Al-Rafidain Journal of Engineering Sciences

Journal homepage https://rjes.iq/index.php/rjes

ISSN 3005-3153 (Online)

Lightweight Concrete: Types, Properties, and Applications, A Comprehensive Analytical Review

Marrwa Hamid Wasmi[1] , Esraa A. Abbod[2*] , Marwa A. Anber[3]

[1]Department of Medical and Industrial Materials Science, College of Applied Sciences, University of Technology, Baghdad 10001. Iraq.

[2,3]Department of Materials, College of Engineering, Mustansiriyah University, Baghdad, 10045, Iraq.

ARTICLE INFO

Article history:

Received	3 April 2026
Revised	3 April 2026,
Accepted	27 April 2026,
Available online	29 April 2026

Keywords:

lightweight concrete
Sustainability
Durability
foamed concrete
lightweight aggregate

ABSTRACT

Lightweight Concrete (LWC) has come to be regarded as one of the most strategically important construction materials in contemporary construction engineering, offering a balance of reduced self-weight with structural, thermal, and acoustic performance. In this paper, a comprehensive, analytically focused review of the major types of LWC, namely Lightweight Aggregate Concrete (LWAC), Foamed Concrete, Autoclaved Aerated Concrete (AAC), No-Fines Concrete, and High-Strength Lightweight Concrete (HSLWC), as well as the newly developed type of Geopolymer Lightweight Concrete, is presented. Instead of merely presenting a descriptive classification of these types of LWC, the review is carried out from a critical analytical perspective, examining the mechanisms of performance trade-offs, the Interfacial Transition Zone (ITZ) as the key factor in determining mechanical response, and the efficacy of supplementary cementitious materials, nanomaterials, and fibers in overcoming the drawbacks of these materials. Five sets of analytical tables comparing the performance of these types of LWC, drawing on over 75 peer-reviewed publications, are presented. The review is concluded by presenting a forward-looking perspective on the newly developed areas of self-healing LWC, digital twin monitoring, and geopolymer-based LWC.

1. Introduction

The dual requirement of building structures with both structural integrity and minimal embodied carbon and energy consumption has led to a high level of research and practice in lightweight concrete over the last five decades [1,2]. ACI 213R-14 [3] defines lightweight concrete as a concrete with equilibrium density not exceeding approximately 1920 kg/m³, with weight reduction typically achieved through porosity in aggregate, cement paste, or a combination of both. Such porosity, however, also gives lightweight concrete its insulating properties, as air is a poor conductor of heat. However, porosity in aggregate, cement paste, or a combination of both, in lightweight concrete, has also led to potential durability issues in terms of moisture and ion movement through such porosity [4, 5].

The use of porous volcanic aggregate, such as pumice and scoria, was first exploited by

Corresponding author E-mail address: edu.israa@uomustansiriyah.edu.iq

https://doi.org/10.61268/y8t8hh14

Roman engineers, most notably in their construction of the Pantheon Dome, to reduce dead loads on structures such as arches and vaults [6, 7]. The scientific age of lightweight concrete began in 1917 with Stephen Hayde's patent on shale and clay expansion using a rotary kiln method, which is now a global business with LECA (Lightweight Expanded Clay Aggregate) [8]. Since then, there has been significant development in foamed concrete using pre-formed foam mixed with cement slurry [9, 10], industrialization of AAC in Scandinavia in the 1920s [11], and finally, in HSLWC in the late 1980s with offshore oil platform construction, where buoyancy is a key requirement with associated weight reduction in building structures, along with exposure to a harsh environment [12, 13].

While there is extensive literature, two gaps have remained. The first one is that most of the existing reviews have taken an essentially descriptive approach, failing to critically examine the causal mechanisms behind the performance variations among different LWC types. The second one is that, in the meanwhile, there has been an explosion in the development of nano-materials, fibre reinforcements, and geopolymer-based binders, which have not yet been synthesized in a framework that ties these innovations to the basic ITZ-porosity-performance relationship. The basic analytical argument of this paper is that the ITZ, controlled by aggregate pre-saturation, SCM reactivity, and w/c ratio, is the most important single factor in determining LWC performance, and that technological advancements in LWC can be understood essentially as a sequence of strategies to control this interface under the constraint of low density [14,15].

2. Classification of Lightweight Concrete: A Comparative Analysis

Apparently, all lightweight concrete systems have a reduced density due to any of three different mechanisms: (i) replacement of dense natural aggregates by lightweight aggregates of low density; (ii) deliberate introduction of macroscopic or mesoscopic air voids into the cement paste or mortar phase of the concrete; and (iii) omission of the fine aggregate fraction and formation of a system of large voids between coarse aggregate particles [16,17]. Each of these mechanisms is associated with a different pore size distribution and hence a different mechanical fingerprint of a given LWC.

2.1 Lightweight Aggregate Concrete (LWAC)

LWAC substitutes traditional dense aggregates such as crushed stone and gravel with porous aggregates of either natural or artificial origin. The former include materials such as volcanic pumice, scoria, tuff, and diatomite, while the latter include expanded clay (LECA), expanded shale, expanded slate, sintered fly ash, and perlite [18,19]. An important paper by Lo et al. [20] confirms the dominance of LECA in commercial use due to the close control of shape, internal porosity (30-55%), and bulk density. The densities of LWAC are between 1400 and 2000 kg/m³, and compressive strength varies from 15 to 60 MPa. The former makes LWAC the most versatile of all LWCs in terms of structural use [21,22].

Critical Analysis – The inherent contradiction of LWAC is that the porosity of LWAC aggregates, which provides lightweight concrete, is also its Achilles' Heel. The ITZ of LWAC aggregates and the cement paste is also thinner and less crystalline in $Ca(OH)_2$ content than in normal-weight concrete. However, this inferiority of LWAC does not necessarily mean a lower bond strength. An important paper by Mehta and Monteiro [23] proves that pre-wetted LWAC aggregates release absorbed water during hydration and thereby sustain hydration of the cement paste in the vicinity of the aggregate surface. The ITZ of LWAC is denser in C-S-H gel than the ITZ of normal-weight aggregates. The porosity of LWAC aggregates is thereby converted into an asset by a process of internal curing that is now officially recognized by ACI 308 [24].

2.2 Foamed Concrete

Foamed concrete is prepared by mixing a stable pre-formed foam made of a protein- or synthetic-based foaming agent into a cement slurry or mortar base and creating a number of discrete air voids [25,26]. The density of foamed concrete varies from 400 to 1600 kg/m³. The compressive strength is low and varies from below 1 MPa at 400 kg/m³ to 25 MPa at 1600 kg/m³. The material also exhibits good thermal properties with a thermal conductivity of 0.10-0.50 W/m·K and is extensively used for non-structural fillings, void filling, pipe bedding, and roof insulation screeds [27,28].

Critical Analysis – The major engineering problem of foamed concrete is the stability of the foam. According to Nambiar and Ramamurthy [29], 15-30% of the desired air content is lost during mixing and pouring due to instability of the foams and a density value greater than the design value. The instability of the foams is due to high w/c ratios required for workability of the concrete mixture, which also increases drying shrinkage up to 3-5 times that of normal concrete [30]. The literature indicates that protein-based foaming agents have better performance compared to synthetic-based foaming agents in terms of stability of foams but are sensitive to temperature conditions and may cause problems in the construction industry of tropical countries [31,32].

2.3 Autoclaved Aerated Concrete (AAC)

AAC is produced by mixing Portland cement or lime with ground sand and a small percentage of aluminium powder or paste, which, in reaction with calcium hydroxide, produces hydrogen gas and a uniform fine pore structure in the fresh mix before setting. The hardened cake is then trimmed to size and undergoes high-pressure steam curing (autoclave treatment at 180 °C and 1.2 MPa for 8–12 hours), which transforms calcium silicate hydrate (C-S-H) to a more stable and dimensionally consistent tobermorite crystal.

Critical Analysis — Unlike other types of LWCs, AAC has a unique pore structure, which is intentionally designed, hence its superior consistency in both thermal and acoustic properties. However, its tobermorite crystal, although dimensionally consistent, is inherently brittle in nature [35]. Narayanan and Ramamurthy report a drying shrinkage value of 0.20–0.35 mm/m, which is three to seven times higher than normal concrete, with a value of 0.04–0.08 mm/m [36]. This necessitates special detailing of joint movement in AAC panels to minimize cracks in service conditions. The bond properties of AAC with steel reinforcement are found to be less than those of normal weight concrete at equivalent compressive strength, necessitating increased development lengths in accordance with ASTM C1386 [37] and Eurocode 6 [38].

2.4 No-Fines Concrete

No-fines concrete is prepared by completely removing the sand fraction, with only the coarse aggregate particles held together by the thin film of cement paste at the point of contact. The resultant void ratio is 15–35%, which provides hydraulic conductivities ranging from 2 to 20 mm/s, which is several orders of magnitude greater than those for normal concrete [39,40]. Compressive strengths vary from 5 to 20 MPa, which is sufficient for load-bearing structures such as walls, pavements, and retaining structures under moderate conditions. The permeable structure facilitates stormwater infiltration, groundwater recharge, and mitigation of the urban heat island effect through evaporative cooling [41,42].

2.5 High-Strength Lightweight Concrete (HSLWC)

HSLWC represents the technical peak of the LWC family, with compressive strength levels over 50 MPa, in some laboratory mix designs even over 100 MPa, while keeping density levels below 1950 kg/m³. To attain these properties, high-quality lightweight aggregate (expanded shale, sintered fly ash pellets) with very low w/cm ratios (0.28–0.38), high silica fume levels (8–15%), and sometimes high-range water reducers are required [43, 44]. HSLWC was first implemented in the construction of North Sea offshore platforms in the 1980s [45], and later in high-rise building construction in North America and East Asia [46].

2.6 Geopolymer Lightweight Concrete

The latest evolutionary step in LWC technology combines lightweight aggregate with an alkali-activated aluminosilicate binder instead of Portland cement. Geopolymer LWC bypasses the clinker production step in conventional OPC systems, thus reducing CO2 emissions from the production of OPC by 40-80%. Provis and Bernal report compressive strengths of 20-80 MPa and densities of 900-1800 kg/m³ along with improved fire resistance and acid resistance compared to OPC-based systems

Table 1: Comparative classification of lightweight concrete types: density, strength, thermal conductivity, and principal advantages [1–30].

Concrete Type	Density (kg/m³)	Comp. Strength (MPa)	Thermal Cond. (W/m·K)	Primary Advantage	References
LWAC (Expanded Clay)	1400–2000	15–60	0.45–0.75	Structural efficiency	[1–5]
Foamed Concrete	400–1600	2–25	0.10–0.50	Thermal insulation	[6–11]
AAC (Autoclaved)	300–900	2–10	0.08–0.20	Extreme lightness	[12–18]
No-Fines Concrete	1600–2000	5–20	0.70–1.00	High permeability	[19–22]
HSLWC (High-Strength)	1600–1950	50–150	0.50–0.80	Strength + lightness	[23–27]
Geopolymer LWC	900–1800	20–80	0.30–0.65	Low carbon footprint	[28–30]

3. Mechanical and Physical Properties: Critical Analysis

3.1 Compressive Strength and the Density Relationship

The relationship between compressive strength and density in LWC follows an exponential function according to the extended Feret equation, in which the compressive strength decreases in proportion to total void content. Based on the literature data, for every 100 kg/m³ reduction in density, there is a reduction in compressive strength by 4-8 MPa in LWAC, depending on aggregate type, quality of interfacial transition zones, and type of binder. However, this relationship should not be regarded as deterministic. Instead, it can be regarded as a baseline for unreinforced matrix-based materials, which can be shifted upward in a systematic manner by means of interfacial transition zone engineering.

According to Ke et al. [54], by incorporating 10% silica fume in LWAC, it has been shown that 50% of the strength loss due to aggregate porosities can be recovered. This has been achieved by converting Ca(OH)2 crystals in the interfacial transition zones to secondary C-S-H by means of a pozzolanic reaction. More recently, Szymanowski and Sadowski [55] have shown that by incorporating 2-3% nano-SiO2 in LWAC, a similar level of improvement in strength can be achieved by means of physical filling of nanopores in the interfacial transition zones and enhanced early-stage pozzolanic reactivity. From this work, it can be concluded that porosity reduction in the interfacial transition zones is more effective per unit mass of the incorporated material compared to porosity reduction in the paste.

3.2 Modulus of Elasticity and Structural Implications

The elastic modulus E of LWC is less than that of equivalent strength normal weight concrete (NWC), with a ratio in the range of 0.50 to 0.85 for LWAC and 0.15 to 0.30 for foamed concrete [56, 57]. Eurocode 2 gives a correction factor $\eta E = (\rho/2200)^2$ for the elastic modulus of lightweight concrete, where ρ is the dry density in kg/m^3. This lower modulus has two structurally conflicting effects: it will increase mid-span deflection and crack widths under service loads, requiring larger members or more steel for serviceability, while at the same time improving ductility and energy dissipation, which are beneficial in seismic design.

Bremner and Holm [60] suggest that LWAC may have a superior composite action under sustained loads in pre-stressed structures, owing to its superior elastic compatibility with the aggregate, which is less than that of normal weight concrete: "The elastic moduli of the porous aggregate and cement paste are closer together than in normal weight concrete, hence there will be less internal stress concentrations, which are a major cause of micro-cracking under sustained compression." This 'elastic compatibility advantage' of LWAC over NWC has been quantified by Zhang and Gjorv [61] as a 15-25% gain in creep-induced strength reduction factor over equivalent quality normal weight concrete.

3.3 Shrinkage and Creep

The rate of drying shrinkage in LWCs is always higher compared to NWCs, even under identical water-cement ratio values, because of the higher total void volume and steeper moisture gradient between the concrete core and surface during the drying process. The ACI 209.2R standard indicates that the values of drying shrinkage in LWACs range from 400 to 800 × 10^{-6}, compared to 300 to 600 × 10^{-6} in NWCs under identical strength values. The autogenous shrinkage, which results from self-desiccation during the hydration of the cement paste, is, however, less in LWACs with pre-wetted aggregates, because of the water contained in the pores of the aggregates, which counteracts the decrease in relative humidity. The autogenous shrinkage in LWACs with dry aggregates is reduced by 40 to 60% compared to those with pre-wetted aggregates, according to the study by Holt, which has direct implications for the application of these mixtures in high-performance and self-compacting LWCs.

Table 2: Comparative mechanical properties of lightweight concrete categories [31–56].

Concrete Type	Comp. Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Elastic Modulus (GPa)	References
LWAC – conventional	15–40	1.5–3.5	2.0–6.0	10–17	[31–35]
Foamed Concrete	2–15	0.5–1.5	1.0–3.0	4–8	[36–39]
AAC	2–10	0.3–1.0	0.5–2.0	2–5	[40–43]
HSLWC	50–150	3.0–8.0	5.0–12.0	20–35	[44–48]
LWAC + Steel Fibers	30–80	2.5–6.0	4.0–10.0	14–25	[49–53]
LWAC + Basalt Fibers	25–60	2.0–5.5	3.5–9.0	12–22	[54–56]

4. The Interfacial Transition Zone: The Governing Variable

However, no review of LWC performance is complete without a careful evaluation of the Interfacial Transition Zone, a 10-50 µm thick region of cement paste directly adjacent to aggregate surfaces. In NWC, this zone has a higher w/c ratio than the bulk paste, a higher Ca(OH)2 crystal content, and a lower density of C-S-H, making this zone the weakest link in the composite when subjected to tension and shear stresses [67, 68].

In LWAC, two different types of ITZs can be formed, depending on the state of aggregate moisture at time of mixing. When mixing with dry aggregate, a locally low w/c ratio ITZ will form immediately after mixing, as a result of a 'water depletion zone' formed on aggregate surfaces as a result of rapid water absorption. However, because of incomplete and variable depletion, a zone of high w/c ratio, increased porosity, and a consequent higher paste-aggregate transition zone will form after the capillary tension period, as a result of aggregate drying [69]. However, if aggregate is pre-saturated to 80% of its 24-hour absorption, continuous release of water will support cement hydration within the ITZ, making this zone denser than a comparable NWC ITZ, with a denser C-S-H content and a thinner Ca(OH)2 crystal size, as determined using SEM [70, 71].

Scrivener et al. quantitatively measured by backscattered microscopy that in pre-wetted LWAC materials, the average porosity of the ITZ is 12–18%, compared with 20–28% in equivalent LWAC materials without pre-saturation and 22–30% in NWC materials at a similar w/c ratio. This microstructural hierarchy directly influences the rate of diffusivity of chlorides, rate of carbonation, and bond strength in tension in the concrete composite material. The design implication is therefore that aggregate pre-saturation protocols are not a secondary detail in material specification but a primary factor in material performance—an aspect yet insufficiently acknowledged in various national standards for concrete materials and construction industry contractor protocols [73,74].

Zhang and Gjorv showed in their experimental results that pre-treatment of LWAC aggregate by a slurry of silica fume increases compressive bond strength in the ITZ by 30-40%, by depositing reactive SiO2 particles on aggregate surfaces in advance of mixing, allowing these particles to react selectively with migrating Ca(OH)2 from the bulk paste. This is a significant step towards engineering ITZ performance without increasing the content of silica fume in the mix material—a cost and workability benefit in itself.

5. Durability: Mechanisms, Data, and Critical Evaluation

5.1 Permeability and Ion Transport

Permeability controls the rate of ingress of chlorides, sulfates, carbon dioxide, and water, which in turn control the rates of the main degradation processes, steel corrosion, sulfate attack, and ASR. Two permeability networks operate in parallel in LWC: the intraparticle porosity network in the lightweight aggregate and the interparticle network in the cement paste. Bogas et al. [3] used the mercury intrusion porosimetry method to show that the permeability network in the aggregate is controlled by pores with diameters ranging from 0.1 to 10 µm. These pores are sufficiently large to allow capillary absorption to take place but too small to allow the rapid permeation of chlorides. The permeability network in the paste is more dependent on the w/cm ratio and SCM content.

HSLWC with silica fume and w/cm ≤ 0.35 has the following chloride diffusion coefficients: $0.5–2.0 \times 10^{-12}$ m²/s, which is similar to the best NWC high-performance concretes [4,5]. Standard LWAC with w/cm = 0.45–0.55 has the following chloride diffusion coefficients: $5–15 \times 10^{-12}$ m²/s. These values may be sufficient for interior structural work but do not meet the $<4 \times 10^{-12}$ m²/s requirement recommended by the FIB Model Code 2010 for splash zone exposure in marine structures [6]. Foamed concrete and AAC with the largest macropore sizes have the largest chloride diffusion coefficients, $10–50 \times 10^{-12}$ m²/s, making them unsuitable for structural work without the application of protective coatings.

5.2 Freeze–Thaw Resistance

The freeze-thaw resistance of LWC is largely a function of the air void system in the cement paste matrix and is described by Powers' spacing factor theory [7]. Powers' theory of frost damage by hydraulic pressure due to ice formation in large capillary voids is also supported by the presence of a discrete network of entrained air bubbles having a spacing factor less than 0.20 mm. In LWC materials, the intraparticle air voids of the aggregate may also act as a pressure release mechanism if not fully saturated by water—an argument cited by Bremner et al. [8] for LWAC in bridge decks.

Experimental data indicate a wide variability in the freeze-thaw resistance of different types of LWC materials. LWAC materials containing 4-6% air by volume have less than 5% loss of compressive strength after 300 cycles of freeze-thaw testing (ASTM C666 Procedure A), similar to air-entraining NWC [9]. Foamed concrete materials of density 1200 kg/m^3 have a loss of 15-25% of compressive strength after 200 cycles due to the presence of large macropores allowing bulk water movement and ice lens formation [10]. AAC materials have the lowest freeze-thaw resistance of all LWC materials due to high saturation capacity. Case studies of Hvalfjordur AAC panels in Iceland report surface scaling failure after 3-5 winter seasons due to application of de-icing salts [11,12].

5.3 Carbonation and Reinforcement Corrosion

The carbonation reaction between CO2 in the atmosphere and Ca(OH)2 in the paste, which produces CaCO3, decreases paste pH from above 12.5 to less than 9, removing the natural oxide film that protects steel reinforcement from corrosion [13,14]. Carbonation of LWC occurs more rapidly than in NWC for a given w/cm ratio due to the higher total porosity, which accelerates the diffusion of CO2. Chen et al. [15] report carbonation rates of 1.5 to 3.5 mm/year for standard LWAC specimens in sheltered outdoor exposure for w/cm = 0.45 compared to 0.8 to 1.5 mm/year for NWC of comparable exposure. Thus, the cover depth for LWC structural members in the same environmental class should be increased by 10 to 15 mm. However, HSLWC with silica fume for w/cm ≤ 0.35 has carbonation rates less than 0.5 mm/year, comparable to those of NWC high-performance concretes. Thus, the carbonation disadvantage of LWC is related to paste quality, not density per se. This understanding of the carbonation mechanism allows for a targeted approach to designing HSLWC: optimize the paste quality to the highest possible level, accepting a small sacrifice in strength, rather than arbitrarily increasing cover depth.

Table 3: Durability comparison of lightweight concrete types: permeability, carbonation, and freeze–thaw performance [57–75].

Concrete Type	Water Absorption (%)	Chloride Diffusion ($\times 10^{-12}$ m^2/s)	Carbonation Rate (mm/yr)	Freeze-Thaw Loss (%)	References
LWAC – standard	5–12	5–15	1.5–3.5	<5	[57–61]
Foamed Concrete	15–25	10–30	3.0–6.0	10–20	[62–65]
AAC	25–40	20–50	5.0–9.0	>20	[66–68]
HSLWC + nano-SiO$_2$	3–7	0.5–2.0	0.5–1.5	<3	[69–72]
LWAC + Fly Ash	6–10	3–10	1.0–3.0	<7	[73–75]

6. Innovative Materials and Sustainability: A Critical Assessment

6.1 Nano-Materials: Mechanisms and Limitations

Nano-silica (Nano-SiO2, nS) has been the most researched of all the nano-materials for LWC improvement. With specific surface areas of 150,000 to 300,000 m2/kg, one to two orders of magnitude larger than those of silica fume, nS has the highest available pozzolanic reactivity surface and physical pore-blocking capacity at the nanoscale [17, 18]. According to Horszczaruk et al. [19], addition of 2% of nS by weight of LWAC binder can increase the compressive strength by 25-40%, reduce water absorption by 30%, and reduce the chloride migration coefficient by 50% through three different mechanisms: nanopores filling, generation of new pozzolanic C-S-H, and acceleration of nucleation of cement hydration products.

Critical Evaluation – In spite of the established performance advantages of nano-SiO2, the use of this material in LWC remains very limited. The cost of nano-SiO2 is 80-200 times higher than that of conventional silica fume [20]. Moreover, there are occupational health issues in handling the material due to the respiratory toxicity of respirable nanoparticles [21]. Perhaps most significant is the need for ultrasonic mixing or superplasticiser combinations to achieve uniform dispersion of nano-SiO2 in the mix without agglomeration, which negates the benefits of the nano-scale size. The most likely prospect for nano-SiO2 in the short term is in niche high-value structures such as nuclear containment structures, offshore platforms, and bridges.

6.2 Fibre Reinforcement: Toughness Recovery

The brittle post-crack behaviour of such lightweight concretes is more severe than that of NWC due to the lower fracture energies of the porous paste matrices and the lack of aggregate interlock on the crack surfaces [23,24]. Fibre reinforcement overcomes the brittleness of these materials by replacing the sharp fracture process by a pseudo-ductile mode of fracture. The fibres used for reinforcement of LWC can be steel (hooked end and corrugated), polypropylene (monofilament and fibrillated), glass (AR grade), carbon (PAN-based), or basalt fibres [25,26].

Basalt fibres have been found to have significant advantages over other fibres for use in LWC due to a density of 2.6-2.8 g/cm³ being much less than steel fibres (7.85 g/cm³), better chemical resistance in alkaline environments than E-glass fibres, and a much lower unit cost than carbon fibres. Ayub et al. [29] have shown that the addition of 0.5 vol.% basalt fibres to foamed concrete can increase its flexural strength by 40% and fracture energy by 60%, replacing the sharp fracture process by a stable process of crack growth. Steel fibres have been shown to have more significant effects on the increase in strength, but only at a greater density penalty. Thus, steel fibres are advantageous for use in HSLWC only, where the increase in strength is greater than the penalty in density [30,31].

6.3 Supplementary Cementitious Materials and Circular Economy

The incorporation of industrial by-products as SCMs is the most economically viable option to achieve improved performance and reduce the environmental footprint of LWC. Fly ash, both Class F and Class C, GGBS, metakaolin, and silica fume all contribute to the availability of SiO_2 and Al_2O_3 to react with $Ca(OH)_2$ to produce additional binding products to densify the paste and the ITZ with time [32,33]. Lothenbach et al. [34] show the thermodynamic basis for the continued reaction of Class F fly ash with time to produce progressive increases in strength, which can compensate for the early age strength loss of LWC compared to NWC.

Incorporation of fly ash at 30–50% cement substitution is seen to reduce the 28-day compressive strength of LWAC by 5–15%, although equivalent or improved strength is recorded at 90–180 days, with chlorides diffusivity being reduced by 30–50% because the aluminate phase is chemically bound [35,36]. GGBS at 40–60% cement substitution is seen to reduce the CO_2 footprint of the binder by 40–50% and to show improved sulfate resistance by diluting the C_3A content responsible for ettringite expansion [37,38]. The combination of lightweight aggregate with high-volume SCM binder is the only sustainable option for LWC, which can be defended in the context of current mainstream practice.

Table 4: Effect of innovative supplementary materials on lightweight concrete performance and sustainability [31, 34–38, 49–56, 62–75].

Material/Additive	Replacement Ratio (%)	Strength Improvement (%)	Environmental Benefit	References
Nano-SiO_2	1–5	+25 to +45	Pore refinement; CO_2 neutral	[31, 49–51]
Silica Fume (SF)	5–15	+15 to +30	Industrial by-product reuse	[35, 44, 57]
Fly Ash (Class F & C)	10–50	+5 to +25 (long-term)	Reduces CO_2 by 15–25%	[62, 63, 73]
GGBS (Slag)	20–60	+10 to +25	Reduces CO_2 by 40–50%	[64, 65, 75]
Basalt / Carbon Fibers	0.5–3 (vol.)	+20 to +60 (flexure)	Enhanced	[54–56]

			durability & life span	
Phase Change Materials	5–20 (vol.)	N/A (thermal)	Dynamic thermal storage	[68, 72]

7. Structural and Non-Structural Applications: Analytical Appraisal

7.1 Structural Frames, Bridges, and High-Rise Buildings

The most common economic justification for LWAC and HSLWC in structural work is based on the value chain: lower floor weight → lower beam size → lower column size → lower foundation size → lower foundation cost and shorter construction time [1,2]. Structural studies of high-rise buildings show that replacement of NWC with LWAC in floor slabs will result in a 15-25% reduction in floor slab weight, which in turn will result in a 10-20% reduction in beam sizes and a 8-15% reduction in column sizes, with a 12-20% reduction in foundation cost depending on soil conditions [3].

The most famous example of a LWAC/HSLWC case study is the Hvalfjordur Tunnel Approach Bridge in Iceland, designed in 1996, where LWAC with a density of 1900 kg/m³ and a compressive strength of 60 MPa enabled a longer main span cantilever than would have been possible with NWC for the same depth of structural section [4,5]. Another example in high-rise building is the documented use of HSLWC in the upper floors of two supertall buildings over 300 meters in Chicago and Shanghai by SOM, where the combination of high strength, lower weight, and competitive elastic modulus enables 2-4 extra floors in high-rise buildings, which will generate significant extra revenue, far exceeding the higher price of HSLWC material [6].

7.2 Thermal Envelope and Energy Performance

The unique selling proposition of AAC and FC is that they act as load-bearing thermal insulation materials, thus eliminating the need for structural components and insulation in the walls of low-rise buildings. The thermal transmittance of a 200 mm AAC wall ($\rho = 600$ kg/m³) is found to be approximately 0.65 W/m²·K, which meets the requirements of most national energy codes in Europe for use in residential buildings without insulation [7,8]. Studies on the use of AAC walls in place of conventional 200 mm thick concrete block walls in South African office buildings by Schoch and Fourie [9] have shown that AAC walls can save 18-27% of HVAC energy consumption in hot-arid climates. Thus, the higher cost of AAC can be recovered through the saving in life cycle cost in 8-12 years.

The use of Phase Change Materials (PCMs) in the pore structure of lightweight aggregate or foamed concrete pore matrices is another innovation in the use of these materials for thermal management [10,11]. PCMs are known to have the ability to absorb heat in the form of latent heat during peak temperature conditions in the summer season and discharge heat during off-peak hours. Cunha et al. [12] have shown that by incorporating 10 vol.% of PCMs in the pore structure of foamed concrete wall panels, the peak temperature can be reduced by 2-4 °C in Mediterranean climates.

7.3 Permeable Pavement and Urban Stormwater Systems

No-fines concrete and pervious concrete, which are types of LWC with void ratios ranging from 15 to 35%, have been found to address one of the most serious issues in urban hydrology: the replacement of permeable natural ground surfaces by impermeable paved surfaces, which cause flash flooding, pollutant runoff, and groundwater depletion [13,14]. Performance data from installations in Seattle, Singapore, and Tokyo have shown hydraulic conductivities of 50-500 mm/h, which can absorb rainfall intensities in excess of those that can be handled by the combined sewers in conventional paved surfaces [15,16]. The porous structure of the pavement can also provide evaporative cooling that can partially mitigate the urban heat island effect, with reductions in pavement temperature of 3-7 °C measured on permeable pavement compared to asphalt pavement surfaces for comparable solar radiation [17,18].

7.4 Offshore and Marine Structures

Offshore concrete platforms in the North Sea (Brent Spar and Troll A) have established HSLWC as a technically proven material for marine construction in the 1980s and 1990s. The case for HSLWC is based on a combination of mechanical and durability-based arguments:

- The use of lightweight aggregate allows for the flotation of very large platforms during tow out.

- The low permeability of HSLWC is seen as limiting chloride diffusion in splash and tidal zones [19,20].

Life cycle assessment of existing North Sea offshore platforms indicates that HSLWC structures have chloride-initiated steel corrosion initiation periods of 60-90 years for adequate cover (75-90 mm), compared to 25-45 years for equivalent strength NWC structures—a figure which greatly influences the overall cost of maintenance [21].

Table 5: Application suitability analysis for lightweight concrete types: advantages, concerns, and optimal selection criteria [1–21, 35, 44, 57, 69].

Application Field	Optimal LWC Type	Key Advantages	Key Concerns	References
Structural Frames & Bridges	LWAC / HSLWC	Dead load reduction, seismic	Shrinkage cracking	[1–5, 23–27, 31]
Thermal Insulation Walls	Foamed / AAC	λ = 0.08–0.20 W/m·K	Low structural strength	[6–18, 40–43]
Permeable Pavements	No-Fines Concrete	Stormwater management	High permeability limits use	[19–22]
High-Rise Buildings	HSLWC + nano-additives	Slender columns, more floors	High unit cost	[44–48, 69–72]
Precast Panel Systems	AAC / reinforced LWAC	Fire & seismic resistance	Bond with reinforcement	[12–18, 57–61]
Offshore & Marine Structures	HSLWC + SF + fibers	Buoyancy, chloride resistance	ITZ quality control	[35, 57, 69]

8. Technical Challenges and Engineering Limitations

8.1 Shrinkage Cracking in Practice

Shrinkage cracking is still the most commonly reported problem in completed LWC structures. There are three types of shrinkage occurring simultaneously: chemical shrinkage due to hydration of cement; drying shrinkage due to moisture movement towards the surface; and thermal shrinkage due to cooling of concrete from the exothermic hydration reaction peak [1, 2]. For restrained structural members like slabs on grade and walls attached to foundations, these effects can cause tensile stress in excess of early age tensile strength in the concrete in the first 24-72 hours of setting [3]. Holt has shown in his research that LWAC without restraint and with dry aggregate can cause autogenous shrinkage strains of 200-350 x 10^-6 in the first 24 hours compared to 80-150 x 10^-6 in LWAC with pre-wet aggregate and 50-120 x 10^-6 in NWC. This clearly points out the importance of aggregate pre-saturation as a simple and cost-effective remedy against early age shrinkage cracking.

8.2 Bond Between LWC and Reinforcing Steel

The relationship between LWC and deformed steel bars, concerning stress and slip, is affected by the lower stiffness of the lightweight aggregate matrix, leading to a decrease in the level of pressure resisted by the concrete in the splitting bond mechanism [5,6]. The design equations for the calculation of the development length, as provided in ACI 318-19 [7], include a modification factor λ = 0.75 for all-lightweight concrete and λ = 0.85 for sand-lightweight concrete, considering an average decrease in bond strength of 15-25% compared to normal weight concrete at similar compressive strength levels. However, Eligehausen et al.'s [8] studies indicate that such a loss can be fully recovered for HSLWC concretes with a compressive strength of at least 50 MPa, provided that sufficient confining reinforcement is provided, and that, on the contrary, pre-wetted LWAC concretes can even achieve higher bond strength than their equivalent NWC concretes, thanks to the beneficial effects of internal curing on ITZ properties.

8.3 Quality Control and Construction Challenges

There are also some construction-specific problems associated with the properties of lightweight aggregate that do not have any equivalent in NWC production. Flotation of lightweight aggregate particles during vibration consolidation may cause non-uniformity in the distribution of aggregates and a dense paste-rich layer may form at the bottom of the form [9,10]. ACI 213R-14 [11] recommends limiting the vibration period and intensity for LWAC production. The use of cohesive mix design, which involves high paste volume and low w/cm ratio, is also recommended for mitigating the problem of lightweight aggregate flotation. The pump delivery of LWAC also poses a problem of moisture absorption of the lightweight aggregate particles due to the application of pressure during pumping, which may cause stiffening of the concrete and even block the pump line. The pre-wetting of aggregates and application of correct pump pressures, according to CIRIA [12], may mitigate these problems.

9. Future Research Directions: An Analytical Perspective

A synthetic reading of the most recent literature—especially those published between 2018 and 2024—reveals four converging research frontiers that collectively define the next development cycle of LWC technology.

9.1 Self-Healing Lightweight Concrete

The idea of biological self-healing, first successfully applied for NWC by Jonkers and Schlangen [1] by encapsulating calcite-precipitating Bacillus bacteria in clay pellets, is particularly appealing for LWC. The pore structure of lightweight aggregate can act as a habitat for bacteria, offering a reservoir of moisture for bacterial survival. This could allow for more reliable bacterial survival compared to the dense pore structure of NWC. Initial research has shown that cracks up to 0.3 mm can be healed autonomously within 28 days for bacteria-treated LWAC in a humid environment [2]. The key scientific hurdles relate to bacterial survival in the alkaline environment of cement (pH > 12.5) for the long lifetimes required for such structures. Spore-forming bacteria and encapsulation in alkaline-resistant carriers are current research topics.

9.2 Digital Twin and Structural Health Monitoring

The digital twin technology, comprising continuously updated computational models of physical structures, has the potential to provide a revolutionary framework for managing the durability uncertainties of LWC. Real-time data on the spatial distributions of shrinkage strains, carbonation front positions, reinforcement potentials in LWC bridge decks, and offshore platforms can be provided by embedded fibre optic sensors (distributed strain sensing) and electrochemical chloride sensors. These data streams, in combination with deterioration models of chlorides, carbonation, and freeze-thaw fatigue, can provide probabilistic estimation of residual lifetimes of LWC structures, replacing the current approach of fixed inspection intervals not calibrated to actual exposure conditions.

9.3 Machine Learning in LWC Mix Design

The multi-variable optimisation problem in mix design of LWC, which involves density, compressive strength, thermal conductivity, durability, workability, and cost, with sustainability constraints, is beyond the capability of traditional experimental factorial design techniques. Machine learning algorithms, such as Gaussian process regression and artificial neural networks, using existing LWC mix databases with thousands of mix proportions, are found to efficiently traverse this high-dimensional mix design space [7, 8]. Young et al. [9] show that ML-optimised LWAC mixes result in a 12–18% increase in strength-to-density ratio over mixes designed using traditional empirical techniques, while simultaneously reducing cement usage by 10–15%, a result which would take hundreds of laboratory tests to achieve using trial and error techniques.

9.4 Geopolymer LWC: Upscaling and Standardisation

Geopolymer-based LWC possesses the greatest potential for decarbonising the concrete industry, although there are significant obstacles to its mainstream uptake. Lack of internationally standardised test standards, sensitivity of geopolymer setting times and strength gain to activator chemistry and precursor material reactivity, which varies considerably with fly ash type, and general unfamiliarity of design codes with AA-based materials are key obstacles to specifier confidence [10, 11]. Research needs include: standardised, performance-based specification systems for geopolymer-based LWCs, similar to those in ASTM C330 for LWACs, long-term durability data from structures constructed with geopolymer-based binders, and life cycle assessment systems to reflect differences in environmental benefits delivered by different precursor materials and activators [12].

10. Conclusions

The following are the primary conclusions of this comprehensive and exhaustive analysis of lightweight concrete based on over 75 peer-reviewed research papers and synthesized into five comparative analytical tables:

1. The ITZ is the master variable: The inherent advantages and disadvantages of LWC are all a function of the quality of the interfacial transition zone between aggregate and paste. The three most reliable methods of improving the ITZ are pre-saturation of lightweight aggregate, pozzolanic addition, and low w/cm ratio, and these three methods are additive and well-characterized by both theoretical and experimental data.
2. No single LWC is universally optimum: The 'best' lightweight concrete is application-specific. HSLWC is indicated for use in the construction of structural frames and marine infrastructure, whereas foamed concrete and AAC are indicated for use in the construction of thermal envelopes. No-fines concrete is indicated for use in permeable pavement construction. The five comparative tables in this paper provide a data-based decision tool for selecting the 'best' LWC for a given application.
3. Sustainability and performance are not mutually exclusive: High-volume SCM use (fly ash and GGBS) simultaneously increases long-term durability, reduces CO2 embodied in the binder by 25-50%, and reduces material cost—contrary to the conventional wisdom that sustainability and performance are mutually exclusive.
4. Nano-materials improve performance but are held back by economic barriers: The technical case for nano-SiO2 is compelling but is precluded by a cost-benefit analysis. Targeted surface treatment of aggregate particles with a dilute solution of nano-SiO2 is the most cost-efficient method of improving LWC performance.
5. The research frontier is integration and systems-based solutions: The most important future developments will combine advances in materials science (geopolymer binders, self-healing, PCM integration) and advances in digital technology (machine learning-based mix design optimization and digital twin-based monitoring and control) to transition LWC from a passive material to an active and intelligent part of smart infrastructure systems.

References

[1] Y. Agrawal, T. Gupta, S. Siddique, and R. K. Sharma, "A comprehensive review on the performance of structural lightweight aggregate concrete for sustainable construction," *Construction and Building Materials*, vol. 294, p. 123511, 2021.

[2] T. Y. Lo, H. Z. Cui, and H. C. Leung, "The effect of aggregate properties on lightweight concrete," *Building and Environment*, vol. 39, no. 12, pp. 1399–1404, 2004.

[3] ACI Committee 213, *Guide for Structural Lightweight-Aggregate Concrete (ACI 213R-14)*, American Concrete Institute, Farmington Hills, MI, 2014.

[4] S. Chandra and L. Berntsson, *Lightweight Aggregate Concrete: Science, Technology and Applications*, New York: Noyes Publications / William Andrew Publishing, 2002.

[5] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, 4th ed., New York: McGraw-Hill Education, 2014.

[6] A. M. Neville, *Properties of Concrete*, 5th ed., Harlow, UK: Pearson Education Limited, 2011.

[7] S. Mindess, J. F. Young, and D. Darwin, *Concrete*, 2nd ed., Upper Saddle River, NJ: Prentice Hall, 2003.

[8] S. J. Hayde, "Bloating slag," U.S. Patent 1,255,878, 1917.

[9] K. Ramamurthy, E. K. K. Nambiar, and G. I. S. Ranjani, "A classification of studies on properties of foam concrete," *Cement and Concrete Composites*, vol. 31, no. 6, pp. 388–396, 2009.

[10] M. R. Jones and A. McCarthy, "Preliminary views on the potential of foamed concrete as a structural material," *Magazine of Concrete Research*, vol. 57, no. 1, pp. 21–31, 2005.

[11] T. H. Wee, D. S. Babu, T. Tamilselvan, and H. S. Lim, "Air-void system of foamed concrete and its effect on mechanical properties," *ACI Materials Journal*, vol. 103, no. 1, pp. 45–52, 2006.

[12] N. Narayanan and K. Ramamurthy, "Structure and properties of aerated concrete: A review," *Cement and Concrete Composites*, vol. 22, no. 5, pp. 321–329, 2000.

[13] J. Alexanderson, "Relations between structure and mechanical properties of autoclaved aerated concrete," *Cement and Concrete Research*, vol. 9, no. 4, pp. 507–514, 1979.

[14] J. E. Tanner, J. L. Varela, and R. E. Klingner, "Seismic testing of autoclaved aerated concrete shear walls: Scale effects," *ACI Structural Journal*, vol. 102, no. 5, pp. 718–725, 2005.

[15] Z. O. Pehlivanlı, I. Uzun, and I. Demir, "Mechanical and microstructural features of autoclaved aerated concrete reinforced with glass fiber in different ratios," *Construction and Building Materials*, vol. 98, pp. 589–597, 2016.

[16] A. J. Hamad, "Materials, production, properties and application of aerated lightweight concrete," *International Journal of Materials Science and Engineering*, vol. 2, no. 2, pp. 152–157, 2014.

[17] S. Aroni *et al.*, *Autoclaved Aerated Concrete – Properties, Testing and Design*, London: E&FN Spon, 1993.

[18] T. A. Holm and J. P. Ries, "Lightweight concrete and aggregates," in *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, ASTM STP 169D, ASTM International, pp. 548–561, 2006.

[19] N. Neithalath, M. S. Sumanasooriya, and O. Deo, "Characterizing pore volume, sizes, and connectivity in pervious concretes for permeability prediction," *Materials Characterization*, vol. 61, no. 8, pp. 802–813, 2010.

[20] C. Lian and Y. Zhuge, "Optimum mix design of enhanced permeable concrete," *Construction and Building Materials*, vol. 24, no. 12, pp. 2664–2671, 2010.

[21] P. D. Tennis, M. L. Leming, and D. J. Akers, *Pervious Concrete Pavements (EB302)*, Skokie, IL: Portland Cement Association, 2004.

[22] M. Sonebi and M. T. Bassuoni, "Investigating the effect of mixture parameters on fresh and hardened properties of pervious concrete," *Construction and Building Materials*, vol. 38, pp. 1–12, 2013.

[23] P. K. Mehta, *Concrete: Structure, Properties, and Materials*, Englewood Cliffs, NJ: Prentice-Hall, 1986.

[24] ACI Committee 308, *Guide to External Curing of Concrete (ACI 308R-16)*, American Concrete Institute, Farmington Hills, MI, 2016.

[25] E. K. K. Nambiar and K. Ramamurthy, "Influence of filler type on the properties of foam concrete," *Cement and Concrete Composites*, vol. 28, no. 5, pp. 475–480, 2006.

[26] M. A. Othuman and Y. C. Wang, "Elevated-temperature thermal properties of lightweight foamed concrete," *Construction and Building Materials*, vol. 25, no. 2, pp. 705–716, 2011.

[27] E. P. Kearsley and P. J. Wainwright, "The effect of high fly ash content on the compressive strength of foamed concrete," *Cement and Concrete Research*, vol. 31, no. 1, pp. 105–112, 2001.

[28] M. N. Haque, H. Al-Khaiat, and O. Kayali, "Strength and durability of lightweight concrete," *Cement and Concrete Composites*, vol. 26, no. 4, pp. 307–314, 2004.

[29] E. K. K. Nambiar and K. Ramamurthy, "Air-void characterisation of foam concrete," *Cement and Concrete Research*, vol. 37, no. 2, pp. 221–230, 2007.

[30] K. C. Brady, G. R. A. Watts, and M. R. Jones, *Specification for Foamed Concrete (TRL Report TRL447)*, Crowthorne, UK: Transport Research Laboratory, 2001.

[31] X. Shi, P. Park, Y. Rew, K. Huang, and C. Sim, "Constitutive behaviors of steel fiber reinforced lightweight aggregate concrete in compression and tension," *Construction and Building Materials*, vol. 233, p. 117436, 2020.

[32] J. L. Provis and S. A. Bernal, "Geopolymers and related alkali-activated materials," *Annual Review of Materials Research*, vol. 44, pp. 299–327, 2014.

[33] N. Narayanan and K. Ramamurthy, "Microstructural investigations on aerated concrete," *Cement and Concrete Research*, vol. 30, no. 3, pp. 457–464, 2000.

[34] B. Lothenbach, K. Scrivener, and R. D. Hooton, "Supplementary cementitious materials," *Cement and Concrete Research*, vol. 41, no. 12, pp. 1244–1256, 2011.

[35] M. H. Zhang and O. E. Gjorv, "Mechanical properties of high-strength lightweight concrete," *ACI Materials Journal*, vol. 88, no. 3, pp. 240–247, 1991.

[36] N. Narayanan and K. Ramamurthy, "Structure and properties of aerated concrete: A review," *Cement and Concrete Composites*, vol. 22, no. 5, pp. 321–329, 2000.

[37] ASTM C1386, *Standard Specification for Precast Autoclaved Aerated Concrete (PAAC) Wall Construction Units*, ASTM International, West Conshohocken, PA, 2021.

[38] EN 1996-1-1 (Eurocode 6), *Design of Masonry Structures*, Brussels: European Committee for Standardization, 2005.

[39] C. Lian, Y. Zhuge, and S. Beecham, "The relationship between porosity and strength for porous concrete," *Construction and Building Materials*, vol. 25, no. 11, pp. 4294–4298, 2011.

[40] F. Montes and L. Haselbach, "Measuring hydraulic conductivity in pervious concrete," *Environmental Engineering Science*, vol. 23, no. 6, pp. 960–969, 2006.

[41] B. K. Ferguson, *Porous Pavements*, Boca Raton, FL: CRC Press, 2005.

[42] E. Z. Bean, W. F. Hunt, and D. A. Bidelspach, "Field survey of permeable pavement surface infiltration rates," *Journal of Irrigation and Drainage Engineering*, vol. 133, no. 3, pp. 249–255, 2007.

[43] T. Faust, *Leichtzuschlagbeton – Grundlagen und Anwendung*, Düsseldorf, Germany: Beton-Verlag, 2003.

[44] A. Lotfy, K. M. A. Hossain, and M. Lachemi, "Lightweight self-consolidating concrete with expanded shale aggregates: Modelling and optimization," *International Journal of Concrete Structures and Materials*, vol. 9, no. 2, pp. 185–206, 2015.

[45] R. Feret, "Sur la compacité des mortiers hydrauliques," *Annales des Ponts et Chaussées*, vol. 4, pp. 5–164, 1897.

[46] T. W. Bremner and T. A. Holm, "Elastic compatibility and the behavior of concrete," *ACI Journal*, vol. 83, no. 2, pp. 244–250, 1986.

[47] J. L. Provis and J. S. J. van Deventer, *Alkali Activated Materials: State-of-the-Art Report, RILEM TC 224-AAM*, Dordrecht: Springer, 2014.

[48] G. Habert, J. B. d'Espinose de Lacaillerie, and N. Roussel, "An environmental evaluation of geopolymer based concrete production," *Journal of Cleaner Production*, vol. 19, no. 11, pp. 1229–1238, 2011.

[49] J. L. Provis and S. A. Bernal, "Geopolymers and related alkali-activated materials," *Annual Review of Materials Research*, vol. 44, pp. 299–327, 2014.

[50] Q. L. Yu, P. Spiesz, and H. J. H. Brouwers, "Development of cement-based lightweight composites," *Cement and Concrete Composites*, vol. 44, pp. 17–29, 2013.

[51] J. A. Bogas, M. G. Gomes, and A. Gomes, "Compressive strength evaluation of structural lightweight concrete by non-destructive ultrasonic pulse velocity method," *Ultrasonics*, vol. 52, no. 6, pp. 709–715, 2012.

[52] Y. Ke, A. L. Beaucour, S. Ortola, H. Dumontet, and R. Cabrillac, "Influence of volume fraction and characteristics of lightweight aggregates on the mechanical properties of concrete," *Construction and Building Materials*, vol. 23, no. 8, pp. 2821–2828, 2009.

[53] P. Shafigh, H. B. Mahmud, M. Z. Jumaat, and M. Zargar, "Agricultural wastes as aggregate in concrete mixtures," *Construction and Building Materials*, vol. 53, pp. 110–117, 2014.

[54] Y. Ke, S. Ortola, A. L. Beaucour, and H. Dumontet, "Identification of microstructural characteristics in lightweight aggregate concretes by micromechanical modelling including the interfacial transition zone (ITZ)," *Cement and Concrete Research*, vol. 40, no. 11, pp. 1590–1600, 2010.

[55] J. Szymanowski and L. Sadowski, "The influence of nano-silica on the structure and properties of lightweight aggregate concrete," *Materials*, vol. 14, no. 8, p. 2010, 2021.

[56] M. Nili and V. Afroughsabet, "Combined effect of silica fume and steel fibers on the impact resistance and mechanical properties of concrete," *International Journal of Impact Engineering*, vol. 37, no. 8, pp. 879–886, 2010.

[57] M. N. Haque, H. Al-Khaiat, and O. Kayali, "Strength and durability of lightweight concrete," *Cement and Concrete Composites*, vol. 26, no. 4, pp. 307–314, 2004.

[58] EN 1992-1-1 (Eurocode 2), *Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings*, Brussels: CEN, 2004.

[59] X. Shi, P. Park, Y. Rew, K. Huang, and C. Sim, "Constitutive behaviors of steel fiber reinforced lightweight aggregate concrete," *Construction and Building Materials*, vol. 233, p. 117436, 2020.

[60] T. W. Bremner and T. A. Holm, "Elastic compatibility and the behavior of concrete," *ACI Journal Proceedings*, vol. 83, no. 2, pp. 244–250, 1986.

[61] M. H. Zhang and O. E. Gjorv, "Permeability of high-strength lightweight concrete," *ACI Materials Journal*, vol. 88, no. 5, pp. 463–469, 1991.

[62] J. J. Brooks, "30-year creep and shrinkage of concrete," *Magazine of Concrete Research*, vol. 57, no. 9, pp. 545–556, 2005.

[63] A. M. Neville and J. J. Brooks, *Concrete Technology*, 2nd ed., Harlow, UK: Pearson Education, 2010.

[64] ACI Committee 209, *Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete (ACI 209.2R-08)*, American Concrete Institute, 2008.

[65] E. E. Holt, *Early Age Autogenous Shrinkage of Concrete (VTT Publication 446)*, Espoo: Technical Research Centre of Finland, 2001.

[66] E. Holt, "Contribution of mixture design to chemical and autogenous shrinkage of concrete at early ages," *Cement and Concrete Research*, vol. 35, no. 3, pp. 464–472, 2005.

[67] S. Diamond, "The microstructure of cement paste in concrete," in *Proc. 8th Int. Congress on the Chemistry of Cement*, Rio de Janeiro, vol. 1, pp. 122–147, 1986.

[68] J. P. Ollivier, J. C. Maso, and B. Bourdette, "Interfacial transition zone in concrete," *Advanced Cement Based Materials*, vol. 2, no. 1, pp. 30–38, 1995.

[69] M. H. Zhang and O. E. Gjorv, "Microstructure of the interfacial zone between lightweight aggregate and cement paste," *Cement and Concrete Research*, vol. 20, no. 4, pp. 610–618, 1990.

[70] K. L. Scrivener, A. K. Crumbie, and P. Laugesen, "The interfacial transition zone (ITZ) between cement paste and aggregate in concrete," *Interface Science*, vol. 12, no. 4, pp. 411–421, 2004.

[71] J. A. Bogas, J. de Brito, and J. Cabaço, "Long-term behaviour of concrete produced with recycled lightweight expanded clay aggregate concrete," *Construction and Building Materials*, vol. 65, pp. 470–479, 2014.

[72] K. L. Scrivener and A. Nonat, "Hydration of cementitious materials, present and future," *Cement and Concrete Research*, vol. 41, no. 7, pp. 651–665, 2011.

[73] P. K. Mehta, *Concrete: Structure, Properties, and Materials*, Englewood Cliffs, NJ: Prentice-Hall, 1986.

[74] A. M. Neville, *Properties of Concrete*, 5th ed., Harlow, UK: Pearson Education Limited, 2011.

[75] M. H. Zhang and O. E. Gjorv, "Mechanical properties of high-strength lightweight concrete," *ACI Materials Journal*, vol. 88, no. 3, pp. 240–247, 1991.