A Compact Review on the Waste-Based Lightweight Concrete: Advancement and Possibilities

M. M. U. Islam, J. Li, R. Roychand, and M. Saberian

Abstract Lightweight concrete (LWC) has been used for more than 2000 years, and the technical development of waste-based LWC is still proceeding. Notably, the very first representative concrete mix of infrastructural LWC was introduced for building a family house in Berlin, Germany, a few decades ago. The unique and distinctive combination of waste-based LWC successfully creates an appealing alternative to traditional concrete aggregates in terms of durability, robustness, cost, energy-saving, transportation, environmental advantages, innovative architectural designs and implementations, and ease of construction. Numerous researchers have attempted to utilize waste materials to produce LWC, aiming to bring both ecological and economical solutions to the construction industry over the past few decades. Waste materials, such as crushed glass, waste tire rubber, masonry rubber, chip rubber, plastics, coconut shells, palm oil fuel ash, palm kernel shells, fly ash, and rice husks, possess lower specific gravity than traditional concrete aggregates. Thus waste-based LWC can be a significant replacement for conventional raw materials (cementitious material and aggregates) as it requires less strength than conventional concrete for both structural and non-structural applications. Although waste-based LWC is well recognized and has proven its scientific potential in a broad range of applications, there are still uncertainties and hesitations in practice. Therefore, the primary objective of this study was to demonstrate the current state-of-the-art understanding and advancement of waste-based LWC over the past decades. Furthermore, an equally critical discussion is reported to shed light on the potential benefits of LWC. We highlight how the performance of LWC has been enhanced significantly over the period, and understanding of the properties of waste-based LWC has advanced.

Keywords Lightweight concrete · Lightweight concrete aggregates · Mechanical properties · Structural bond behavior · Thermal conductivity · Waste materials

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1 Introduction

Knowledge of lightweight concrete (LWC) dates back almost 3000 years [1]. A number of LWC-based superstructures can be found around the Mediterranean, the most noteworthy of which are the Pantheon Dome and the Port of Cosa, both of which were built in the early age of the Roman Empire. LWC has a considerable number of advantages, such as better fire resistance, thermal insulation, and low density. Notably, implementation of LWC has been extensively explored as a non-structural and structural material.

In the past few decades, LWC has become a significant and resourceful material that has been considerably developed, thanks to scientific endeavors [2, 3]. Indeed, LWC is one of the exciting materials in the contemporary construction sector due to its immense advantages, both ecologically and structurally. In the case of structural advantages, LWC has crucial applications, particularly in heavy structure design, where the dead load governs the total weight and that dead load is substantially greater than the anticipated service load, such as for bridges and multistorey buildings. The lessened self-weight that originates from the utilization of the LWC in structures delivers accountable cost savings and flexibility. LWC also improves fire resistance, and seismic structural response offers longer structural spans, reduces reinforcement ratios, and lowers the cost of foundation materials. Furthermore, precast elements manufactured using LWC reduce placement and transportation costs [4, 5]. For bridges, LWC facilitates longer spans and more lanes. For instance, LWC can be used on one side of a cantilever bridge, while normal-weight concrete (NWC) is used on the other side to facilitate the weight balance for a longer span. From the ecological aspect, LWC possesses lower thermal conductivity than NWC and hence plays a significant role in saving energy when introduced as a thermal insulation material. Moreover, implementation of LWC produced from controlled thermal lightweight materials lessens the energy consumption by air acclimatizing in both warm and cold countries. Nowadays, energy-shortage problems are escalating at an alarming and upsetting rate, and it has become a worldwide concern. Most importantly, the waste materials produced from the agricultural and industrial sectors can be utilized to manufacture the LWC following an eco-friendly and economical approach, which assists in mitigating climate change. In this review, we focused on compiling the standpoints and previous scientific efforts related to LWC to improve knowledge of the entire scenario and identify the research gaps. Notably, this compilation sheds light on the advancement and possibilities of LWC to inspire new researchers for further progress.

2 Lightweight Aggregate Concrete (LWAC)

LWAC can be manufactured using artificial or natural lightweight aggregates (LWAs) to substitute the conventional aggregates in NWC [6]. There are a number of LWAs that possess various physical and mechanical characteristics allowing LWAC to be produced with varying ranges of strengths and densities [7]. Different types of LWAs are also commercially available, which has pushed researchers to investigate and compare them in the production of high-strength LWACs [8]. As an example, several natural materials (perlite or vermiculite), recycled waste materials (crushed glass, waste tire rubber, masonry rubber, chip rubber, and plastics), and argillaceous materials (clay, slate, and shale) have been used by previous researchers in the manufacture of LWAC. Moreover, a significant number of research has been conducted into utilizing agricultural wastes, such as coconut shells, palm oil fuel ash, palm kernel shells, and apricot shells. Including these wastes in the manufacture of LWAC brings sustainable solutions to significant environmental issues [9, 10].

It is well known that the LWAs possess higher porosity than normal-weight aggregates (NWAs) [11] and thus lower strength values together with larger deformations [12]. These characteristics suggest that LWAs will be the weakest constituent, having a significant role in the ultimate performance of the manufactured concrete mix. Furthermore, LWAs usually constitute >50% total volume of the concrete [13]. It is therefore crucial to carefully implement LWAs to improve the overall performance of the LWAC mix in both the fresh and hardened phases. A significant number of researchers have conducted detailed investigations of LWAs properties, such as grading, absorption, and particle size, on the thermal and mechanical behaviors of LWAC. Table 1 shows the requirements for compressive strength and splitting tensile strength of LWAs according to ASTM C331 [14].

Table 1 Requirements for compressive and splitting tensile strength of lightweight aggregates (LWAs)

Concrete type	Dry density, kg/m^3	Minimum splitting tensile strength at 28 days (MPa)	Minimum compressive strength at 28 days (MPa)
LWA	1760	2.2	28
	1680	2.1	21
	1600	2.0	17
Mixture of LWAs and NWAs	1840	2.3	28
	1760	3.1	21
	1680	2.1	17

NWAs, normal-weight aggregates

3 Structural Bond Behavior of LWC

It is necessary to have adequate bonding between the concrete matrix and reinforcing bars for (i) gaining an efficient beam action, (ii) crack control, and (iii) improving ductility [15]. Furthermore, all the empirical equations in the standard codes greatly depend on sufficient bonding between the cement matrix and reinforcing bars [16]. Hence, a reduction in bonding may lead all the design basics towards invalidation. There are two mechanisms for achieving improved bond strength: mechanical (bearing and friction action) and physiochemical (linkage/adhesion) [17]. The adhesion/linkage force originates from the chemical reaction between the surface of the reinforcement and the cementitious matrix. The friction forces come from the bearing force and rough contact, resulting from interlocking between the reinforcing ribs and the concrete matrix [18].

Several researchers have investigated the bond strength behavior of LWC and described the factors that can adversely affect the bond strength. These crucial factors, such as the water–cement ratio (w/c), aggregate types, the diameter of the reinforcement bars, admixtures, surface texture and type of reinforcing bars, types of lateral confinement, and bond strength, significantly control the bond strength [19]. Many equations have been developed to predict the bond strength of LWC, and three are presented below [20–22]:

$$\tau = \left[171.9\left(\frac{h}{d}\right)^2 - 24.2\left(\frac{h}{d}\right) + 1.29\right] f'_c \qquad (1)$$

$$\tau = \left[\frac{37.5}{(d + l_d)^{0.25}} - 9.4\right] f'^{0.5}_c \qquad (2)$$

$$\tau = K \cdot [44.5 - 60(w/c)] \cdot \frac{\rho_d}{2200} \qquad (3)$$

where h is the reinforcing rib height, d is the reinforcing bar diameter, l_d is the length of embedment, f'_c is the compressive strength, w/c is the water–cement ratio, and ρ_d is the dry density of LWC.

4 State of the Art

Extensive research on LWAC (Table 2) has led to many structural applications, such as high-rise buildings, long-span bridges, and buildings where the foundation conditions are vulnerable, and also in highly dedicated applications, such as offshore and floating structures. Moisture content and density are the major factors controlling the thermal conductivity properties of LWAC, whereas the mineralogical properties

Table 2 Engineering properties of waste-based lightweight aggregate concrete

Waste material	Replacement type	Aggregate size	Content (%)	Mechanical properties at 28 days				Thermal conductivity (W/m K)	Remarks	References
				Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)			
Rice husks	Cement	Powder	0–35	42–24	2.6–1.8	4.1–2.7	32–29	–	Decreased the mechanical properties by the addition of rice husk	[33]
	Cement	Powder	0–20	68–48	5.1–4.4	8.1–6.9	–	–	20% replacement of cement with rice husk improved the properties	[34]
	Cement	Powder	0–15	36–41	4.5–4.9	–	–	1.21–0.99	Improved thermal conductivity	[35]
	Cement	Ultrafine	10	47	–	–	–	–	Improved compressive strength	[36]
Palm oil fuel ash (POFA)	Cement	300 µm	0–25	41.8–36	3.8–3.1	6.6–4.2	15.8–13.9	–	10% POFA improved the mechanical properties of LWC	[2]

(continued)

Table 2 (continued)

Waste material	Replacement type	Aggregate size	Content (%)	Mechanical properties at 28 days				Thermal conductivity (W/m K)	Remarks	References
				Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)			
	FA	0.1–250 µm	0–15	27–35	2.2–3.3	2.1–3.9	60–78	–	Addition of 15% POFA content improved the mechanical properties	[37]
	Cement	300 µm	0–30	32.6–24.9	2.8–2.6	–	–	Varied from 27 to 40 °C for 26 h	Thermal conductivity improved for up to 30% POFA content	[38]
Oil palm shell (OPS)	CA	2.36–9 mm	100	41.8–36	3.8–3.1	6.6–4.2	15.8–13.9	–	Adopting OPS as CA can reduce the consumption of NCA	[2]

(continued)

Table 2 (continued)

Waste material	Replacement type	Aggregate size	Content (%)	Mechanical properties at 28 days				Thermal conductivity (W/m K)	Remarks	References
				Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)			
	CA	≤2.36 mm	100	2.1–20	–	–	–	0.4–0.9	Palm shell foamed concrete	[39]
	CA	8 mm	50	34.2–41.3	2.77–3.2	3.8–4.9	–	–	OPS improved the properties	[40]
Waste tire rubber	CA	8–15 mm	100	18	3.34	3.74	15.28	–	Proposed new method to improve the mechanical properties	[4]
	FA	≤4.75 mm	5–25	26–41	3–3.8	3.6–4.4	–	–	Fracture energy increased with the addition of rubber and fibers	[41]

(continued)

Table 2 (continued)

Waste material	Replacement type	Aggregate size	Content (%)	Mechanical properties at 28 days				Thermal conductivity (W/m K)	Remarks	References
				Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)			
	FA	1–2 mm	0–20	20.53–33.94	2.25–3.7	3.42–5.5	21.95–33	–	Improved ductile properties	[42]
	FA	1–3 mm	0–15	43–53	3.44–3.8	4.77–6.4	2.52–2.7	–	Addition of rubber decreased properties	[43]
	CA	5–20 mm	40	24.1–28.2	2.4–3.0	4.9–6.1	25.9–28	–	Brittleness index reduced due to the addition of rubber	[44]
	FA	0.075–4 mm	0–20	22–20	–	–	–	1.0–0.9	Improved thermal conductivity	[13]
Waste glass	CA	≤5 mm	0–70	39–45	2.4–3.6	4.4–6.6	–	–	Decreased the properties	[45]
	FA	≤2 mm	100	56–57	–	–	–	1.1–0.9	Improved conductivity	[46]

(continued)

Table 2 (continued)

Waste material	Replacement type	Aggregate size	Content (%)	Mechanical properties at 28 days				Thermal conductivity (W/m K)	Remarks	References
				Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)			
Coconut shell	CA	4.7–12.5 mm	100	13.8–24	1.84–2.98	2.95–5.65	44–67	–	Useful to produce structural LWC	[47]

CA, coarse aggregate; FA, fine aggregate of the aggregates may affect up to 25% of the thermal conductivity for LWC under a similar density value [3, 23]. The concrete matrix penetrates into the LWAs during mixing of the concrete materials [24]. Nevertheless, the penetration rate dramatically depends on the surface layer and microstructure of the aggregates, viscosity of the concrete matrix, and particle size distribution of the cement. Additionally, both the chemical and physical properties of LWAs influence the strength of the LWAC because of the processes occurring at the interfacial transition zone. The compressive strength of LWC increased from 15.5 to 29 MPa for an increase in cement content from 250 to 350 kg/m^3 by maintaining the same density of $\approx$1500 kg/m^3 [25]. Figure 1a shows the correlation between cube strength and density of LWAC. Another study [26] explored the compressive strength and thermal conductivity of expanded perlite aggregate-based concrete along with the mineral admixtures. They mentioned that using fly ash and silica fume as cementitious materials can reduce the thermal conductivity values by up to 15%, while the compressive strength and density of the concrete were also lowered by 30%. LWC using diatomite as the LWA was manufactured with a density ranging from 950 to 1200 kg/m^3 and compressive strength from 3.5 to 6 MPa, and thermal conductivity was found to increase from 0.22 to 0.30 W/(m K) for a cement content of 250–400 kg/m^3. LWC associated with expanded glass and clay as the LWAs exhibited higher resistance to chloride ion penetration and water with a cement content of 500 kg/m^3 and unit density of 1400 kg/m^3, and the compressive strength of the LWAC reached 24 MPa at 28 days. LWAC produced with dredged silt as the LWA exerted densities from 800 and 1500 kg/m^3 for the varying binder content of 364, 452, and 516 kg/m^3 [27, 28]. The dredged silt-based LWAC exhibited compressive strength from 18 to 42 MPa with thermal conductivity of 0.5–0.7 W/m K at 28 days. It was observed that the density of the LWC crucially affects the strength of the concrete for similar cement and water content. The thermal conductivity of LWC is significantly influenced by various factors such as cement content, water content, and the type and content of LWA [29, 30]. LWC bricks were manufactured using rice husk ash (RHA) and expanded polystyrene as LWAs, and the maximum cement replacement by RHA was 10% by weight [31]. The effect of zeolite inclusion for autoclaved concrete was investigated by using aluminum to introduce a pore-forming agent, where zeolite was used with a total content of 535 kg/m^3. The highest compressive strength of 3.3 MPa was attained with 50% replacement, and the thermal conductivity was 0.18 W/(m K). In another study, autoclaved concrete was produced using bottom-ash as the LWA and as fractional replacement of cement, where the bulk density was $\approx$1400 kg/m^3 with the increase in compressive strength ranging from 9 to 11.6 MPa, and thermal conductivity varying from 0.5 to 0.61 W/(m K) [32]. Figure 1b shows the correlation between thermal conductivity and dry density of LWAC.

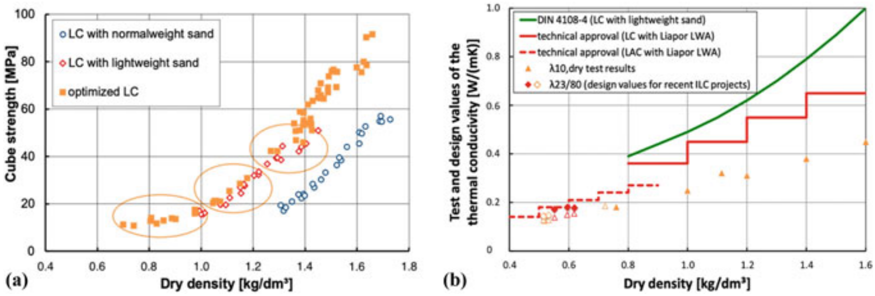

Fig. 1 Correlation between **a** cube strength and dry density for lightweight concretes with different compositions at 28 days [48], and **b** thermal conductivity and dry density for LWC [49]

5 Possibilities

The compilation of previous research gives a clear indication that the thermal and mechanical behaviors of LWAC have been extensively developed and investigated. However, there have been few studies related to the structural applications of LWAC. We suggest widening the scope of LWAC for investigation of its structural application and behaviors, so complete guidelines can be provided to design engineers, assisting them with all required design aids and data. Further studies, especially on the mechanics of lightweight materials, would establish confidence and trust in the potential applications of LWAC as a structural element. Another limitation (i.e., the higher time-dependent deformations of LWAC) requires further investigation. Figure 2 shows some of the superstructures that have been built with LWAs.

Fig. 2 **a** LWC: Schweiz 2003 (Gartmann house), with density 1,100 kg/m^3, strength 12.9 MPa, and thermal conductivity 0.32 W/m K [50], **b** Infra LWC: Berlin 2007 (Schlaich house) with density 760 kg/m^3, strength 7.4 MPa, and thermal conductivity 0.18 W/m K [51], **c** LWC: Stuttgart 2012 (house H36) with density 1,000 kg/m^3, strength 10.9 MPa, and thermal conductivity 0.23 W/m K [50], **d** Infra LWC: TU Eindhoven 2015 (Pavilion) with density 780 kg/m^3, strength 10 MPa, and thermal conductivity 0.13 W/m K [50]

6 Conclusions

LWAC is an exceptionally versatile material that can be implemented in a broad range of applications. Though LWAC has been used for the past two millennia, there are still some limitations that have been reported and discussed in this review. Clear and straightforward definitions have been given for different types of LWAC, and a critical analysis of the mix design, aggregates properties, testing, and classifications of LWC was presented. Several limitations of LWAC have been discussed and presented as crucial information on the state of the art. Infra LWC is a new research area to be explored. We recommend further essential studies to develop a strong design and reliable construction methodology to confirm product quality.

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