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Review

Industrial Wastes-Cum-Strength Enhancing Additives Incorporated Lightweight Aggregate Concrete (LWAC) for Energy Efficient Building: A Comprehensive Review

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Abstract: Lightweight aggregate concrete (LWAC) exhibits the advantages of thermal insulation, reduces energy consumption building costs, improves building efficiency and easy construction. Furthermore, the utilization of industrial wastes in concrete is advantageous in terms of environmental sustainability. In order to explore this, several researchers investigated the idea of integrating industrial wastes in LWAC. However, the lack of knowledge regarding the performance of industrial waste-based lightweight aggregate concrete hinders the adaptation of this concept and application of LWAC in the construction sector. Therefore, this paper summarizes the research in relation to the sustainable LWACs containing oil palm shell (OPS), lightweight expanded clay aggregate (LECA), vermiculite, perlite, pumice and sintered fly ash as lightweight aggregate, along with industrial wastes and strength-enhancing additives (viz. fibers, polymers, etc.). Firstly, desirable physical, chemical, morphological and mineralogical characterization of different lightweight aggregates are presented, and then a comprehensive overview on fresh, hardened, durability and thermal properties of LWAC incorporating industrial wastes are discussed in comparison with normal weight concrete. The review also highlights the current challenges and suggests the research gaps for further development of eco-friendly LWAC. It is concluded that vermiculite, perlite, pumice, OPS, sintered fly ash and LECA with some suitable industrial waste materials have the potential to be used in the construction sector. Moreover, LWAC with industrial waste has 50–65% lower carbon emission (kg CO_2 eq/m^3) in the environment. The scientific contribution of this paper provides insights into different LWACs and the knowledge base for future research and paradigm shift of using LWACs as more common alternative building materials.

Keywords: lightweight aggregate concrete; industrial waste; thermal insulation; energy-efficient building; sustainability

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1. Introduction

In the 21st century, energy-efficient buildings are one of the important issues, which include both techno-economic and sustainable environmental factors [1]. Energy-efficient buildings are designed to use energy as little as possible. Many developing countries are leading towards the construction of green buildings using cost-effective, durable concrete. The huge demand for concrete in the infrastructural development using normal-weight aggregates (NWAs) has reduced the natural stone deposits, which causes irreplaceable damage to our environment. As a result, the priority of searching for sustainable materials has been enhanced worldwide. LWAC is one such alternative to normal weight aggregate concrete (NWC) with various physical, mechanical, social and economic advantages [2]. Figures 1 and 2 show the current trend of research (year-wise and location-wise) in the area of lightweight aggregate concrete (Source: https://www.scopus.com/; accessed on 12 September 2021). The trend shows that day by day, the practical use of LWACs is increasing and thus requires the current status of the research conducted to date.

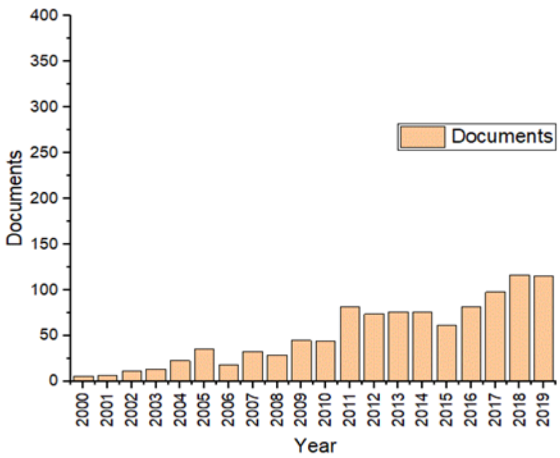

Figure 1. Year-wise research trend.

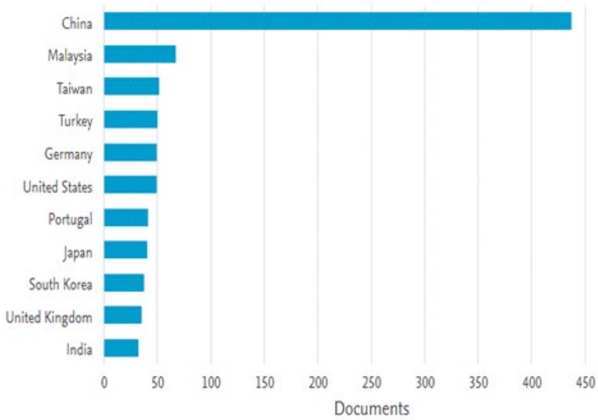

Figure 2. Location-wise research trend.

The use of lightweight aggregates (LWA) in concrete has the following advantages:

1. Less dead load, structure stability as well as economic viability [2];
2. Cost reduction [3];
3. Relatively low thermal conductivity [4–6];
4. Has application in prestressed concrete, high rise buildings, etc. [7,8];
5. Improves the workability if pre-wetted prior to use in concrete [9].

However, lower absolute mechanical strength, higher water absorption, porosity, etc., are some of the negative impacts. LWAC is an alternative solution to NWC, especially when lightweight energy-efficient solutions are needed. Thus, to overcome the problem of natural stone deterioration and for making energy-efficient buildings, different lightweight concretes are used. Chart 1 shows the classification of LWAC. It can be ascertained from the flow chart that LWAC can be used for load-bearing and non-load-bearing purposes. Different LWAs commonly used in making LWAC are vermiculite, OPS, perlite, LECA, pumice, scoria, tuff, cinder, lytag, etc. (Koksal et al. [1]). LWAs are a type of coarse/fine aggregates used for the manufacturing of LWC products, and these products are used in different structural work (Alengaram et al. [2]). LWAs have a cellular type structure and were used for producing different types of masonry blocks, wall panels, cladding and LWC. When they are used as fine aggregates, they function similar to active pozzolanic materials. It can be produced from the naturally available raw materials such as expanded clay, shale, slate, etc., as well as from SCMs such as FA and slags, etc.

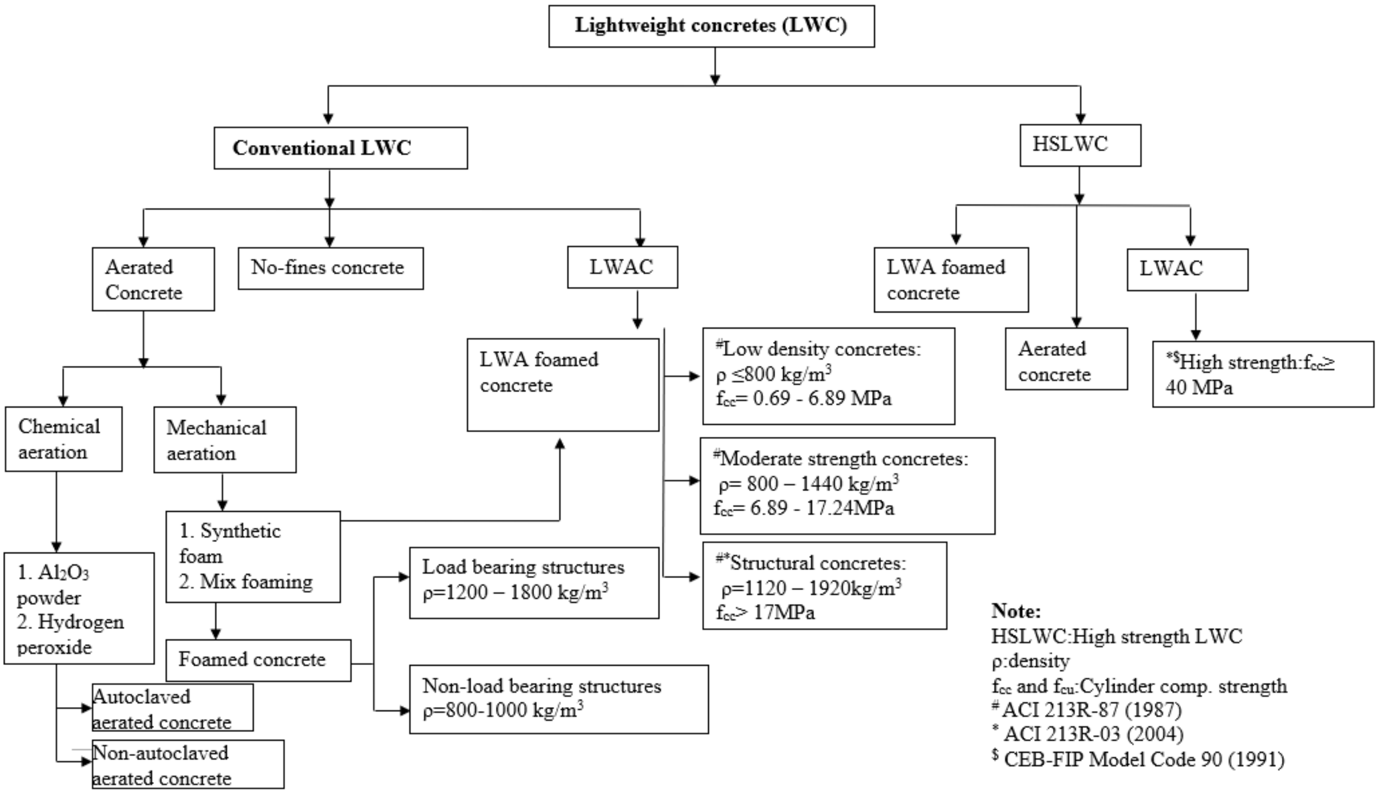

Chart 1. Classification of lightweight concretes.

The cellular structure within the particles is formed at high temperatures, generally at 1100 °C or higher. Due to the cellular structure of particular aggregate particles, the aggregates are light in weight, and the specific gravity, as well as the unit weight of LWAs, is lower than that of NWAs. The maximum size grading designations of LWAs generally available are 19 mm, 13 mm or 10 mm. LWAs have more water absorption (up to 5 to 20%) and allow limited access for fresh cement paste into the open pores of the LWAs. Due to their porous structure, LWAs require to be wet for 24 h before adding it into the mix. In the case of LWC, the bond between the aggregate and the matrix is stronger than the normal concrete. LWC provides a reduction in dead loads and improves the thermal and fire properties of buildings. It is necessary to limit the slump to improve the workability, durability and avoid segregation. In LWC, excessive mixing should be avoided because it tends to crack the LWA particles (ACI 213 [10]).

The paper presents the wide classification of different kind of LWAs that are used to develop LWACs and discuss their physio-chemical and morphological characterization. Additionally, fresh, hardened, functional and durable properties of sustainable LWAC are presented along with the effect of different SCMs and fibers to improve the performance of LWACs. Furthermore, ongoing research activities at CSIR-CBRI on the effect of marble slurry and Class-F fly ash on LECA incorporated LWAC is also discussed.

2. Types of LWAs

In general, LWAs can be divided into two categories.

2.1. Natural Aggregate

Natural LWAs are the materials that are available as natural resources. These are naturally ready to use with mechanical treatment, i.e., crushing and sieving. Mostly, natural LWAs are of volcanic origin, e.g., pumice and scoria [11,12]. Thus, they are only found in a few areas of the world. Pumice is formed when the molten lava from the explosive eruption of a volcano cools [13]. Quick cooling freezes the material existing at the molten state, which does not have zero probability of a crystallization process. Scoria is darker in color than pumice but has all the properties same as that of pumice. Volcanic tuffs are a kind of volcanic rock, which develops pores through rapid cooling and hardening of lava. The pore may vary from 10% to 60%. These tuffs are classified as rhyolite, dacite, andesite, etc. Similarly, volcanic slag is also derived from lava, which is less vitreous and more crystalline slag-like materials. These all-natural LWAs are used to produce LWC with a density range from 1860 to 1988 kg/m^3 [14–16].

2.2. Manufactured/Artificial Aggregate

These LWAs are classified as brick rubble, cinder, sintered cinder, blast-furnace slag, LECA, etc. These types of aggregates are produced by thermal treatment of either naturally occurring materials such as clay, shale, vermiculite, perlite and slate, etc., or industrial byproducts/waste materials such as FA, municipal solid waste (MSW), waste of dredging, blast furnace slag, etc. Cinder LWAs are produced as coal burnt residues in the industrial boilers. The residue is melted and sintered to form cinders. Sintered fly ash is developed at a temperature of 1100–1300 °C [17]. They have a hard, coarse red shell and fine pore structures, which are commercially available in a size range of 7 to 30 mm. Similarly, foamed blast-furnace slag aggregates are produced by sintering slag at a temperature of 1400–1600 °C. The size range lies between less than 3 mm and 20 mm, with a varying bulk density of 300 to 700 kg/m^3. LECA is produced using clay or shale after heating at the point of incipient vitrification (at a temperature of about 1200 °C) [18]. After exposure, clay/shale expands or bloats to seven times their original volume and forms a cellular structure that remains stable even after cooling. In the market, different kind of LECA is available by different names such as hydite, rocklite, lytag, aglite, keramzit, etc. In a similar manner, expanded perlite is developed after exposing perlite at a temperature of 900–1100 °C, which leads to an increase in volume by 15–20 times [19]. Vermiculite is a type of mica with high magnesium content, which is formed at a temperature of 900 °C [20].

3. Different LWAs and Their Use to Develop Green Building Materials

There are different types of LWAs that are used in the construction of buildings [21]. Some vitally used LWAs are vermiculite, OPS, perlite, LECA, pumice and sintered fly ash. Tables 1 and 2 summarize the physical and chemical characterization results obtained by several researchers.

Table 1. Physical properties of LWAs.

Type of Aggregate	References	Specific Gravity	Water Absorption for 24 h (%)	Fineness Modulus (FM)	Bulk Density (Compacted) (kg/m^3)
OPS	Mannan and Ganapathy [22]; Teo et al. [4]; Shafigh et al. [14]; Sobuz et al. [23]; Eziefula et al. [21]	1.17–1.30	33.0–19.6	5.64–6.24	572–656
LECA	Maghsoudi et al. [5]; Real et al. [24]; Bogas and Cunha [11]; Shafigh et al. [25]	0.51–1.18	16.42–26.5	15.8–5.96	273–667
Vermiculite	Schackow et al. [26]; Divya et al. [27]; Arun et al. [28]	1.10–3.0	2.65	2.46	-
Perlite	Demirbog and Gul [29]; Karakoc and Demirboga [19]; Oktay et al. [30]; Zulkifeli and Saman [31]	0.12–0.42	82.5	-	200
Pumice	Hossain [32]; Sari and Pasamehmetoglu [33]; Gunduz and Ugur [34]; Binici et al. [35]; Kockal and Ozturan [15]	1.57–3.10	-	-	870
Sintered Fly ash	Guneyisi et al. [36]; Gomathi and Sivakumar [37]	2.10–2.25	0.14	6.24	-

Table 2. Chemical Composition of LWAs.

Type of Aggregate	References	Chemical Components (%)								
		Main					Minor			
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
OPS	Shafigh et al. [14]; Foong et al. [38]	18.47–21.32	4.27–6.20	2.06–3.62	64.09–65.41	2.08–2.43	4.25–5.50	0.28–0.73	0.21–0.25	1.41–1.80
LECA	Al-Bahar and Bogahawatta [39]; Sajedi and Shafigh [40]; Masoud et al. [41]	53.3–66.05	15.05–19.78	6.2–9.52	1.05–2.98	0.78–3.67	0.23–0.25	2.55–4.1	0.17–1.54	1.37–15.11
Vermiculite	Koksal et al. [1]; Abidi et al. [42]; Sayadi et al. [43]	36.9–46	10–17.7	5.50–11.2	1–3.5	16–35	0.02–0.10	1–6	0.13–0.2	7.5–9.2
Perlite	Turkmen and Kantarci [44]	71–76	9.91–16	0.40–1.57	0.5–2.19	0.01–0.28	0.04–0.10	4–5	2.9–4	1.48–2.0
Pumice	Demirel and Kelestemur [45]; Binici et al. [35]; Onoue et al. [46]	41.41–63.4	12.97–21.9	1.26–11.41	1.8–13.73	0.3–15	0.44–0.50	1.73–5.40	1.80–5.20	1.60–7.32
Sintered Fly ash	Kayali [47]; Kockal and Ozturan [15]; Guneyisi et al. [36]	56.2–64.60	19.58–28.5	4.0–7.23	0.54–4.24	0.66–4.64	0.30–0.69	0.01–5.95	0.32–2.06	0.49–5.10

3.1. OPS Concrete (OPSC)

OPS are considered as agricultural waste and lighter in weight, which is found in abundance all over the world. Malaysia is one of the largest oil palm producers in the world, which produces 4 MT of OPS annually [2]. During the extracting process of oil from the oil palm tree, OPS are generated, which is a waste product. In order to protect the environment, action was taken to utilize OPS as LWAs. The dumped oil palm kernel shells left at the factory yard are shown in Figure 3**.** Figure 4 shows that OPS aggregate has an irregular flaky, angular shape.

Figure 3. OPS dumped at the factory yards [2]. (Reprinted with permission from Alengaram et al. (2013), 2021, Elsevier).

Figure 4. OPS of different sizes [2]. (Reprinted with permission from Alengaram et al. (2013), 2021, Elsevier).

The concrete with compressive strength of more than 25 MPa was achieved using OPS as a lightweight coarse aggregate. The construction of low-cost buildings can be performed using OPS concrete. Mannan and Ganapathy [22] compared the different properties of OPS concrete with control concrete. It was found that the 28-day compressive strength, flexural strength and splitting tensile strength of OPS concrete were between 20 and 24 MPa, 2.75 and 4.00 MPa and 1.78 and 2.41 MPa, respectively. The 28-day elasticity modulus of OPS concrete was 0.70–0.76 × 10^4 MPa. OPS concrete showed 14% higher drying shrinkage than control concrete at 90 days, and it also had higher water absorption. Mannan and Ganapathy [48] studied the different properties of concrete using OPS as a coarse aggregate and fly ash (FA). It was found that the OPS concrete containing FA showed lower air content compared to control concrete without FA. The density of the fresh concrete of OPS concrete lies between 1910 and 1958 kg/m^3. The 28-day compressive strength of samples was in the range of 20.1–24.2 MPa, which satisfies the requirement of structural LWC. Olanipekun et al. [3] studied the strength characteristics as well as the cost analysis of concrete made by using OPS and crushed granular coconut shells. The level of replacement for LWA with coarse aggregate was in the range of 25 to 100%. The results show that by increasing fractions of OPS, the uniaxial compressive strength of LWA concrete was decreased. A cost reduction between 30% and 42% could be achieved using OPS as a coarse aggregate in concrete production.

Teo et al. [4] investigated the properties of OPS-based LWAC and found that the 28-day air-dry density and compressive strength were 1960 kg/m^3 and 28.12 MPa, respectively. The 28-day tensile strength, flexural strength and elastic modulus were found as 2.02 MPa, 4.97 MPa and 5.31 GPa, respectively. The curing condition affects the durability of OPS concrete in a significant manner. OPS concrete in water curing gave better durability performance than normal weight concrete. Shafigh et al. [14] studied the different properties such as air content, cube compressive strength, density and water absorption of OPS-based high strength lightweight concrete (HSLC). Five types of curing conditions with different OPS concrete mixtures were taken, and then their compressive strength was determined. The effect of partial replacement of limestone powder (as a filler material) by the fine aggregate was determined. It was observed that the workability of the developed concrete was decreased by increasing limestone powder content. Water absorption of high-strength OPS concrete varies from low to high range, which is a good sign of strong concretes. Alengaram et al. [2] investigated that OPSC inherited high strength to density ratio than that of NWC. It was also shown that OPSC could be used to produce medium to high strength concrete.

Liu et al. [49] studied the physico-mechanical and thermal properties of OPS foamed geopolymer concrete (OPSFGC). OPSFGC mixtures were prepared to have densities of 1300, 1500 and 1700 kg/m^3 in which an artificial foaming agent was used for casting. The control OPS non-foamed geopolymer concrete (OPSNFGC) was cast for comparison studies. It was found that the 28-day compressive strengths of OPSFGC of all three densities were lower than the OPSNFGC. As the density decreases, the 28-day splitting tensile strength and modulus of rupture also decreases. The thermal conductivity of the mix with a density of 1300 and 1500 kg/m^3 was 0.47 and 0.50 W/mK, respectively. Sobuz et al. [23] studied the characteristics of concrete produced using OPS fractions ranging from 0 to 50% by replacing conventional coarse aggregate. The compressive strength was reduced with the increasing percentage of OPS aggregates. The structural requirement of LWC was satisfactory. Mo et al. [50] described the effect of steel fiber on the hardness features such as flexural toughness, compressive toughness and fracture parameters of steel fiber OPS concrete (SFOPSC). The outcome of adding steel fiber in the range of 0.5 to 1.0% in SFOPSC on the tensile strength, compressive toughness and flexural toughness was improved by 1.41 times, 6 times and 16 times, respectively. Mo et al. [51] made a comparison between lightweight OPS concrete and NWC of 25, 35 and 45 MPa strength grades. It was concluded that young modulus, indirect tensile strength and drying shrinkage of OPS concrete was lower than that of NWC, while the bond strength of OPS concrete was 80% higher.

Mo et al. [52] studied the durability properties of OPS concrete in which cement and natural sand were replaced with ground granulated blast furnace slag (GGBS) and manufactured sand, respectively. GGBS was also found to be of great use in improving the long-term compressive strength gain as well as bringing down the strength reduction in OPS concrete when exposed to heat. The use of GGBS as a partial cement substitution in the OPS concrete resulted in an increase in compressive strength gain compared to OPS concrete without GGBS. Eziefula et al. [21] performed comparative studies of different mechanical properties of OPSC with periwinkle shell concrete. The mechanical strength and bulk density of periwinkle shells and OPS-based concrete qualify for the requirements of LWACs. However, the strength characteristics of OPS concrete were inferior to that of the periwinkle shell-based concrete. Khankhaje et al. [53] investigated different properties of OPSC and cockleshell concrete (CSC). It was found that CSC possesses better properties compared to OPSC. It was due to the high water absorption capacity of OPS. Alengaram et al. [54] studied microscopic analysis of OPS using scanning electron microscope as shown in Figure 5, which shows micro pores (size: 16–24 µm) on the convex surface of OPS surface, which causes high water absorption.

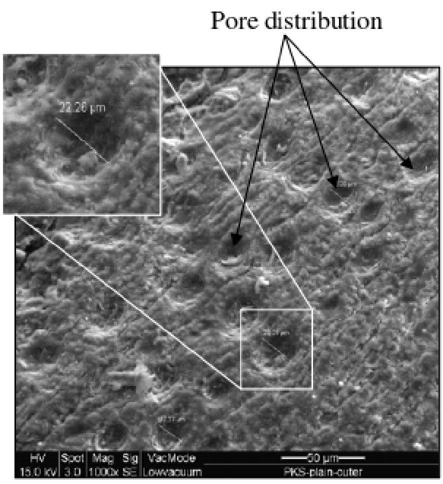

Figure 5. Micro-pores on outer surface [54]. (Reprinted with permission from Alengaram et al. (2011), 2021, Elsevier).

3.2. LECA Concrete

LECA aggregates are manufactured from low-lime plastic clay. For aggregate preparation, clay is firstly heated and then dried. After drying, sintering is performed in specific kinds of rotary kilns at a temperature of 1100–1300 °C. In this process, the gas, i.e., released after the heating process, becomes entrapped inside the pellets during cooling. LECA aggregates have rounded irregular shapes [55] and incorporate many multi-separated interconnected voids of different sizes, which make them lightweight. The morphology of LECA is shown in Figure 6. LECA is mostly dark brown or reddish or brown-red or gray in colors. These aggregates are also available in yellow or black color due to variation in chemical composition and process of manufacturing. It has a pH value of 7 and is thus inert in nature. It can be used as a replacement for both coarse and fine aggregates.

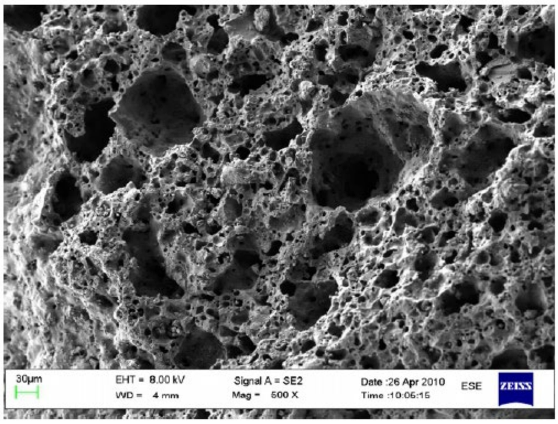

Figure 6. Surface image of a LECA particle under SEM showing pores [56]. (Reprinted with permission from Nkansah et al. (2012), 2021, Elsevier).

Zach et al. [5] studied the possible use of the non-stationary hot-wire method for determining the thermal conductivity of the LECA concrete coefficient. It was found that the thermal conductivity of LECA concrete ranged from 0.14 to 0.16 W/m.K. Maghsoudi et al. [57] developed self-compacting lightweight concrete (SCLC) using LECA. Various mix designs of SCLC were cast to obtain the final standard SCLC, with a compressive strength of 20.8–28.5 MPa at 28 days. Zohrabi et al. [58] investigated the mechanical properties of LWC containing LECA with metakaolin, polypropylene (PP) and steel fibers. The PP fibers have more effect on the energy absorption capability of LWC rather than on strength properties. The addition of 1% steel fibers increased the compressive strength and flexural strength by 36.3% and 52.6%, respectively. Grabois et al. [6] investigated the fresh and hardened properties of steel fibers incorporated SCLC. The 28-day compressive strength was found above 30 MPa for a density of 1700–1900 kg/m^3. Concretes with coarse and fine LWAs depicted higher drying shrinkage than those containing only coarse LWAs. The results showed that the thermal conductivity decreased by 60% by using coarse and fine LECA aggregates.

Bogas and Cunha [11] investigated the physico-mechanical behavior of non-structural lightweight concrete (NSLWC), which was developed by volcanic scoria. The different properties of various NSLWC fill solutions were analyzed. It was found that the concrete incorporated with coarse LECA aggregate, with a diameter of 4–8 mm showing thermal conductivity of 0.23 W/mK, while the tensile and compressive strength at 28 days were found as 0.5 and 5.3 MPa, respectively. The 28-day modulus of elasticity was 4.9 GPa with capillary absorption of 0.501×10^{-3} mm/min$^{0.5}$. Vijayalakshmi and Ramanagopal [59] reviewed the utilization of LECA to produce structural LWC. Further, different fresh and mechanical properties of the developed concrete using LECA aggregates were compared with NWCs. Shafigh et al. [25] compared the engineering characteristics of NWCs with concrete containing two types of LWAs, namely, LECA concrete and oil-palm-boiler-clinker (OPBC) concrete. Natural coarse aggregates were replaced with these LWAs, and then fresh and hardened properties were explored. It was found that the 28-day compressive strength

OPBC concrete was about 27% higher than the LECA concrete. While the modulus of elasticity of the OPBC and LECA concretes was 59% and 37% of that of NWC, respectively.

Heiza et al. [60] analyzed the effect of varying reinforcement ratios on reinforced two-way slabs keeping the dimensions constant. LECA was used to produce a structural LWC with low density and high self-compacting features. LECA was suggested to be pre-wetted since it provides higher strength. Reddy et al. [61] studied the flexural strength of conventional concrete with partial to complete substitution of coarse aggregate by LECA. Thus, the overall use of LECA fine and coarse aggregates can reduce the demand for natural aggregates while designing concrete structures. The LECA concrete gives low density compared to conventional concrete and provides better insulation against heat and sound, while the cube's compressive strength was reduced continuously with the increase in percent substitution of natural aggregate by LECA.

3.3. Vermiculite Concrete

Vermiculite LWA is formed due to weathering action or hydrothermal changes in biotite or phlogopite. It is basically a hydrous phyllosilicate or hydrated magnesium aluminum silicate mineral, which shows volumetric expansion after the heating process and thus causes exfoliation. After exfoliation, vermiculite forms elongated concertina particles, which have specific characteristics such as incombustible, lightweight, compressible, inert and highly absorbent. It has an appearance similar to mica and is available in various parts of the world such as India, the USA, Australia, Russia, South Africa, Bulgaria, etc. In construction practices, these aggregates impart good thermal resistance at a cheaper cost. Sundhakumar [62] investigated the microstructure of expanded vermiculite (EV) and inferred that the lower thermal conductivity of EV-containing cementitious products is caused by a large number of air voids presented in it. The SEM micrograph of vermiculite is shown in Figure 7.

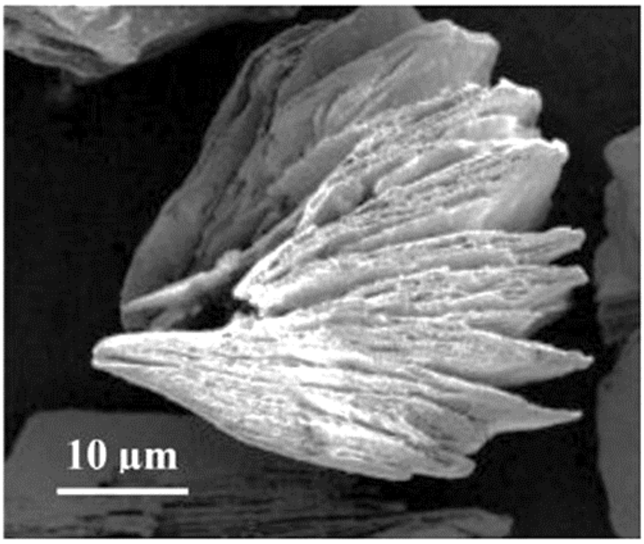

Figure 7. SEM micrograph of vermiculite [42]. (Reprinted with permission from Abidi et al. (2015), 2021, Elsevier).

Lorenzon et al. [63] investigated the properties of cement–vermiculite mortar (CVM), which showed similar physical characteristics to that of the wood in terms of thermal performance. CVM absorbed more amount of water and lost water rapidly compared to the pinewood manufactured box. As a result, it was obtained that the exfoliated vermiculite mortars can be used as boxes for honeybees instead of pinewood. Al-Jabri et al. [64] utilized vermiculite and polystyrene beads by replacing OPC cement and developed concrete blocks. It was found that polystyrene incorporated LWC blocks provide lower thermal conductivity as compared to vermiculite and conventional concrete. Schackow et al. [26]

developed the LWC containing vermiculite and expanded polystyrene (EPS) along with a water-reducing super plasticizer and air-entraining agent (AEA). After developing LWC, different mechanical and thermal properties were compared. At a lower incorporation percentage, both AEA and LWAs impart higher compressive strength for LWC. The density observed for EPS LWC and vermiculite LWC ranged from 1.070 g/cm^3 to 1.250 g/cm^3 and 1.130 g/cm^3 to 1.290 g/cm^3, respectively. Vermiculite LWC had less thermal conductivity.

Koksal et al. [1] compared the physico-mechanical, thermal and micro structural properties of EV and silica fume (SF) incorporated cement-based mortars. At elevated temperatures, the strength and durability attributes were improved using SF in vermiculite containing lightweight mortars. The thermal conductivity of developed mortars depicted a decrement up to 0.257 W/mK, which showed an increment of 58.2% in overall thermal performance behavior. Abidi et al. [42] utilized vermiculite, perlite and cement to produce novel lightweight composite material for building construction, and then various thermo-mechanical properties were studied. It was found that thermal conductivity was decreased with an increase in porosity rate. When the matrix was reinforced with 5 to 25 by wt% of vermiculite, the thermal conductivity of the composite decreased from 0.50 to 0.45 W/mK. Gunasekaran et al. [65] studied the properties of mortar by replacing natural sand with vermiculite in the range of 5 to 30% by wt. of sand. It was concluded that the use of vermiculite mortar is quite economical and provides better compressive strength.

Divya et al. [27] studied the different parameters such as compressive strength, flexural strength and split tensile strength after using vermiculite aggregates as partial substitution with 40 to 60% by weight of fine aggregate. The optimum strength was observed to be at a 50% substitution ratio. Sairam and Sailaja [66] replaced different percentages of cement and fine aggregate with vermiculite and FA mineral admixtures. Then, different mechanical properties of the M35 grade of LWC were investigated, and it was found that strength decreased with an increasing amount of vermiculite content. Mo et al. [20] developed cement mortar by partially replacing sand with EV. It was found that the density and strength of mortar were reduced, while the water absorption rate, thermal resistance and stability of the developed mortar were increased after incorporating EV.

3.4. Perlite Concrete

Siliceous volcanic rocks are the naturally occurring resources, which are also known as perlite. Perlite is formed naturally after the hydration of obsidian and has amorphous nature. It has the unusual characteristic of largely expanding when heated, which is the main cause of its lower density. The specific feature that differentiates perlite from other volcanic glasses is that when rapidly heated at a temperature ranging between 900 °C and 1200 °C, it expands about 5 to 20 times of its original volume. This makes it lightweight and insulating. It is suitable to produce LWC using expanded perlite due to its low density. The major applications of perlite LWA are LWC blocks, masonry mortar, plasters, ceiling tiles, etc. Globally, the largest producer of perlite is Turkey, with total reserves of about 4.5 billion tons. The later age strength is generally improved for the products made using perlite aggregate due to the high water absorption capacity of expanded perlite. The morphology of the perlite aggregate is shown in Figure 8.

Karakoc and Demirboga [19] studied the properties of concrete mixtures with variable expanded perlite aggregate (EPA)–fine aggregate ratios. The mixtures have 0–30% EPA. Under dry and wet curing conditions, compressive strength at 28 days ranged from 40 to 57 and 54 to 81 MPa, respectively. At 30% EPA content, thermal conductivity was found minimum. Sengul et al. [67] investigated the mechanical and thermal properties of LWC containing EPA. Mixtures were prepared by partially substituting natural aggregate by EPA, and it was observed that the unit weight of LWC in fresh state varied between 700 and 2000 kg/m^3. The uniaxial compressive strength and Young's modulus of LWC were reduced by increasing EPA amount. Water absorption and sorptivity coefficient increase at high EPA content. From a thermal performance point of view, thermal conductivity was improved by adding EPA content. Gandage et al. [68] used class C FA and perlite as cement and fine aggregates, respectively. Thermal conductivity was measured at five different temperatures readings. It was concluded that as the test temperature was increased, the thermal conductivity decreased. Comparative high 28-day strengths were obtained at 5% perlite content.

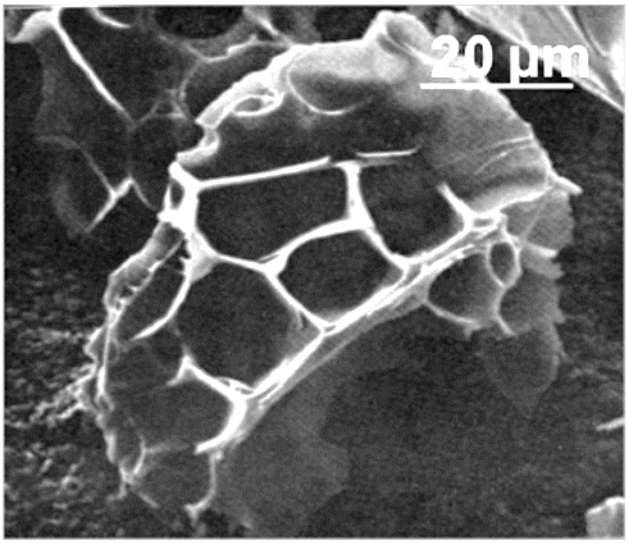

Figure 8. SEM micrographs of perlite [42]. (Reprinted with permission from Abidi et al. (2015), 2021, Elsevier).

Oktay et al. [30] investigated the properties of concrete containing SF, super plasticizer (SP) and AEAs with a fixed w/c ratio. Normal aggregates were replaced by EPA at different volume fractions. A reduction in bulk density and thermal performance was observed. Zulkifeli and Saman [31] studied the compressive and flexural strength of mortar using EPA. It was found that the modulus of rupture and strength was increased at a temperature of 200 °C. Karatas [12] studied the thermal resistance of self-compacting mortars (SCM) that were developed by normal and LWAs such as EPA and pumice. SF and FA were used as mineral additives. Bulk density, porosity and water absorption results were determined for the hardened SCM. Results of the experiments showed that the use of LWAs increased the total water absorption and porosity of mortars. The compressive strength of specimens (which were exposed to 300 °C) was increased due to the incorporation of EPA up to 10%. Kotwica et al. [69] studied the methodology for utilizing waste EPA as a valuable, high-performance pozzolanic supplementary building material. The results showed that the addition of ground waste EPA leads to gains in strength up to 50%. Polat et al. [70] developed lightweight mortar and concrete using EPA. It was concluded through experimentation that as compared to controlled samples, strength, ultrasonic pulse velocity (UPV) and shrinkage were reduced with increasing EPA content, while the degree of hydration was increased with increment in EPA content. Wan et al. [71] used three LWAs, i.e., EPA, scoria and polystyrene, to produce lightweight self-compacting concrete (LWSCC), and then different fresh and hardened properties were determined. It was reported that all LWAs imparted a negative effect on the workability and compressive strength of LWSCC. Demir and Baspinar [72] confirmed the inert behavior of expanded perlite aggregates for all test conditions. No crystalline phase was formed around the perlite grains as shown in Figure 9.

Figure 9. The pore structure of the perlite in the fly ash–lime–gypsum mixture [72]. (Reprinted with permission from Demir and Baspinar (2008), 2021, Elsevier).

3.5. Pumice Concrete

Pumice, also known as pumicite in its fine powder form, is categorized as a volcanic rock that contains highly vesicular volcanic glass and generally looks light in color. Due to its durability and hardness, pumice has been used in LWC for years. Pumice aggregates produce lightweight fire-resistant and sound insulating LWC blocks. The pumice can be used to manufacture low-density LWC that can be used in high-rise buildings structures with significantly improved functional properties. It does not increase the total load of the structure; thereby, it is a very useful material for the repair of the old monuments. Fine pumice is used to develop mortars and provides good thermal insulating properties. Gunduz and Ugur [34] developed the LWAC with fine pumice (FPA) and coarse pumice aggregates (CPA). The study showed that the pumice aggregate concrete possesses lower thermal conductivity. It was also concluded by the authors that the major influencing parameters for thermal performance were the cement/fines ratio and dry unit weight.

Gunduz [73] studied different structural and functional properties of pumice aggregate lightweight concrete (PALWC). Lower aggregate/cement ratio showed higher compressive strength, modulus of elasticity and density, while on the other hand, higher aggregate/cement ratio showed lower water absorption, shrinkage and thermal performance. Parhizkar et al. [13] investigated the properties of volcanic pumice. The results showed that the volcanic pumice lightweight concretes fulfilled the requirements of lightweight structural concrete. Tasdemir et al. [74] compared the properties of seven different LWC, developed by using pumice aggregates, fine natural aggregate and coarse limestone aggregate. The compressive strength of the concretes was compared, which showed that the strengths of the expanded polystyrene beads were lower than the pumice or EPA. Kilincarslan et al. [75] used the pumice aggregates of four different kinds. The physico-mechanical properties and thermal performance of the developed concretes were also investigated. The result showed that the Nevsehir kind of pumice aggregate was the most suitable type of LWAs to be used in foam concrete.

3.6. Sintered Fly Ash Concrete

Commercially, sintered FA aggregates are known as lytag. It is manufactured by pyro-processing of fly ash, which is a waste product generated from thermal power plants. The main process to develop sintered FA is sintering and pelletization at a temperature range from 1150 to 1350 °C. The sintered FA aggregates are found in brown color with a black internal core (Figure 10). The pore sizes range between 10 and 200 μm, as depicted in Figure 11.

Figure 10. Sintered FA aggregates (left) and their cross-section (right) [76]. (Reprinted with permission from Nadesan and Dinakar (2017), 2021, Elsevier).

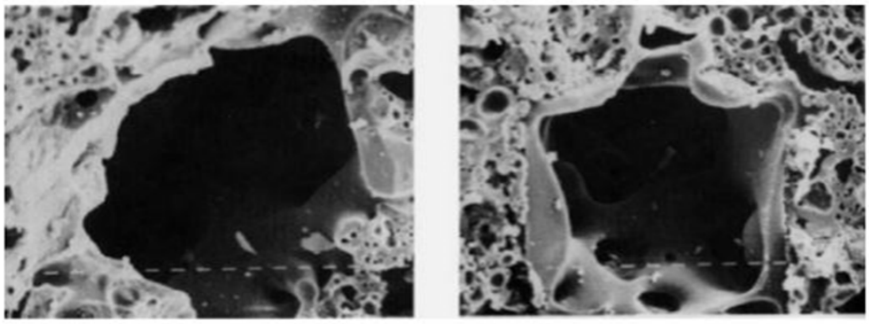

Figure 11. Microstructure of sintered fly ash aggregate (×320) [77]. (Reprinted with permission from Swamy and Lambert (1981), 2021, Elsevier).

Kockal and Ozturan [78] developed LWC using various kinds of sintered FA aggregates. The results showed that low specific gravity of cold-bonded and sintered FA aggregate was helpful for the production of LWC with densities within the range of 1860–1943 kg/m^3. Twenty-eight days uniaxial compressive strength and elastic modulus ranged from 42.3 to 55.8 MPa and 22.4 and 28.6 MPa, respectively. Kockal and Ozturan [15] investigated the effect of aggregate properties on the strength and durability of lightweight FA aggregate concrete. In the development of LWAC, three different types of LWA, i.e., sintered lightweight ash aggregates, cold bonded lightweight FA aggregate and normal-weight aggregate, were used. Then, the effects of all three aggregates on physico-mechanical and durability properties of developed concrete were determined. Sintered FA aggregate concretes had more strength and elasticity modulus than cold-bonded ash aggregate concretes. Nadesan and Dinakar [76] studied the utilization of sintered FA aggregate to produce structural LWC. The results showed that the sintered FA aggregate concrete satisfies the requirement of structural LWC.

4. The Comparisons among Different LWAs/LWACs on the Basis of Various Parameters

Researchers reported different properties of LWC, which are shown in Table 3. Majorly, the investigated properties were uniaxial compressive strength, split tensile strength, modulus of rupture or flexural strength, thermal conductivity, elastic modulus, water absorption, etc. For comparison purposes of compressive strength, splitting tensile strength, density and thermal conductivity, graphs containing six major LWAs are depicted in Figures 12–15. The control concrete (CC) showed the maximum compressive strength among all LWC, i.e., 38 MPa, as presented in Figure 12. As the content of LWA in concrete increased, the compressive strength decreased. Here, 50% pumice used in concrete gave maximum compressive strength up to 36 MPa, while vermiculite LWC showed minimum compressive strength. The tensile strength of conventional concrete was varied in the range from 4 to 4.7 MPa, as depicted in Figure 13. Adding LWA in the mix proportion showed a gradual decrement in tensile strength. Forty percent FA sintered aggregate replacement showed maximum tensile strength, while 40% OPS replacement provided minimum strength. Figure 14 shows that perlite used as an aggregate showed a maximum density around 2300 kg/m^3, while pumice concrete showed a minimum density of 1300 kg/m^3. The thermal conductivity of LWC was lower than the NWCs. As shown in Figure 15, LECA concrete showed minimum thermal conductivity when used as a whole in place of coarse aggregate while control concrete showed maximum k value, i.e., 2.3 W/mK.

Table 3. Fresh, hardened and durability properties of LWAs, as per the literature.

Aggregate Type	References	Compressive Strength	Splitting Tensile Strength	Flexural Strength	Thermal Conductivity	Modulus of Elasticity	Water Absorption
OPS	Mannan and Ganapathy [22]	✓	✓	✓		✓	
	Sobuz et al. [23]	✓	✓	✓		✓	
	Mo et al. [51]	✓	✓			✓	
	Mo et al. [52]	✓					✓
LECA	Maghsoudi et al. [57]	✓				✓	
	Zohrabi et al. [58]	✓		✓			
	Kumar and Prakash [79]	✓	✓				
	Heiza et al. [60]	✓		✓			
	Reddy et al. [61]	✓					
	Al-Jabri et al. [64]	✓			✓		
Vermiculite	Schackow et al. [26]	✓					
	Koksal et al. [1]	✓		✓	✓		✓
	Divya et al. [27]	✓	✓	✓			
	Mo et al. [20]	✓					✓
	Arun et al. [28]	✓	✓	✓			
	Karakoc and Demirboga [19]	✓			✓		
Perlite	Sengul et al. [67]	✓			✓	✓	✓
	Gandage et al. [68]	✓		✓	✓		
	Polat et al. [70]	✓					
	Wan et al. [71]	✓	✓				
	Gunduz and Ugur [34]	✓	✓		✓	✓	✓
Pumice	Gunduz [73]	✓			✓	✓	✓
	Parhizkar et al. [13]	✓	✓				✓
	Tasdemir et al. [74]	✓			✓	✓	
	Kilincarslan et al. [75]	✓			✓		
Sintered fly ash	Kockal and Ozturan [78]	✓	✓			✓	
	Kockal and Ozturan [15]	✓	✓			✓	✓
	Nadesan and Dinakar [76]	✓	✓			✓	

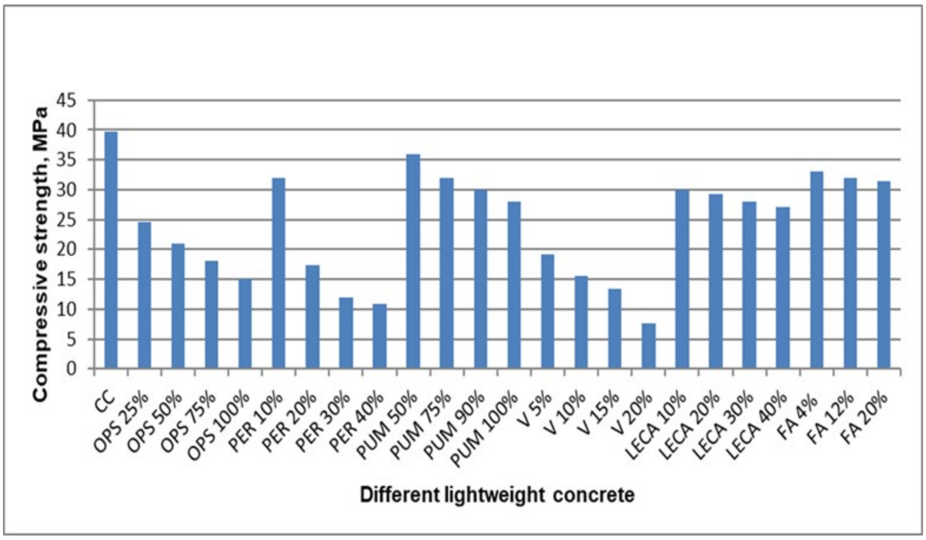

Figure 12. Compressive strength of different LWACs.

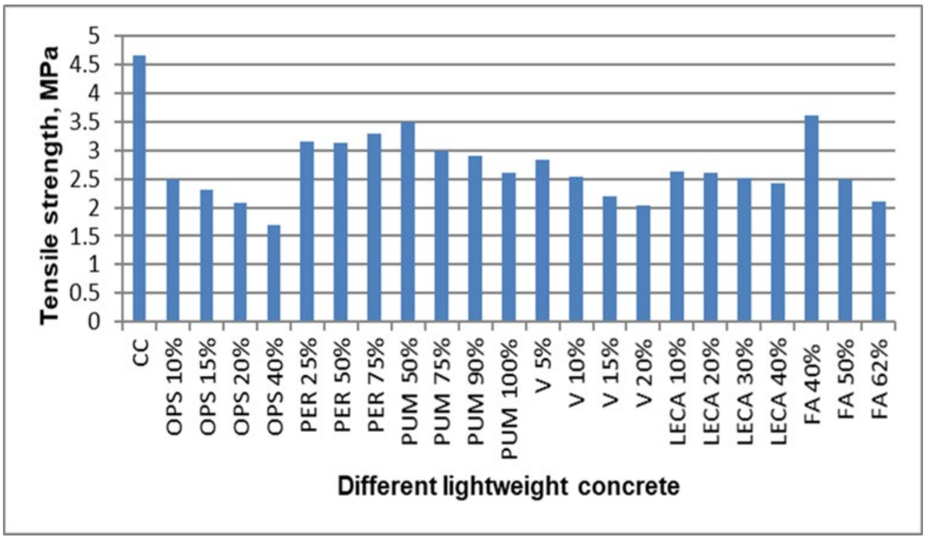

Figure 13. Tensile strength of different LWACs.

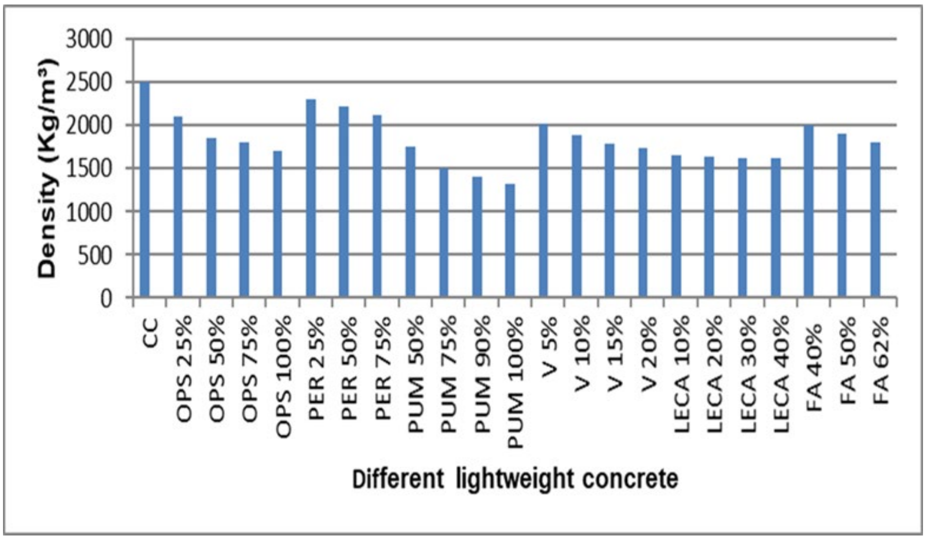

Figure 14. Density of different LWACs.

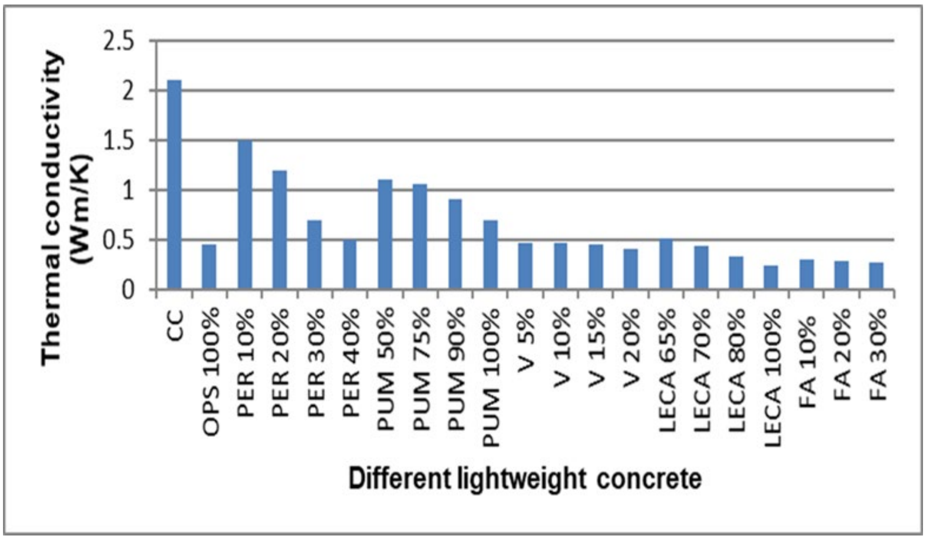

Figure 15. Thermal conductivity of different LWACs.

Figure 14 shows that perlite used as an aggregate showed a maximum density around 2300 kg/m^3, while pumice concrete showed a minimum density of 1300 kg/m^3. The thermal conductivity of LWC was lower than the NWCs. As shown in Figure 15, LECA concrete showed minimum thermal conductivity when used as a whole in place of coarse aggregate while control concrete showed maximum k value, i.e., 2.3 W/mK.

5. Research and Development at CSIR-CBRI

A systematic R&D work was conducted at CSIR-Central Building Research Institute, Roorkee (Haridwar, India), on the development of LWACs using LECA and Class F FA and dry marble slurry powder (MSP). In this study, optimization of LECA aggregates, cement, w/c ratio was performed. LECA was used as a coarse and fine aggregate in three different sizes: 0–2 mm, 2–8 mm and 8–15 mm. The FA was obtained from NTPC-Dadri (UP), which was classified as class F based on ASTM: C618. The specific gravity of FA was 2.24 and fineness 325 m^2/kg. The marble slurry used in this study was obtained from Udaipur, Rajasthan (India). The mean particle size of MS was 9.54 µm. According to Blaine's apparatus of specific surface area, the specific surface area of MS was 350 m^2/kg. MS has a higher surface area than that of OPC and FA, which can fill capillary pores as well as gel pores. In order to increase the workability of LWC, a polycarboxylate ether-based superplasticizer (SP) is used. Ordinary tap water is used in all types of concrete mixes.

Different physico-mechanical properties of the developed concrete specimens along with thermal conductivity were determined. According to ACI 213R-87, the minimum compressive strength for structural LWC should be 17.2 MPa. Mix contains OPC: 400 kg/m^3; sand: 550 kg/m^3; 15% MS + 15% FA by replacement of cement; LECA: 325 kg/m^3; SP (%): 0.78 with w/c ratio of 0.40 satisfied the requirement of LWC, i.e., 20.4 MPa. According to ASTM C330, a minimum splitting tensile strength of 2.0 MPa is a requirement for structural grade lightweight aggregate concrete. The same mix shows the tensile strength of 2.8 MPa, which satisfies the strength criteria of LWAC. The optimized mix showed the maximum flexural strength out of all concrete mixes, i.e., 3.1 MPa. Thermal conductivity (k value) of concrete was measured using the guarded hot plate method followed by IS: 3346–1980 (Figure 16). Specimens of dimensions 300 mm $\times$ 300 mm $\times$ 50 mm were cast for testing. The results revealed that the thermal conductivity of the LWC using 15% MS + 15% FA along with LECA shows a lower k value, i.e., 0.21 W/mK.

Figure 16. Thermal conductivity test set up for LWAC containing fly ash and marble waste.

The SEM results revealed that the incorporation of 15% FA and 15% MS in the LWAC mix showed denser structure as compared to control concrete with LECA only. The inclusion of MS into concrete improved the microstructure due to the filler effect and acceleration of hydration. Less crystalline phase was observed in the interfacial transition zone (ITZ) of the optimized mix (containing 15% MS + 15% FA) at 28 days. The improvement of microstructure and ITZ also resulted from the internal curing by pre-wetting of lightweight aggregate (Figure 17a–d).

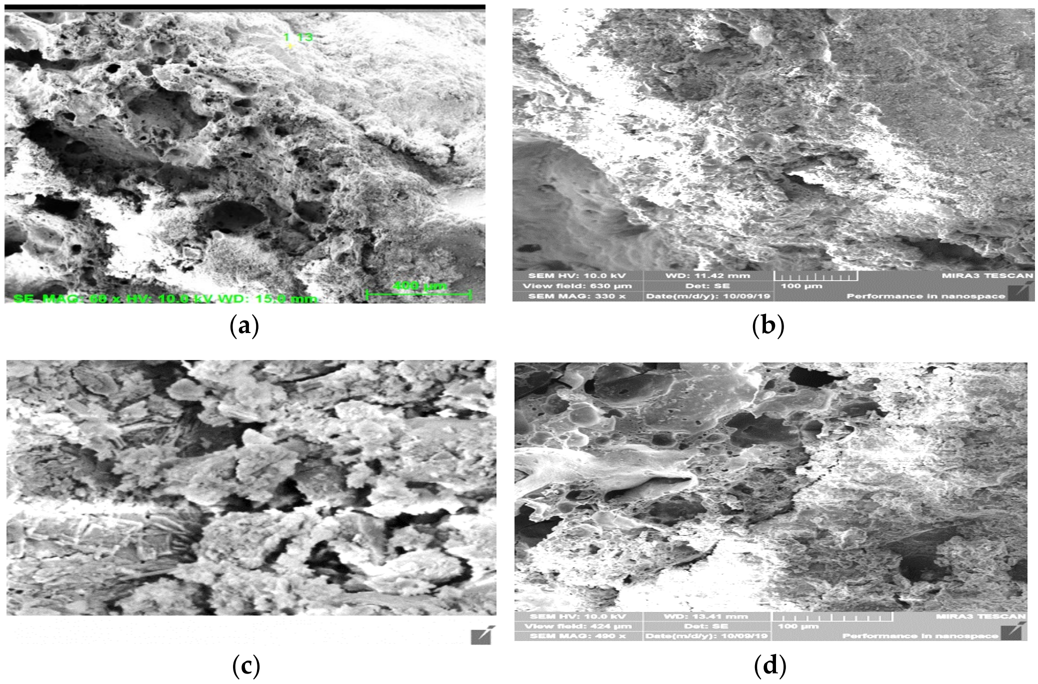

Figure 17. SEM Results of laboratory prepared LWAC specimens. (**a**) Control concrete; (**b**) FA 30%; (**c**) MS 30%; (**d**) FA15% + MS15%.

Thus, the usage of LECA with 15% FA + 15% MS as a cement replacement in LWC shows better compressive, tensile, flexural strength and lower thermal conductivity, and hence it can be proposed for structural purposes. Further research is in process in regard to different durability aspects along with different functional properties such as fire resistance and sound insulation properties.

6. Conclusions

The current paper reviews the prior studies conducted on the properties and uses of LWAs to develop sustainable concrete as green building materials. The utilization of sintered FA, vermiculite, pumice, OPS, LECA and perlite as LWA to produce LWC in building construction was reviewed through the recent and past literature. The physical, mechanical, durability, functional and structural behaviors of LWACs were discussed. Nowadays, LWACs have become an important low-cost green building material that imparts high thermal resistance properties with a reduced dead load of the superstructure. As the LWAs have different types of physical and mechanical characteristics, on the basis of end-user applications, available LWACs are used for different construction purposes.

7. Recommendations for the Further Research

On the basis of the existing literature, a few recommendations are proposed below:

1. Studies of hardened, durable and functional properties for different LWACs in various Indian climatic conditions;
2. Comprehensive studies of different durability attributes of high-performance LWAC containing different SCMs, fibers and polymers;
3. Statistical modeling for durability properties based on theoretical and empirical studies along with their validation in the fields;
4. Field studied for fire resistance of LWA concrete incorporated with SCMs, fibers, fire-resistant admixtures, etc.;

5. Study investigating the toughness and fracture energy of LWACs (LECA, OPS, sintered fly ash, pumice, perlite, vermiculite) is needed as these properties are necessary while modeling their mechanical behavior.

Thus, it is envisaged that LWACs, because of their techno-economic and environmental advantages, are supposed to capture their major share in the building industry in the 21st century. For this optimism, the most important additional motivating factor is the ever-increasing importance of the need for sustainable development. This is the appropriate time to utilize industrial byproducts such as fly ash, GGBS, silica fume, etc., by thinking more futuristically and investing in R&D for the sake of our world, its environment and its construction industry.

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