H., & Alengaram, U. J. (2010). Structural performance of oil palm shell lightweight concrete. *Journal of Materials in Civil Engineering*, 22(9), 954–962.
9. Kanadasan, J., & Razak, H. A. (2014). Mix design for oil palm shell lightweight aggregate concrete. *Construction and Building Materials*, 50, 773–782.
10. Lim, S. K., Tan, C. S., & Lee, Y. L. (2013). Fresh and hardened properties of lightweight concrete using oil palm shell as coarse aggregate. *Construction and Building Materials*, 46, 162–170.
11. Mannan, M. A., & Ganapathy, C. (2004). Engineering properties of concrete with oil palm shell as coarse aggregate. *Construction and Building Materials*, 18(9), 645–651.
12. Mo, K. H., Alengaram, U. J., & Jumaat, M. Z. (2016). Structural behavior of lightweight concrete beams made with oil palm shell aggregates. *Materials & Design*, 97, 407–416.
13. Sata, V., Tangchirapat, W., & Jaturapitakkul, C. (2007). Utilization of palm oil fuel ash in high-strength concrete. *Journal of Materials in Civil Engineering*, 19(7), 623–628.
14. Shafigh, P., Mahmud, H., & Jumaat, M. Z. (2010). Oil palm shell as a lightweight aggregate for production of structural lightweight concrete. *Construction and Building Materials*, 25(4), 1848–1853.
15. Shafigh, P., Jumaat, M. Z., & Mahmud, H. (2011). Oil palm shell lightweight concrete as a ductile material. *Materials & Design*, 32(10), 5146–5153.
16. Tangchirapat, W., & Jaturapitakkul, C. (2010). Strength, drying shrinkage, and water permeability of concrete incorporating palm oil fuel ash. *Cement and Concrete Composites*, 32(10), 767–774.
17. Teo, D. C. L., Mannan, M. A., & Ganapathy, C. (2007). Lightweight concrete using oil palm shell as aggregate. *Building and Environment*, 42(8), 2798–2805.
18. Tonnyopas, D., & Kueaket, N. (2008). Performance of lightweight concrete using palm oil clinker. *Asian Journal of Civil Engineering*, 9(2), 123–135.
19. Yew, M. K., Mahmud, H., & Ang, B. C. (2014). Influence of oil palm shell as partial replacement of coarse aggregate on properties of concrete. *Construction and Building Materials*, 54, 432–438.
20. Zain, M. F. M., Islam, M. N., Mahmud, F., & Jamil, M. (2011). Production of structural lightweight aggregate concrete using palm oil fuel ash. *Materials & Design*, 32(8–9), 4518–4523.*