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# Structural Lightweight Concrete Incorporating Sustainable Lightweight Aggregates: A Review

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***Abstract***

Structural lightweight concrete (SLWC) offers substantial advantages over conventional concrete by reducing dead load, enhancing thermal insulation, and lowering seismic vulnerability in multi-storey and long-span structures. Traditional SLWC production has relied heavily on energy-intensive manufactured aggregates, such as expanded clay and sintered fly ash, which pose environmental concerns. This review examines recent advances in SLWC produced using sustainable alternatives—naturally occurring pumice, treated oil palm shell (OPS), recycled lightweight concrete aggregate (RLA) from demolished blocks, and waste crushed bricks (WCB)—in combination with supplementary cementitious materials (SCMs) including metakaolin, silica fume, fly ash, and ground granulated blast-furnace slag.

The paper synthesizes findings on aggregate pretreatment, mixture proportioning, and mechanical performance, showing that appropriately designed SLWC systems achieve 28-day compressive strengths of 25–45 MPa at equilibrium densities below 2000 kg/m³, thereby satisfying major code requirements (ACI 213R, ASTM C330, DIN 1045-1). Pumice-based concretes incorporating 15–18% metakaolin demonstrate strengths up to 40 MPa and sharply reduced sorptivity, while treated OPS concretes with silica fume or slag attain 25–31 MPa at densities around 1700–1750 kg/m³. Recycled lightweight aggregate concretes with 25–35% RLA maintain structural-grade strengths and thermal conductivities in the range 0.49–0.75 W/(m·K). Full replacement of natural aggregates with WCB yields compressive strengths exceeding 39 MPa when combined with 15% silica fume or metakaolin, alongside favorable interfacial transition zone characteristics confirmed by scanning electron microscopy, X-ray diffraction, and thermogravimetric analysis.

Durability assessment reveals that highly reactive SCMs—particularly metakaolin and silica fume—refine pore structure, reduce capillary water absorption, and enhance residual strength after exposure to elevated temperatures up to 600 °C. Among SCMs, slag exhibits superior fire resistance, retaining approximately 85% of ambient-temperature strength after 600 °C exposure. However, existing data remain largely short-term and specimen-scale, with limited information on long-term freeze–thaw resistance, chloride ingress, carbonation, and full-scale structural behavior under service conditions.

The review identifies critical research gaps, including the need for integrated durability testing programs, multi-parameter response-surface models linking strength, stiffness, sorptivity, and thermal conductivity, and pilot field applications with real-time monitoring of deflection, cracking, and thermal performance. Future work should also translate validated performance into explicit design provisions—density–strength reduction factors, bond and shear coefficients for alternative aggregates, and fire-rating guidelines—to facilitate the wider adoption of these eco-efficient structural lightweight concretes in routine design practice.

***Keywords***

Structural lightweight concrete, Lightweight aggregates, Supplementary cementitious materials, Waste clay brick aggregate, Silica fume, Elevated temperature performance

## 1 Introduction

Structural lightweight concrete (SLWC) is increasingly recognised as a key material for reducing structural self-weight, improving thermal performance and enhancing sustainability in modern construction. Normal-weight concretes, although capable of providing high strength and stiffness, impose significant dead loads and thus demand larger member sizes and higher seismic forces, particularly in multi-storey and long-span structures (Demirel et al., 2019; Green et al., 2011). In contrast, SLWC, typically defined by equilibrium densities in the range 1400–2000 kg/m³ and compressive strengths above about 17–21 MPa, allows substantial reductions in dead load while satisfying structural performance criteria specified in major standards such as ACI 213R and ASTM C330 for beams, slabs and load-bearing walls (Demirel et al., 2019; Wongkvanklom et al., 2018).

Traditionally, structural lightweight aggregate concrete has relied on manufactured aggregates such as expanded clay, expanded shale and sintered fly ash, whose production involves high energy consumption and associated environmental burdens. Recent research has therefore focused on natural lightweight aggregates and waste-derived aggregates that can simultaneously reduce density, conserve natural resources and valorise industrial or demolition by-products. In this context, naturally occurring pumice, oil palm shell (OPS), recycled lightweight concrete aggregate (RLA) from damaged blocks and waste crushed bricks (WCB) have emerged as promising coarse and fine aggregates for SLWC, particularly when combined with supplementary cementitious materials (SCMs) such as silica fume, metakaolin, fly ash and slag to improve strength and durability (Green et al., 2011; Swamynadh and Muthumani, 2018; Wongkvanklom et al., 2018; Hussein et al., 2022; Demirel et al., 2019).

Work on pumice aggregate concretes has shown that structural lightweight pumice aggregate concrete (LPAC) with equilibrium unit weights below about 1850–1900 kg/m³ can achieve compressive strengths up to 40 MPa when mixture design is optimised, aggregates are pre-saturated and low water-to-binder ratios are used. Green et al. (2011) developed both low-strength (17.5–35 MPa) and high-strength (>35 MPa) LPAC mixtures using New Zealand pumice, reporting 28-day strengths around 40–46 MPa at unit weights of approximately 1840–1960 kg/m³, along with bond and shear strengths exceeding the requirements of the New Zealand Concrete Structures Standard NZS 3101. Demirel et al. (2019) further demonstrated that pumice-sand SLWC incorporating metakaolin, designed via response surface methodology, can sustain compressive strengths exceeding 30 MPa after exposure to elevated temperatures up to 400–600 °C, with metakaolin contents around 18% providing an optimum balance between strength enhancement, reduced sorptivity and improved thermal resistance.

Agricultural waste aggregates, especially OPS, represent another important class of structural lightweight aggregates. OPS, a by-product of the palm oil industry, exhibits low density (≈350–600 kg/m³) but high water absorption (about 22–30% in 24 h), and therefore requires pre-treatment to be used structurally. Swamynadh and Muthumani (2018) showed that treatment with water-repellent admixtures can reduce OPS water absorption from about 24% to ≈2%, and that SLWC mixtures with OPS coarse aggregate, water-to-cement ratios of 0.35–0.40 and 15% replacement of cement by silica fume or GGBS can achieve compressive strengths in the range of 30–33 MPa at densities around 1700–1750 kg/m³. These OPS concretes satisfied structural criteria for both compressive (≥25 MPa) and splitting tensile strengths (≈3.4–4.0 MPa), while the treated OPS also provided internal curing and reduced sorptivity, suggesting favourable durability performance compared to untreated OPS concrete.

Recycled and demolition-derived lightweight aggregates provide a third route to structural lightweight concretes with improved resource efficiency. Wongkvanklom et al. (2018) investigated SLWC containing recycled lightweight concrete aggregate (RLA), produced by crushing autoclaved lightweight concrete blocks, used to replace up to 45% of fine limestone aggregate. With a constant water-to-binder ratio of 0.24, 10% silica fume and a superplasticizer, 28-day strengths between 16.5 and 30.3 MPa and densities between 1586 and 1820 kg/m³ were obtained. Although compressive strength, modulus of elasticity (≈16.5–25.2 GPa) and thermal conductivity (≈0.49–0.75 W/mK) decreased with increasing RLA content, these values still lay within the working range for SLC; in particular, mixtures with 25–35% RLA satisfied ASTM C330 strength–density requirements for structural lightweight concrete. Hussein et al. (2022) extended this recycling concept to construction and demolition waste by completely replacing natural fine and coarse aggregates with WCB and modifying the paste with 5–15% SCMs (silica fume, fly ash, metakaolin, slag). They reported that 15% metakaolin or 15% silica fume can produce SLWC with 28-day compressive strengths of 39.5 and 41.5 MPa, respectively, and dry densities below 1950–2000 kg/m³, while flexural strengths of about 5.5–6.1 MPa and improved splitting tensile strengths were achieved. Microstructural analyses (SEM, XRD, TGA) indicated denser interfacial transition zones and increased C–S–H formation in mixes with silica fume and metakaolin, explaining the enhanced mechanical and durability behaviours.

Durability, particularly under moisture transport and high-temperature exposure, is a critical aspect of structural lightweight concretes. Demirel et al. (2019) showed that increasing metakaolin content in pumice-sand SLWC reduces sorptivity significantly, with optimum mixes (≈18% metakaolin) exhibiting low capillary absorption and improved residual strength after exposure to 400–600 °C; response surface models derived from their data allow prediction of compressive strength as a function of metakaolin content and temperature. Hussein et al. (2022) found that WCB-based SLWC incorporating 15% slag exhibited the best residual compressive strength after 600 °C, outperforming mixtures with silica fume, fly ash or metakaolin at the same replacement level, while all WCB concretes maintained beneficial thermal insulation properties. For OPS concretes, Swamynadh and Muthumani (2018) reported sorptivity values comparable to normal-weight concretes once OPS had been treated, indicating that the combined use of water-repellent impregnation and SCMs can counteract the high intrinsic porosity of the lightweight aggregate.

Collectively, these studies demonstrate that a wide spectrum of natural, agricultural, industrial and recycled aggregates can be engineered, often with the aid of modern SCMs and pre-treatment strategies, to produce structural lightweight concretes with densities typically between 1600 and 1900 kg/m³ and 28-day compressive strengths in the 25–40 MPa range. Pumice-based concretes, treated OPS concretes, RLA-based SLWC and WCB-based SLWC all satisfy or nearly satisfy relevant code-based strength–density criteria while offering additional benefits in terms of thermal insulation, internal curing, and waste utilisation (Green et al., 2011; Swamynadh and Muthumani, 2018; Wongkvanklom et al., 2018; Hussein et al., 2022; Demirel et al., 2019). However, the available literature remains dispersed by aggregate type, mixture design methodology and target performance, and there is a lack of unified comparisons across systems regarding mechanical properties, durability indices and thermal behaviour.

Accordingly, the present review aims to synthesise and critically evaluate recent developments in structural lightweight concrete produced with (i) naturally occurring pumice aggregates, (ii) agricultural by-product aggregates such as OPS, (iii) recycled lightweight concrete aggregates from damaged blocks, and (iv) waste clay brick aggregates, with particular emphasis on mixtures incorporating SCMs like metakaolin, silica fume, fly ash and slag. The review will focus on (a) aggregate characteristics and pre-treatment techniques; (b) mixture design approaches and resulting strength–density relationships; (c) mechanical properties including stiffness, tensile and bond behaviour; (d) durability under moisture ingress and high-temperature exposure; and (e) microstructural features, especially the interfacial transition zone, that govern long-term performance. By integrating findings across these material systems, the review seeks to identify common mechanisms controlling structural efficiency and durability of SLWC, clarify the trade-offs between strength, density and thermal performance, and highlight research gaps and future directions for the development of robust, eco-efficient structural lightweight concretes tailored to regional resource availability.

## 2 Materials and mixture concepts

Structural lightweight concrete (SLWC) is defined in major standards as concrete with an equilibrium density below about 2000 kg/m³ and a compressive strength typically above 17–21 MPa, enabling its use in load-bearing elements while reducing dead load and improving thermal performance (ACI 213R; ASTM C330; DIN 1045-1).(Demirel et al. 2019; Wongkvanklom et al. 2018; Hussein et al. 2022)

### 2.1 Classification and code requirements for SLWC

Codes such as ACI 213R and ASTM C330 specify SLWC by minimum 28-day compressive strength of about 17 MPa and density between roughly 1350–2000 kg/m³ for structural grades, while European provisions (e.g. DIN 1045-1) similarly limit dry density below 2000 kg/m³ for lightweight structural classes.(Wongkvanklom et al. 2018; Hussein et al. 2022) In practice, mixtures using recycled lightweight aggregate, pumice, treated oil palm shell and waste clay brick reported densities in the 1600–1900 kg/m³ range with compressive strengths from about 25 to over 40 MPa, satisfying these structural lightweight criteria.(Green et al. 2011; Swamynadh and Muthumani 2018; Demirel et al. 2019; Hussein et al. 2022)

### 2.2 Pumice aggregates and LPAC mixtures

Naturally occurring volcanic pumice provides low density and adequate particle strength, allowing structural lightweight pumice aggregate concrete (LPAC) with unit weights below about 1850–1900 kg/m³ and 28-day strengths up to about 40 MPa.(Green et al. 2011; Demirel et al. 2019) Experimental programs using pumice as coarse (and partly fine) aggregate, combined with low water-binder ratios and microsilica or metakaolin, produced mixtures that met or exceeded New Zealand structural bond and shear requirements, indicating that pumice LPAC can safely replace normal-weight concrete in beams and slabs.(Green et al. 2011; Demirel et al. 2019)

### 2.3 Treated oil palm shell as structural coarse aggregate

Oil palm shell (OPS), a porous agricultural by-product, has a bulk density of roughly 350–600 kg/m³ and high water absorption, making it a potential coarse lightweight aggregate once its sorptivity is reduced by water-repellent treatment.(Swamynadh and Muthumani 2018) When OPS concrete is proportioned with a water–cement ratio around 0.35 and partial cement replacement by silica fume or ground granulated blast-furnace slag, 28-day compressive strengths of about 25–31 MPa and density near 1700–1750 kg/m³ can be achieved, comparable to normal-weight concrete but at 25–35% lower unit weight.(Swamynadh and Muthumani 2018)

### 2.4 Recycled lightweight concrete aggregate from damaged blocks

Recycled lightweight aggregate (RLA) can be obtained by crushing damaged autoclaved aerated or other lightweight concrete blocks into fine particles with very high water absorption and low unit weight, typically around 50–60% absorption and about 700 kg/m³ bulk density.(Wongkvanklom et al. 2018) In structural lightweight mixtures where RLA replaced up to 45% of fine limestone by weight, compressive strengths between roughly 16–30 MPa and densities of about 1600–1800 kg/m³ were reported, with 25–35% replacement levels satisfying ASTM C330 strength–density criteria for SLWC.(Wongkvanklom et al. 2018)

### 2.5 Waste clay brick aggregates as full replacement

Waste crushed brick (WCB) from demolition or factory rejects can be processed into fine and coarse aggregates and used as 100% replacement of natural aggregate in SLWC, giving dry densities below about 1950 kg/m³.(Hussein et al. 2022) With proper mixture design and use of supplementary cementitious materials, WCB concretes have achieved 28-day compressive strengths above 30 MPa, and up to about 39–42 MPa when 15% metakaolin or 15% silica fume was used as cement replacement, while still maintaining structural lightweight density and acceptable workability through pre-wetting and superplasticizer use.(Hussein et al. 2022)

### 2.6 Metakaolin, silica fume, fly ash and slag as SCMs in SLWC

Metakaolin is a highly reactive calcined clay with finer particles than Portland cement, which refines pore structure, reduces sorptivity and increases compressive strength of pumice-sand SLWC, with an optimum replacement around 15–18% beyond which dilution effects cause a slight strength decrease.(Demirel et al. 2019) In WCB-based SLWC, silica fume and metakaolin at 10–15% cement replacement significantly increase strength and reduce water absorption, while fly ash tends to lower early strength and slag shows superior residual strength after exposure to 600 °C, indicating different roles of SCM type in mechanical, durability and high-temperature performance.(Hussein et al. 2022).

**3 Mechanical properties of SLWC systems**

SLWC mixtures in this study generally achieved 28-day compressive strengths in the 25–45 MPa range at densities below 2000 kg/m³, satisfying the usual structural lightweight criteria while exhibiting aggregate-controlled stiffness and tensile behaviour.(Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Demirel et al. 2019; Green et al. 2011; Hussein et al. 2022)

**3.1 Density–strength relationships and compliance with codes**

For the RLA system, increasing recycled lightweight fines from 0 to 45% reduced density from 2222 to 1586 kg/m³ and 28-day compressive strength from 58.3 to 16.5 MPa, with the 25–35% series (1820–1701 kg/m³; 30.3–19.8 MPa) lying above the ASTM C330 density–strength envelope for SLWC.(Wongkvanklom et al. 2018) WCB mixes with full aggregate replacement had dry densities below 1950 kg/m³ and compressive strengths up to 41.5 MPa when 15% silica fume or 15% metakaolin was used, thus meeting DIN 1045-1 lightweight density and typical structural strength demands.(Hussein et al. 2022) Pumice-sand concretes with metakaolin also fell in the structural band, with unit weights around 1850–1900 kg/m³ and 28-day strengths between about 29 and 36 MPa.(Demirel et al. 2019; Green et al. 2011)

**3.2 Compressive strength development**

RLA concretes showed a monotonic strength drop with higher recycled fraction, but still reached 19.8–30.3 MPa at 28 days for 35–25% RLA at constant low w/b, indicating that paste quality can partly offset weaker aggregate skeleton.(Wongkvanklom et al. 2018) Pumice SLWC with metakaolin exhibited an optimum around 18% replacement, where 28-day strength peaked at about 36 MPa and then slightly decreased at 25% because of dilution of clinker phases; strength loss after 400–600 °C was also minimized near this optimum.(Demirel et al. 2019) In WCB concretes, 15% silica fume and 15% metakaolin increased 28-day compressive strength from 32 MPa (control) to roughly 41.5 and 39.5 MPa, respectively, and retained 71–78% of this strength after 600 °C when slag was used, underlining the role of SCM type in both early and residual strength.(Hussein et al. 2022) OPS-based SLWC designed at w/c ≈ 0.35 achieved 28-day strengths of 25–31 MPa, with silica fume giving faster early strength than slag, but slag catching up at later ages.(Swamynadh and Muthumani 2018)

**3.3 Tensile and flexural behaviour**

Splitting tensile strengths of OPS lightweight concretes at 28 days were about 3.4–4.0 MPa, comparable to or slightly higher than the companion normal-weight control, even though compressive strength was lower, giving ft/fc ratios of roughly 0.16–0.17 for LWC versus 0.12–0.13 for normal concrete.(Swamynadh and Muthumani 2018) Flexural strength of WCB SLWC after 28 days ranged from about 4.0 to 6.1 MPa, increasing by over 30% when 15% silica fume or about 27% when 15% metakaolin was used, while fly ash and slag replacements tended to reduce flexural resistance at constant strength level.(Hussein et al. 2022) These results indicate that rough, angular lightweight aggregates and refined ITZ from SCMs can compensate for lower matrix stiffness, so that tensile and flexural capacities are not penalized to the same degree as compressive strength.

**3.4 Elastic modulus and stiffness**

For the RLA series, the static modulus at 28 days decreased from 45.8 GPa at 0% RLA to 16.6 GPa at 45% RLA, with the 25–45% lightweight range giving 16.5–25.2 GPa, slightly below ACI 318 predictions for normal concrete but consistent with other SLWCs at similar strengths.(Wongkvanklom et al. 2018) A regression of modulus versus compressive strength for these mixtures had the form $E = 4.85\ f_c^{0.5} + 3.27$ (GPa), and the authors showed that their points lay above previous LWA datasets, which they attributed to the very low w/b and stiff limestone–pumice aggregate skeleton.(Wongkvanklom et al. 2018) Demirel et al. reported moduli for pumice–metakaolin SLWC in the 20–30 GPa band at densities around 1.85–1.9 t/m³, again lower than normal concrete but adequate for serviceability design of floor systems and walls when reduced stiffness is accounted for in analysis.(Demirel et al. 2019) In OPS concretes, the lower aggregate stiffness and high porosity yielded a modest reduction in dynamic and static modulus relative to granite aggregate concrete, but values remained within the 18–24 GPa range typical of structural lightweight mixtures at 30–35 MPa.(Swamynadh and Muthumani 2018)

### 3.5 Bond and shear performance of pumice concretes

High-strength pumice aggregate concretes with equilibrium unit weights around 1840–1890 kg/m³ and 28-day strengths of 39.5–46 MPa were tested in pull-out, and their average bond stresses exceeded the NZS 3101:2006 design bond stress for lightweight concrete by a factor of about 2.4 after normalizing for compressive strength, indicating very safe development-length provisions.(Green et al. 2011) Companion shear-span beams without stirrups, cast from the same pumice mixes, reached ultimate shear stresses of about 4.0–4.6 MPa against NZS 3101 nominal values below 1 MPa, and their behaviour was at least comparable, and in some cases superior, to a normal-weight control beam of similar compressive strength.(Green et al. 2011) The smoother shear planes and aggregate-fracture mode observed in pumice beams confirm that, provided mixture design controls porosity and strength, pumice SLWC can safely meet code bond and shear requirements without special detailing beyond existing lightweight factors.

## 4 Durability and thermal performance

SLWC systems in the reviewed studies combine relatively low sorptivity and capillary uptake with dense ITZs, stable performance up to about 400 °C, and thermal conductivities mostly in the 0.5–0.9 W/mK range, giving a clear advantage over normal-weight concretes for both durability and insulation.

### 4.1 Sorptivity and water absorption of different SLWC systems

Pumice–metakaolin SLWC showed a marked fall in sorptivity as the metakaolin content increased, dropping from $1.315\times10^{-3}$ to $0.256\times10^{-3}$ and then $0.201\times10^{-3}$ cm/s$^{0.5}$ between 0, 18 and 25% MK, which tracked the increase in compressive strength and reflected void refinement. Water absorption of these mixes remained within the usual SLWC band, while OPS concretes with treated shells achieved internal curing benefits but still exhibited 24 h aggregate water absorption around 22–30%, so aggregate pre-treatment and repellent were needed to bring global sorptivity down to a structural range.  In WCB-based LWCs, total water absorption after 24 h capillary contact ranged from about 3.4 kg/m$^2\cdot$h$^{0.5}$ for the reference mix to around 2.5–2.7 kg/m$^2\cdot$h$^{0.5}$ when 15% silica fume or metakaolin was used, and increased to nearly 4.0 kg/m$^2\cdot$h$^{0.5}$ with 15% fly ash, again showing that fine pozzolans with high reactivity and filler effect are the most effective at suppressing capillary transport. The RLA system sat at the lower end of conventional absorptions, with 28-day water absorption between 3.28 and 7.87% for 25–45% RLA and a clear monotonic rise with recycled fraction, directly governed by the 56% water absorption of the fines.

### 4.2 Microstructure and ITZ characteristics (SEM, XRD, TGA)

SEM images of pumice–MK concretes revealed a progressively denser matrix and tighter ITZ as MK rose to about 18%, with metakaolin particles filling capillary pores and generating extra C–S–H that bridges pumice–paste contacts; beyond this level, dilution effects start to counteract microstructural benefits. In WCB SLWC, SEM showed that 15% silica fume and 15% metakaolin produced the most coherent ITZ, with rough, angular brick surfaces well anchored in a dense C–S–H matrix, whereas fly ash mixes at the same level displayed more unfilled voids and microcracks at the interface. XRD and TGA for the same mixes confirmed these impressions: 15% silica fume and 15% metakaolin reduced portlandite peaks and increased the C–S–H-associated mass loss at 100–200 °C compared to the control and fly ash or slag mixes, indicating stronger pozzolanic consumption of $Ca(OH)_2$ and a higher volume of binding hydrates.In the RLA concrete, SEM documented a highly porous recycled matrix with numerous entrapped air bubbles, yet the low w/b and silica fume gave a surprisingly stiff skeleton, and the micro-porous RLA particles were well locked into the paste, explaining why modulus and strength remained respectable even at 35–45% replacement.

**4.3 Behaviour at elevated temperatures (200–800 °C)**

For pumice–metakaolin SLWC, residual compressive strength increased slightly at 400 °C and then fell at 600–800 °C, with the 18% metakaolin mix retaining the highest strength across the temperature range; the optimum MK content both refined the pore structure and reduced free portlandite, tempering spalling and microcracking. WCB-based SLWCs with 15% silica fume and 15% metakaolin reached room-temperature strengths of 41.5 and 39.5 MPa, respectively, and still retained roughly 71–78% of their strength after 600 °C when slag was used, with slag mixes in particular showing the best residual strengths among the SCMs; this was attributed to a more gradual dehydration profile and a robust brick–paste ITZ. In the same series, residual strengths at 200 and 400 °C were actually higher than at 20 °C (up to about 120% of the reference value), consistent with further pozzolanic reaction and sintering of microcracks at moderate temperatures, before the onset of serious decomposition of C–S–H and $CaCO_3$ above 600 °C. Pumice aggregate concretes tested in shear and bond also exhibited good fire robustness: despite aggregate porosity, their low thermal conductivity and stable glassy skeleton helped maintain bond and shear capacity well beyond the conservative NZS 3101 provisions at service-level temperatures.

**4.4 Thermal conductivity and insulation aspects**

RLA-based structural lightweight concretes showed a systematic drop in thermal conductivity from 1.09 to 0.49 W/mK as density decreased from 2222 to 1586 kg/m³ with increasing recycled content, with the 25–45% RLA mixes that fall in the structural density band (1600–1800 kg/m³) giving conductivities in the 0.49–0.75 W/mK range. Pumice SLWC had comparable or slightly lower λ-values at similar densities, benefiting from the intrinsically low conductivity of the vesicular glass; Demirel's metakaolin series remained in the structural lightweight window and combined 28-day strengths around 30–36 MPa with clearly improved thermal resistance compared to normal-weight controls. For WCB concretes, equilibrium densities below 1950 kg/m³ and the brick's ceramic porosity translated into a good compromise between mechanical performance (up to ~41.5 MPa) and insulation, and the authors specifically highlighted their suitability for thermally efficient blocks and panels in hot climates. OPS-based SLWC, while somewhat less efficient thermally than pumice at equal density, still reduced density by about 25–35% relative to normal concrete and, with properly treated shells, maintained water absorption and sorptivity at levels compatible with durable exterior structural use.

**5 Comparative assessment and discussion**

Across the four systems, pumice–MK and WCB–SCM concretes provide the best structural performance and durability, RLA mixes offer the strongest thermal benefits, and OPS concretes sit in a balanced structural–sustainability niche when the shells are properly treated (Demirel 2019; Wongkvanklom et al. 2018; Hussein et al. 2022; Swamynadh and Muthumani 2018; Green et al. 2011).

**5.1 Performance comparison of pumice, OPS, RLA and WCB concretes**

Strength and density: pumice–MK SLWC reaches about 30–36 MPa at 28 days with unit weights ≈1,850–1,900 kg/m³ (Demirel 2019) ; OPS SLWC with treated shells and 15% SF or GGBS gives ≈25–31 MPa at ≈1,700–1,750 kg/m³ (Swamynadh and Muthumani 2018) ; RLA SLC provides 16.5–30.3 MPa at 1,600–1,820 kg/m³ (Wongkvanklom et al. 2018); WCB SLWC with 15% SF or 15% MK reaches ≈39.5–41.5 MPa with dry densities <1,950 kg/m³ (Hussein et al. 2022).

Durability and microstructure: 18% MK in pumice concrete sharply reduces sorptivity (down to $\approx 0.256\times10^{-3}$ cm/s$^{0.5}$) and produces a very dense ITZ (Demirel 2019) ; treated OPS still has inherently porous aggregates, but water-repellent plus SF lowers effective absorption and maintains structural-grade strength (Swamynadh and Muthumani 2018); RLA concretes show rising water absorption (3.28–7.87%) and porosity (6.8–13.9%) with RLA content (Wongkvanklom et al. 2018); WCB mixes with 15% SF or MK exhibit refined ITZ and the lowest absorption among the SCMs, while FA increases early-age porosity (Hussein et al. 2022).

High-temperature behaviour: pumice–MK SLWC retains a high proportion of compressive strength up to 600–800 °C, with slight strength gain at 400 °C for the optimum MK level (Demirel 2019); WCB SLWC with 15% slag shows the highest residual strength after 600 °C (≈85%), whereas SF and MK mixes remain around 70–80% (Hussein et al. 2022); OPS and RLA systems were mainly characterised at ambient temperature but, as lightweight concretes with low conductivity, can be expected to have at least comparable fire robustness to conventional LWC (Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018).

**Indicative comparison**

| System | f′c (MPa) | ρ (kg/m³) | Absorption / sorptivity | Elevated T | Thermal k (W/mK) |
|---|---|---|---|---|---|
| Pumice+MK | 30–36 | 1,850–1,900 | Very low sorptivity at 18% MK | Good to 600–800 °C | Low, SLWC range |
| OPS+SF/GGBS | 25–31 | ≈1,700–1,750 | Requires treatment; sorptivity acceptable with WR+SF | Data limited | Lower than NWC, moderate |
| RLA+SF | 16.5–30.3 | 1,600–1,820 | Absorption 3.3–7.9%, porosity 6.8–13.9% | Not systematically tested | 0.49–0.75 (25–45% RLA) |
| WCB+SF/MK/slag | 32–41.5 | <1,950 | Absorption reduced; best with 15% SF or MK | Slag best at 600 °C | Good insulation potential |

### 5.2 Influence of SCM type and level on strength and durability

In pumice systems, raising MK up to about 18% of cement maximises compressive strength (~36 MPa), UPV and pore refinement, while 25% MK gives a modest strength drop owing to dilution (Demirel 2019). In WCB concretes, 15% SF and 15% MK deliver the highest 28-day strengths (≈41.5 and 39.5 MPa) and lowest water absorption, whereas 15% FA and 15% slag reduce early strength and, in the case of FA, increase absorption; slag, however, dominates in residual strength after 600 °C (Hussein et al. 2022). In OPS LWC, 15% SF restores the compressive strength to the NWC range at 28 days, while 15% GGBS shows slower early development but similar strength by 35 days (Swamynadh and Muthumani 2018). Overall, highly reactive fine SCMs (SF, MK) are most effective for simultaneous strength gain, sorptivity control and CH consumption, whereas slag is preferred where fire resistance is paramount and FA is better suited to longer-term strength development than to early-age durability (Demirel 2019; Hussein et al. 2022; Swamynadh and Muthumani 2018).

### 5.3 Structural efficiency versus thermal and sustainability benefits

Pumice–MK and WCB–SF/MK mixes offer the best structural efficiency (high f′c at relatively low density), allowing reduction in member size and seismic demand while maintaining 30–40 MPa strength levels (Demirel 2019; Hussein et al. 2022; Green et al. 2011). RLA and OPS systems sacrifice some stiffness and strength to gain superior thermal and sustainability performance: RLA contents of 25–45% yield k = 0.49–0.75 W/mK at 1,600–1,820 kg/m³, well below typical NWC and competitive with other SLWCs (Wongkvanklom et al. 2018); OPS concretes reduce density by roughly 25–35% compared to NWC and valorise agricultural waste, achieving structural-grade strengths when combined with SF and water repellents (Swamynadh and Muthumani 2018). WCB and RLA concretes directly recycle demolition waste, whereas pumice reduces the need for manufactured LWAs and imported aggregates, so all four systems contribute to resource efficiency in different ways (Wongkvanklom et al. 2018; Hussein et al. 2022; Swamynadh and Muthumani 2018; Green et al. 2011).

### 5.4 Practical mix-design and processing recommendations

Pumice aggregates should be used in fully saturated state—preferably vacuum-saturated—to stabilise workability, avoid in-pump stiffening and achieve reproducible w/b control; structural mixes can target equilibrium densities ≤1,850 kg/m³ with 28-day strengths >35 MPa (Green et al. 2011). OPS should be sieved to a narrow 8–10 mm grading, pre-soaked and treated with hydrophobic water-repellent, which can cut 24 h OPS absorption from ≈24% to ≈2% and markedly improve slump and bond (Swamynadh and Muthumani 2018). For RLA and WCB, both fine and coarse fractions must be brought to SSD and their high absorptions (≈7.5–12.5% for WCB; 56% for RLA itself) explicitly considered in water adjustments and admixture dosing (Wongkvanklom et al. 2018; Hussein et al. 2022).

On binder design, pumice concretes can use ~400–450 kg/m³ binder with MK at ≈15–18% of cement, WCB SLWC benefits from 10–15% SF or MK (plus slag where 600 °C resistance is critical), OPS structural mixes from ~15% SF or GGBS at w/b ≈0.35–0.40, and RLA SLC from ~10% SF with RLA limited to ≈25–35% to keep 20–30 MPa strength and k around 0.64–0.75 W/mK (Demirel 2019; Wongkvanklom et al. 2018; Hussein et al. 2022; Swamynadh and Muthumani 2018). In all cases, low w/b (≈0.24–0.40) in combination with high-range water reducer and carefully controlled paste volume is essential to secure both workability and the refined microstructure that underpins durability in these structural lightweight systems (Demirel 2019; Green et al. 2011).

## 6 Research gaps and future directions

The current body of work demonstrates that pumice, OPS, RLA and WCB can all be engineered into structural lightweight concretes with competitive strength, density and basic durability, but data remain fragmented, short-term and largely specimen-scale, which limits confident code adoption and performance-based design (Demirel 2019; Green et al. 2011; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022). The most important future work therefore lies in long-term durability and fire performance, multi-parameter modelling and optimization, and systematic scale-up to members, systems and codes.

### 6.1 Gaps in long-term durability and fire performance data

Existing pumice–MK, OPS, RLA and WCB studies focus predominantly on 28–90 day properties, sorptivity or single water-absorption measurements, and short-duration thermal exposures up to 600–800 °C, with little information on coupled or long-term degradation mechanisms (Demirel 2019; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022). There are essentially no systematic data on freeze–thaw resistance, chloride-induced corrosion in real reinforcement cages, carbonation depth–time laws, alkali–silica or alkali–silicate reaction susceptibility of WCB/RLA, or on OPS internal curing effects under cyclic drying/wetting, even though all four systems rely on highly porous aggregates and fine SCMs that will strongly affect transport processes (Demirel 2019; Green et al. 2011; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022).

Fire performance work is similarly narrow: pumice–MK and WCB mixes have been tested at discrete temperatures with residual compressive strength and qualitative crack patterns, but without systematic mapping of spalling risk, thermal strain, modulus degradation, bond strength or post-fire transport properties; OPS and RLA concretes are essentially uncharacterised in this regard (Demirel 2019; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022). Future research should therefore prioritise:

Long-term (≥1–2 year) durability programmes on representative structural mixes, including freeze–thaw, chloride ingress under cyclic wetting, carbonation, and combined mechanical–environmental loading, with direct reinforcement corrosion measurements.

Integrated fire tests on reinforced members (beams, slabs, walls) in pumice–MK, OPS, RLA and WCB systems, recording spalling, deflection, bond degradation and residual transport properties, not only cube strength.

### 6.2 Modelling and optimization (RSM, multi-parameter design)

The RSM model developed for pumice–MK SLWC demonstrates that response-surface methods can capture the coupled effects of SCM dosage and temperature on compressive strength with good predictive accuracy, but it remains limited to two variables and a single response (Demirel 2019). Similarly, the RLA and WCB studies report empirical relationships between density, thermal conductivity, porosity, strength and modulus, but without unifying multi-objective frameworks that would allow designers to trade off structural, thermal and durability targets quantitatively (Wongkvanklom et al. 2018; Hussein et al. 2022).

There is a clear opportunity to extend RSM and related multi-parameter tools to:

Include multiple responses (e.g. strength, modulus, sorptivity, thermal conductivity, residual strength after fire) and multiple factors (aggregate volume fractions and conditioning, SCM type and level, w/b, paste volume) for each aggregate family, leading to practical design charts or closed-form "meta-models" for routine use (Demirel 2019; Wongkvanklom et al. 2018; Hussein et al. 2022).

Couple these calibrated response surfaces with optimisation or machine-learning routines to identify Pareto-optimal mixes that simultaneously satisfy structural (f′c, E), serviceability (shrinkage, stiffness), durability (sorptivity, absorption, carbonation/$Cl^-$ proxies) and thermal targets for given exposure classes, including explicit uncertainty bands (Demirel 2019; Wongkvanklom et al. 2018; Hussein et al. 2022).

### 6.3 Scale-up, field applications and code implications

Most of the available data are based on small laboratory specimens, with only pumice concretes having been robustly validated in structural testing against national design standards, and even there the work has focused mainly on strength, bond and shear rather than full-system performance or long-term service behaviour (Green et al. 2011). OPS, RLA and WCB systems have essentially no published results on full-scale beams, slabs, walls or composite systems under realistic loading and restraint, nor on constructability aspects such as pumping, casting in congested reinforcement, or dimensional stability of large elements (Swamynadh and Muthumani 2018; Wongkvanklom et al. 2018; Hussein et al. 2022).

Future work should therefore:

Undertake pilot field applications and large-member tests for each aggregate system (e.g. OPS slabs, RLA or WCB sandwich walls, pumice bridge decks), with in-situ monitoring of deflection, cracking, shrinkage and thermal response over several years, to build confidence beyond coupon-scale data (Green et al. 2011; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022).

Translate validated performance into design provisions: revised density–strength reduction factors, E–f′c relationships, bond and shear coefficients for OPS and WCB concretes, durability reduction factors for high-porosity aggregates, and explicit guidance for thermal design and fire rating of lightweight structural systems, analogous to existing pumice-based code work (Green et al. 2011; Demirel 2019; Hussein et al. 2022).

## 7 Conclusions

This review confirms that structural lightweight concretes based on pumice–metakaolin, recycled lightweight concrete aggregate, treated oil palm shell and waste clay bricks can all satisfy typical strength–density requirements for structural applications while offering significant sustainability benefits through reduced dead load, improved thermal performance and extensive use of waste or locally available aggregates (Demirel et al. 2019; Green et al. 2011; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022). Across these systems, appropriate use of supplementary cementitious materials (silica fume, metakaolin, slag, fly ash) and proper aggregate conditioning enables 28-day compressive strengths in the 25–40 MPa range at equilibrium densities typically below about 1,900–2,000 kg/m³, with parallel improvements in sorptivity, water absorption, interfacial transition zone quality and, in several cases, residual performance after exposure to 400–600 °C (Demirel et al. 2019; Wongkvanklom et al.

2018; Swamynadh and Muthumani 2018; Green et al. 2011; Hussein et al. 2022). At the same time, the surveyed literature highlights that most results are still short-term and specimen-scale, so future work must systematically address long-term durability, fire performance, member- and system-level behaviour and explicit code calibration before these eco-efficient lightweight concretes can be deployed widely in routine structural design (Green et al. 2011; Demirel et al. 2019; Wongkvanklom et al. 2018; Swamynadh and Muthumani 2018; Hussein et al. 2022)

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