construction materials

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Review

A Comprehensive Review on the Performance of Structural Lightweight Aggregate Concrete for Sustainable Construction

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Abstract: Lightweight aggregate concrete is an innovative building material used to reduce the self-weight of a high-rise building. Recently, the use of lightweight aggregate in construction is increasing immensely due to its performance during an earthquake. Lightweight aggregate concrete (LWAC) is a solution for the achievement of sustainability in the construction sector, which helps us cut down the overall cost of a project in massive construction work (tall buildings and bridges). Additionally, using various industrial by-products and waste instead of natural aggregate allows us to reduce the negative impact on the environment. The development of lightweight aggregate concrete with its relevance is still prominent. The performance of lightweight aggregate on various properties of concrete is explored in this study. This study shows that the lightweight aggregate and waste materials of less density can be used for structural applications with a strength equivalent to that of normal weight concrete. The application and advantages of LWAC are also discussed in this study. The paper's overall finding reveals that LWAC can be used in sustainable construction growth and reduce waste by using it as natural aggregate in concrete to maintain environmental sustainability.

Keywords: lightweight aggregate; lightweight aggregate concrete; waste; sustainable construction

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1. Introduction

Structural concrete is the base of all construction activities and is the one of the most used substance, with nearly 3 tons used by each person on earth yearly [1–4]. Most of the current research attention focuses on the use of waste material in various functional concrete such as high strength concrete, self-compacting concrete, high-performance concrete, and lightweight concrete, so a cost-effective material and the performance-based concrete can be obtained [5–9].

Normal concrete has a self-weight of about 2400 to 2500 kg/m^3, which is very heavy, and due to its overall dead load, the size of members of the structure increases [10,11]. Lightweight concrete (LWC) is a type of concrete made of either a lightweight aggregate or expanding agent [12–14]. LWC having a dry density of 300 kg/m^3 up to 1840 kg/m^3 is 23–80% lighter in weight than normal weight concrete [15]. For the structural use of LWC, the unit weight varied in a range of 1400 and 2000 kg/m^3 compared to normal weight concrete of unit weight 2400 kg/m^3 [16,17]. Nowadays different types of lightweight aggregate (LWA) are used in concrete, such as expanded clays and shales, pumice perlite, and various wastes like a blended waste, clay brick, rubber, plastic, oil palm shell, and other agricultural waste to make the concrete lightweight [18–23].

Lightweight concrete was brought into use more than 50 years ago in countries such as the U.S., Italy, Sweden, and U.K., among others [24,25]. The potency of lightweight concrete is its weight and its resistance to weathering. Lightweight concrete has various advantages and disadvantages compared with the normal conventional concrete containing natural sand and gravel (Figure 1). Its significant benefits include structure dead load reduction, overall construction cost reduction, structural steel quantity reduction, decrease in foundation sizes, low thermal conductivity, better fire resistance, and insulation against heat and sound [26–30]. Its disadvantages include porosity, more drying shrinkage, high cost (30–50%), and more care required during placement.

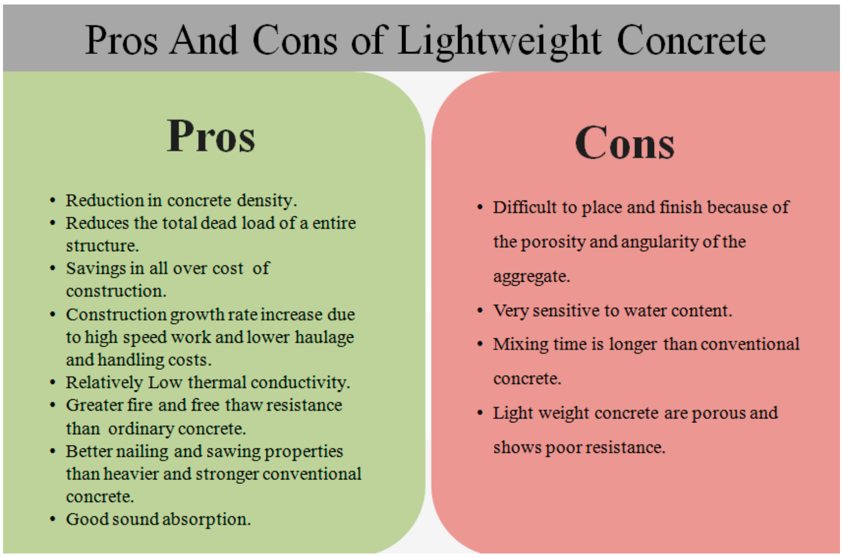

Figure 1. Pros and cons of lightweight concrete (LWC).

The main use of LWC is under beds for floors and roof slab construction, where substantial savings can be achieved by decreasing the dead load. It is also used in some insulated sections of floors and walls [31].

Various research articles have been published recently on LWC with different types of LWA. Kunchala and Tangudu [32] used expanded clay aggregates to replace normal weight aggregate. They showed that expanded clay aggregate had a higher strength compared to the other lightweight aggregate. Guneyisi et al. [33] studied the effect of lightweight artificial aggregate on fresh SCC properties. The workability and compressive strength were influenced by the replacement of natural aggregate with artificial aggregate. Yu et al. [34] developed a lightweight aggregate concrete with hydrophobic expanded silicate of an oven-dry density of about 1000, 1150, and 1400 kg/m^3. They recommended hydrophobic expanded silicate due to its good density to strength ratio for lightweight structural concrete. In the same way, expanded clay aggregates were used by Ahmad et al. [35] to produce concrete having a density range from 800 to 1300 kg/m^3. Adem et al. [36] used different types of crushed bricks in lightweight concrete with a density of about 1980 to 1990 kg/m^3. Kurt et al. [37] produced a lightweight concrete with a dry density of about 845–1031 and 1014–1037 kg/m^3 containing 100% pumice aggregate. The pumice aggregate showed good properties and performance in the lightweight concrete. He et al. [38] found that clay ceramsite lightweight concrete had superior mechanical and fire resistance properties compared to normal concrete.

Polat et al. [39] recorded a higher compressive strength in the lightweight concrete with 10% expanded perlite and pumice aggregate exposed to the 100 freeze-thaw cycles. The fatigue properties of rubberized lightweight self-compacting concrete (SCC) were found to be better than the lightweight SCC [40]. The substitution of normal aggregate by polyolefins aggregates at 30% showed a density reduction of about 23% compared to normal concrete [41]. The abrasion and impact test results of cold–bonded artificial lightweight aggregate concrete were found to be better than the natural aggregate concrete [42]. The physical properties of different LWA are summarized in Table 1 below.

Table 1. Physical properties of lightweight aggregate (LWA) used by different authors.

Authors	Material	Specific Gravity	Density (g/cm^3)	Bulk Density (kg/m^3)	Absorption (%)	Fineness Modulus
Choi et al. [43]	Polyethylene terephthalate (PET) bottles waste	–	1.39	8.44	0.0	4.11
Farj et al. [44]	Polyurethan foam waste	–	–	21	13.9	–
Chia and Zhang [45]	Expanded clay shale	–	1.2	650 ± 25	7.3	–
Zhang and Poon [46]	Expanded clay	–	–	1192	9.41	–
Kockal and Ozturan [47]	Fly ash pellets (Cold bonded)	1.89	–	842	25.5	–
Saikia and Brito [48]	PET-aggregate	–	1.33	351	0.18	–
Gunasekaran et al. [49]	Coconut shell	1.05–1.20	–	650	24.00	6.26
Mannan and Ganapathy. [50]	Oil palm shell	1.17	–	590	23.32	6.24
Senhadji et al. [51]	Polyvinylchloride (PVC)	–	1.4	575	0.0	3.46
Piyaphanuwat and Asavapisit [52]	Ceramic wastes (DWM)	1.78	–	1016	41.27	2.44
Islam et al. [53]	Oil palm shell	1.25	–	684	18.70	5.94
Bogas et al. [18]	Recycled lightweight concrete aggregates (RLCA)	–	1.735	1000	15.7	–
Pal et al. [54]	Fly ash sintered aggregate (Fly ash 2)	1.77	–	835	12.0	–
Aslam et al. [55]	Oil palm shell (OPS)	1.19	–	610	20.5	–
Aslam et al. [55]	Oil palm boiler clinker (OPBC)	1.69	–	860	7.0	
Shah et al. [56]	Oil palm boiler clinker (OPBC)	1.9	–	1471	3.91	5.88
Shafigh et al. [56]	Lightweight expanded clay aggregate (LECA)	0.66	–	273	26.5	5.96
Ahmed et al. [57]	Pumice (sand)	2.3	–	964	3.75	2.56
Ahmed et al. [57]	Pumice (Clay aggregate)	2.53	–	571	6.0	–
Adebakin et al. [58]	Coconut shell	1.14	–	650	24.0	6.54
Real et al. [59]	Leca	–	1.076	624	15.8	–
Real et al. [59]	Stalite	–	1.483	760	3.6	–
Real et al. [59]	Argex (2–4)	–	0.669	377	21.4	–

The biggest drawback of normal conventional concrete is its density, which is high, at about 2400 to 2500 kg/m^3 [60]. Therefore, the use of normal concrete is decreasing across the globe. In the case of weak soil and high-rise structures, the building structure's entire weight is an essential consideration factor in designing the foundations and other structural elements.

LWA is a fundamental material for reducing the unit weight of normal concrete and producing earthquake-resistance structures [61]. Usually, normal concrete is made by using Portland cement and natural aggregates, which gives it a compressive strength of about 55 to 62 N/mm^2. This strength is much more than the required strength for most of the structural applications, so there is a requirement to lighten the strength and weight of concrete by making a lightweight concrete with the desired properties required for most of the structural applications [23,62]. However, developing lightweight structural concrete is a complex science, and it is not easy to fulfill the desired parameters with a lesser amount of materials. The more efficient strength to weight ratio is provided by lightweight concrete for structural elements. The slightly upper cost of the LWC is counterbalanced by reducing the size of the structural elements, which further results in reducing the overall price, as it does not require as much steel and concrete.

Currently, the utilization of structural LWC is limited to mostly large structures like bridges and high-rise buildings. Today, with lightweight aggregate concrete, a considerable economy can be achieved, and additional benefits like faster construction due to lightweight material handling and low thermal conductivity help to conserve energy. The industrial wastes, i.e., fly ash, slag, clinker, rubber, and recycled plastic, etc., can be used for manufacturing lightweight concrete [63–67]. Apart from all these benefits, if the center of gravity does not coincide with the center of the building's rigidity, a higher amount of reinforcement steel is required for normal weight concrete than lightweight concrete structural components. There is no difference in the quantity of steel needed for slabs, but it there are phenomenal savings in the reinforcement cost in columns and beams in such cases. In the various literature, there are many applications based on LWC prepared with natural or artificial LWA [61,68–70].

However, it is important to examine LWC to know the advancement of new material and waste material utilization as a lightweight aggregate in cement-concrete preparation. Therefore, the current study presents the use of various lightweight aggregate and waste materials as a partial replacement of both fine and coarse aggregates in the production of lightweight concrete with its influence on multiple properties.

Types of Lightweight Aggregate

The classification of natural and artificial LWA is shown in Figure 2. Some of the commonly used LWA are shown in Figure 3 and are as follows:

- Pumice: It forms from the supercooled liquid of lava, which contains mainly SiO_2, erupted from volcanoes, and its low density is due to the occurrence of gas bubbles inside it.
- Palm oil shells: It is a waste by-product generated by oil industries while extracting oil from palm shells.
- Perlite: In Japan, a new lightweight aggregate has been developed using perlite, which is called Asano super sight.
- Lightweight aggregates from the treatment of natural aggregates: The clay or shale is heated in a kiln at a high temperature, which causes the material to expand to make it lightweight.
- Expanded clays and shales—This is capable of achieving sufficiently high strength for prestressed concrete.
- Sintered pulverized—It is developed from fuel ash aggregate and used in varied structural use, and its trade name is Lytag in the market.

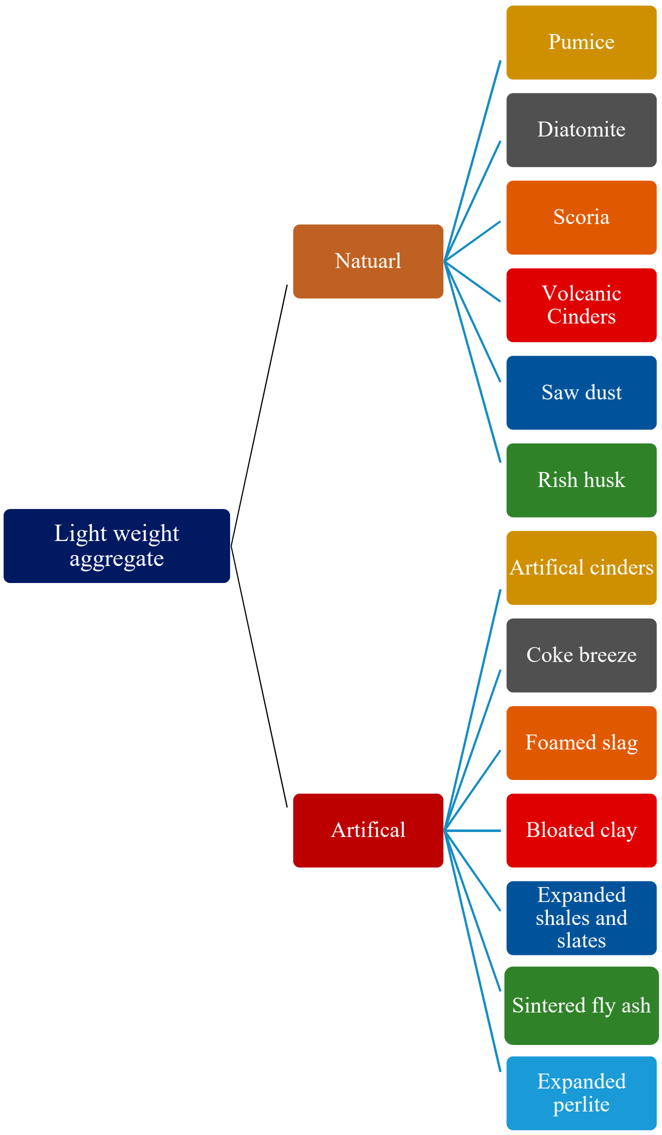

Figure 2. Classification of lightweight aggregate.

Figure 3. Different light weight aggregates (**a**) Pumice "Reprinted from ref. [57]." (**b**) Oil palm shell "Reprinted from ref. [71]." (**c**) Synthetic aggregate "Reprinted with permission from ref. [72]. Copyright 2018 Elsevier" (**d**) Oil palm shell (Boiler clinker) "Reprinted with permission from ref. [73]. Copyright 2016 Elsevier" (**e**) Expanded perlite "Reprinted from ref. [74]." (**f**) Lytag aggregate "Reprinted with permission from ref. [72]. Copyright 2018 Elsevier".

2. Fresh Concrete Properties

A fresh property is an essential parameter for concrete production considered during mixing, transport, placing, and finishing without segregation, measured through a slump test, inverted slump cone test, and K-test [75].

In the available literature, researchers have shown the influence of lightweight aggregate on workability. Shafigh et al. [56] noted the reduction in the slump values of the lightweight concrete containing coarse oil palm boiler clinker and expanded clay aggregate. Abd Elrahman et al. [76] examined concrete's fresh properties containing different expanded aggregate such as Livaver, Liapor, and Ecoglas. They found a negative impact on all the three expanded aggregate lightweight concrete due to the expanded aggregate's high water absorption. Some researchers reported that using different waste materials as lightweight aggregate in concrete decreases the slump value [77,78]. Adhikary and Rudzionis [77] used rubber particles as fine aggregate in the lightweight concrete. The increase in the flow diameter was observed in their study due to the use of the fly ash in the light concrete. Wang et al. [78] noticed the best performance in workability at 20% replacement of lightweight aggregate by the rubber aggregate. Fraj et al. [44] assessed the impact of the addition of polyurethane (PUR) foam waste as a substitute for coarse aggregate (8/20 mm) in concrete. The test results showed that the substitution of normal aggregate with dry PUR-foam decreased the slump value, but pre-wetted PUR-foam aggregates showed good workability.

Ahmad et al. [35] carried out a study on lightweight aggregate concrete containing expanded clay aggregate and silica fume. The expanded clay aggregate was found to be evenly distributed in the lightweight foam concrete. The slump value was found in the range of 245–270 mm. They reported that the expanded clay aggregate had a negligible effect on the workability and silica fume caused a reduction in the slump value.

Choi et al. [43] showed that a higher percentage replacement of waste polyethylene terephthalate bottles (PET) at 75% as aggregate improves the workability of concrete by about 123% compared to normal concrete. Alqahtani et al. [72] showed the inclusion of the synthetic aggregate in the lightweight concrete decreased the slump flow diameter. They observed that the subangular shape and fibrous surface texture of synthetic aggregate result in a lower slump diameter due to the increase in the contact surface area between the aggregate and mortar paste. In another study, partial replacement of sand by oil fuel ash also showed a decrement in the slump value with the incorporation of oil fuel ash [79]. Recently Lv et al. [80] reported that with the rise in replacement % of sand by rubber particle in concrete, the slump flow was found to decrease at various replacement levels. The positive effect on the workability property was reported by Guneyisi et al. [81] in cold bonded fly ash lightweight aggregate with the incorporation of the mineral admixture (fly ash and silica fume). The addition of the fly ash and silica fume as mineral admixture in cold bonded fly ash lightweight aggregate resulted in good workability. Ahmmad et al. [82] evaluated the performance of palm oil clinker as a coarse aggregate in lightweight concrete. They reported that all lightweight concrete mixes made with palm oil clinker aggregate showed consistent values with the site's applied requirement. The slump value reduction was observed in the lightweight concrete containing polyethylene terephthalate (PET) waste [83].The slump value was also found to increase with the addition of expanded clay aggregate in lightweight aggregate concrete compared to normal concrete due to the replacement of cement with silica fume [45].

Thus, from the above research studies, it can be concluded that the slump value decreases with the increase of waste material as aggregate (Figures 4 and 5). Still, with the use of mineral admixture and pre-treatment of waste, the positive effect on workability can also be achieved.

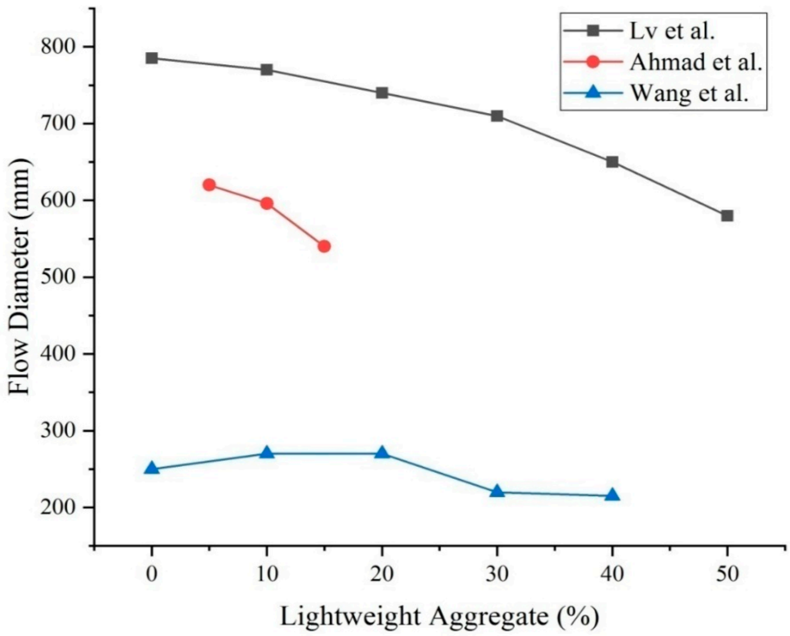

Figure 4. Slump flow diameter of lightweight concrete [35,78,80].

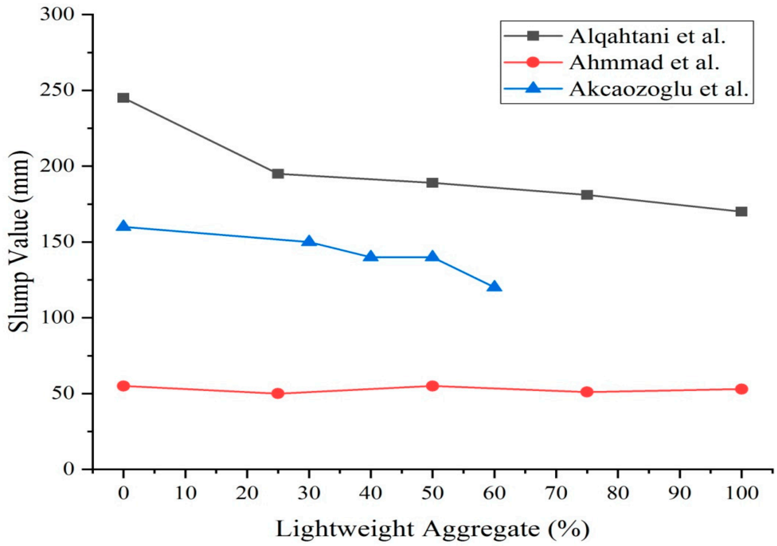

Figure 5. Slump values of lightweight concrete [72,82,83].

3. Hardened Properties

The most critical factor in measuring the hardened state of concrete for its applicability is mechanical properties. This section represents the effects of lightweight aggregate on various mechanical properties like compressive strength, split tensile strength, flexural strength, and modulus of elasticity of LWAC.

3.1. Compressive Strength

Concrete categorization mainly depends on its compressive strength. It is essential to find the concrete strength before its use at the construction sites. To find the effect of lightweight aggregate in different concrete types, studies were conducted by various researchers [84,85]. Lv et al. [84] showed a decrease in compressive strength with the addition of rubber particles as lightweight aggregate in lightweight concrete. Sengul et al. [85] reported the reduction in the compressive strength with the inclusion of porous perlite aggregate in the lightweight aggregate concrete. In some literature studies, it has been established that an increase in lightweight aggregate leads to a decrease in compressive strength [86,87]. Recently Ahmad et al. [79] found better compressive strength at 10% replacement of sand with palm oil fuel ash in lightweight concrete than the control concrete mix. Two different types of lightweight aggregate, expanded perlite aggregate (EPA) and volcanic pumice (VP), were used by Numan et al. [74] to replace coarse aggregate up to 50%. The test results showed a decreasing trend in both the EPA and VP lightweight concrete at various percentages. The increase in rubber particle content from 0% to 100% resulted in a gradual decrease in lightweight concrete compressive strength from 41.5 MPa to 7.8 MPa [80]. Ahmad et al. [35] studied the effect of expanded clay aggregate and silica fume in lightweight foam concrete compressive strength. They showed that lightweight foam concrete's compressive strength was directly related to the expanded clay aggregate volume. The concrete's compressive strength reduced with the incorporation of expanded clay aggregate and silica fume inclusion resulted in the increase in the compressive strength due to the more formation of C-S-H gel. The palm oil clinker aggregate's porous structure improved the bonding as pores of the palm oil clinker filled with the cement paste. Zhang et al. [88] also showed an increase in the compressive strength of concrete with the lightweight shale aggregate due to the strong skeleton structure development in the cement paste.

Muthusamy and Zamri [89] studied the palm oil fuel ash's effect as a partial replacement of cement in the oil palm shell lightweight concrete. Oil palm fuel ash improved the bond between the cement matrix and aggregate in oil palm shell lightweight concrete. The secondary C-S-H formation due to the pozzolanic reaction filled the pores and increased the concrete's compressive strength. Wu et al. [90] investigated the apricot shell lightweight aggregate's influence on lightweight aggregate concrete. The apricot shell aggregate replaced the coarse aggregate. The compressive strength decreased by 8.3%, 19.9%, 31.0% and 32.6% at 25, 50, 75 and 100% apricot shell aggregate inclusion in the lightweight concrete. They observed that the weak strength of the apricot shell aggregate lowers downs the compressive strength of lightweight concrete.

Akcaozoglu et al. [83] found the negative impact of compressive strength with the increment of PET aggregate at 30%, 40%, 50%, and 60%, respectively, as conventional aggregate in LWC. Shafigh et al. [91] investigated the influence of oil palm shell (OPS) incorporation on LWC containing expanded clay. In the study, OPS was used to replace expanded clay at 0, 25, and 50% by its volume. They showed that concrete strength increases at all replacement levels of expanded clay by OPS and curing ages.

However, Ahmmad et al. [82] and Zhang and Poon [46] showed the potential of using various industrial waste (palm oil clinker and furnace bottom ash) as a substitute for natural aggregate in concrete at a higher percentage replacement level. They found better and similar results at a higher percentage replacement of natural aggregate in LWC [82]. The porous structure of the palm oil clinker and shells filled with the cement paste and provide the good bonding strength in LWC [82,91]. The high strength in the furnace bottom ash LWC was found due to the lower w/c ratio in the mixture [46]. The recycled plastic waste replaced the sand at 10%, 15%, 20%, and 30% in the study conducted by Yang et al. [92]. The compressive strength increased up to 15% replacement of sand by recycled plastic waste. The recycled plastic waste as sand-filled the voids in the self-compacting concrete increased the compressive strength of concrete up to 15%. Thus, from the above literature studies and Figure 6, it can be concluded that with LWA and different waste materials, the compressive strength decreased in most of the studies due to their material properties.

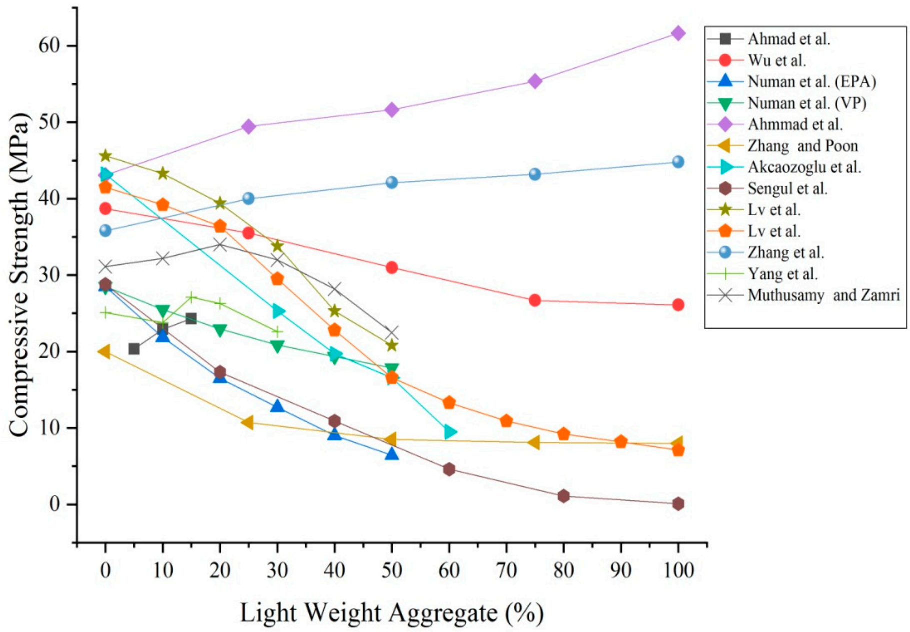

Figure 6. Compressive strength of lightweight concrete [35,46,74,80,82–85,88–90,92].

3.2. Splitting Tensile Strength

To understand the behavior of concrete in tension, a split tensile strength test method (indirect method) is used on cylindrical specimens under the ultimate load. A decreasing trend was observed by various researchers on the split tensile strength in lightweight aggregate concrete containing waste material instead of normal aggregate [47,55,93]. Kockal and Ozturan [47] studied the effect of the lightweight fly-ash aggregate on the concrete properties. They showed that the concrete's compressive strength decreased with the increment of the lightweight fly-ash aggregate in concrete. Aslam et al. [55] reported that the reduction in the split tensile strength of lightweight concrete was due to the weak bonding between the oil palm shell and cement matrix. Recently, Wu et al. [90] studied the behavior of LWC containing apricot shells (AS). The AS was used to replace the normal coarse aggregate at 0%, 25%, 50%, 75%, and 100% in lightweight concrete. The splitting tensile strength results of AS LWC decreased by 4.9%, 9.4%, 24.7%, and 30.7%, respectively, with their replacement of normal weight coarse aggregate.

The effect of incorporation of polypropylene (PP) plastic particles as sand replacement in self-compacting lightweight aggregate concrete (SCLC) was studied by Yang et al. [92]. Fine aggregates were partially replaced at 10%, 15%, 20%, and 30% by PP, respectively. The splitting tensile strength of SCLC was found superior with PP contents up to 15% and after a 15% reduction in strength was noted. The uniform distribution of the plastic particles in the LWC improved the split tensile strength up to 15% replacement of the fine aggregate. The decrease in splitting tensile was observed after 15% partial substitution of natural sand due to more free water and weaker interfacial bonding with cement paste. The contradicted results were found in the study conducted by Zhang et al. [88]. The natural sand was replaced by shale aggregate from 0 to 100% at a 25% incremental level. The split tensile strength of lightweight concrete increased because the shale aggregate's average particle size was larger than natural aggregate. The large replacement of the natural sand in the study showed the split tensile strength increment due to the strong skeleton structure development in the cement mortar.

The synthetic aggregate was also used in the experimental study to replace the two coarse aggregates (Lytag and Pumice) by Alqahtani et al. [72]. They observed the reduction in the split tensile strength test results with both coarse aggregate replacements. Lv et al. [80,84], in the separate studies, also reported the same behavior in split tensile strength with increased rubber particles in LWC. However, from the above research studies and Figure 7, it is clear that the split tensile of LWA concrete decreased with the increment in various types of LWA.

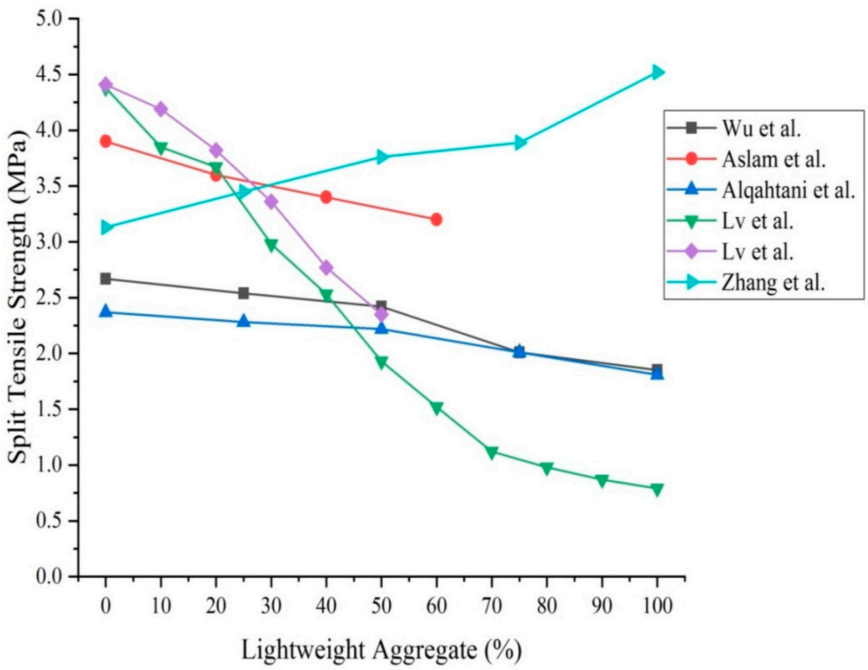

Figure 7. Splitting tensile strength of lightweight concrete [55,72,80,84,88,90].

3.3. Flexure Strength

The flexure strength of concrete is determined to check the concrete structural members subjected to bending load. Various authors in the literature showed the impact on the flexural strength with lightweight aggregate [48,89]. Saikia and Brito [48] observed a decreasing trend in flexure strength with the use of the lightweight aggregate of plastic waste bottles.

Muthusamy and Zamri [89] reported a decrease in the flexure strength of lightweight concrete made with the palm oil shell lightweight aggregate. Apricot shell (AS) lightweight aggregate was used by Wu et al. [90] to examine concrete bending strength. In the study, the normal-weight coarse aggregate was replaced with the apricot shell lightweight aggregate at 0%, 25%, 50%, 75%, and 100%, respectively. The flexural strength of apricot shell lightweight concrete decreased by 2.4%, 8.0%, 21.7%, and 24.8% at 0, 25, 50, 75 and 100% replacement of normal coarse aggregate, respectively. The series of experimental studies conducted by Lv et al. [80,84] noted the reduction in the flexure strength with the rubber particles addition in the lightweight concrete and self-compacting lightweight concrete. The flexure strength reduction was noticed due to the weak bonding between the rubber particle and cement paste in the concrete matrix.

Yang et al. [92] reported that the flexure strength of self-compacting lightweight concrete showed a descending tendency because of free water and weaker interfacial bonding after 15% sand substitution. The flexure strength of self-compacting lightweight concrete was improved by incorporating of plastic contents up to 15% as a sand substitution. The dense interface with good adhesion between the plastic and cement binder increased the flexure strength up to 15%. Kumar et al. [94] studied the effect of various mineral admixtures (silica fume, ground granulated blast furnace slag, and alccofine) on flexure strength properties of coconut shell aggregate concrete. The test results showed a higher flexure strength of concrete made with mineral admixture (granulated blast furnace slag and alccofine) and coconut shell aggregate.

The increase in flexure strength was found by Zhang et al. [88] with the replacement of natural sand by shale aggregate at 0%, 25%, 50%, 75%, and 100%, respectively. They reported the increase in the flexure strength due to the reduction of the pores and gap between the mortar and ceramsite with the increment of fine shale aggregate. Similar flexure strength test results were noted in concrete containing coconut shell aggregate and normal aggregate at two different water-cement ratios (0.42 and 0.44) [49].

However, it can be deduced from the above literature and Figure 8 that the flexure strength of concrete gets reduced using different types and different percentage of various lightweight aggregate.

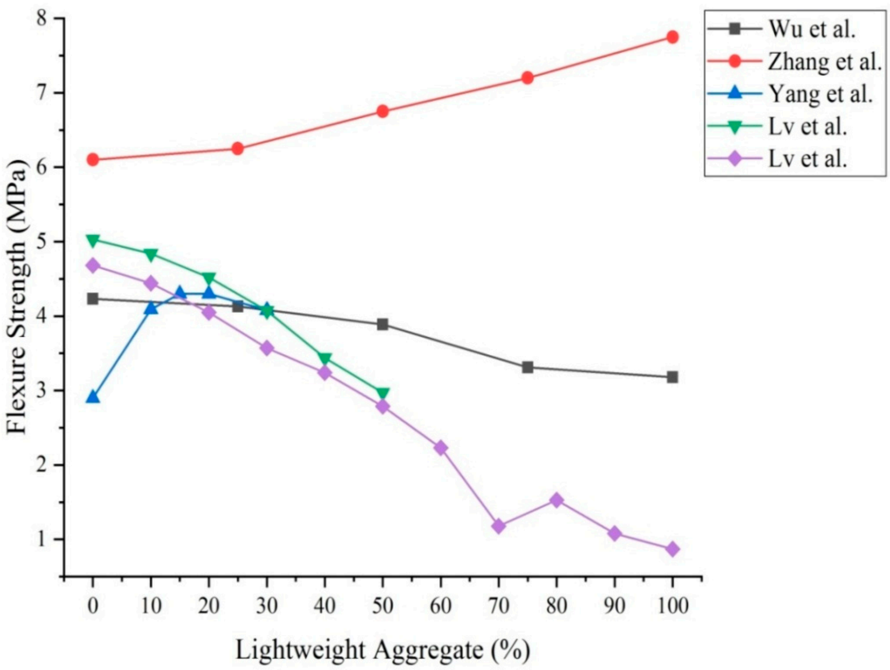

Figure 8. Flexural strength of lightweight concrete [80,84,88,90,92].

3.4. Modulus of Elasticity

Elastic modulus values are determined by the various methods from the stress-strain curve diagram. The modulus of elasticity of concrete depends upon the aggregate and mixture proportion of concrete. The elastic modulus of LWC was found to decrease in many studies with the inclusion of LWA instead of natural aggregate [95,96]. Lo et al. [95] reported the decrement in the sintered lightweight concrete's elastic modulus with the addition of the lightweight sintered high carbon fly ash aggregate. Wongkvanklom et al. [96] showed that the addition of lightweight recycled aggregate in concrete decreased the modulus of elasticity of the concrete. A comparative study on the modulus of the strength of concrete was conducted by Tajra et al. [97] on core-shell lightweight aggregate and expanded clay aggregate. The higher crushing strength of the core-shell structured lightweight aggregate showed an increase in modulus of elasticity of concrete over expanded clay aggregate. The expanded perlite as a sand substitute (0%, 20%, 40%, 60%, 80%, and 100%) in concrete showed a decrement in the elastic modulus of concrete [85]. Wu et al. [90] reported that the low strength of apricot shell aggregate and weak bond in the interfacial transition zone decreased the lightweight concrete's modulus of elasticity.

The increase in modulus of elasticity was noted by Ahmmad et al. [82] in a palm oil clinker based lightweight concrete. The stiffness of palm oil clinker concrete increased with the increasing palm oil clinker content due to the palm oil clinker's high stiffness. Zhang and Poon [46] used furnace bottom ash waste material in concrete. The natural aggregate was replaced at 0%, 25%, 50%, 75%, and 100% with the furnace bottom ash. The test outcomes showed the reduction in the elastic modulus of concrete with the furnace bottom ash percentage level's increment.

Wu et al. [86] used peach shell (PS) at 0%, 25%, 50%, 75%, and 100% to replace natural aggregate. The results of the test showed a decreasing trend in flexure strength of concrete at various PS percentages. The decreasing trend in modulus of elasticity of concrete was found by Miller and Tehrani [30] with the replacement of expanded shale coarse aggregate by rubber. Similar results were also noted with rubber particles' replacement in lightweight concrete and mortar [80,84]. Thus, it can be seen from Figure 9 that the modulus of elasticity reduced with the use of LWA in concrete.

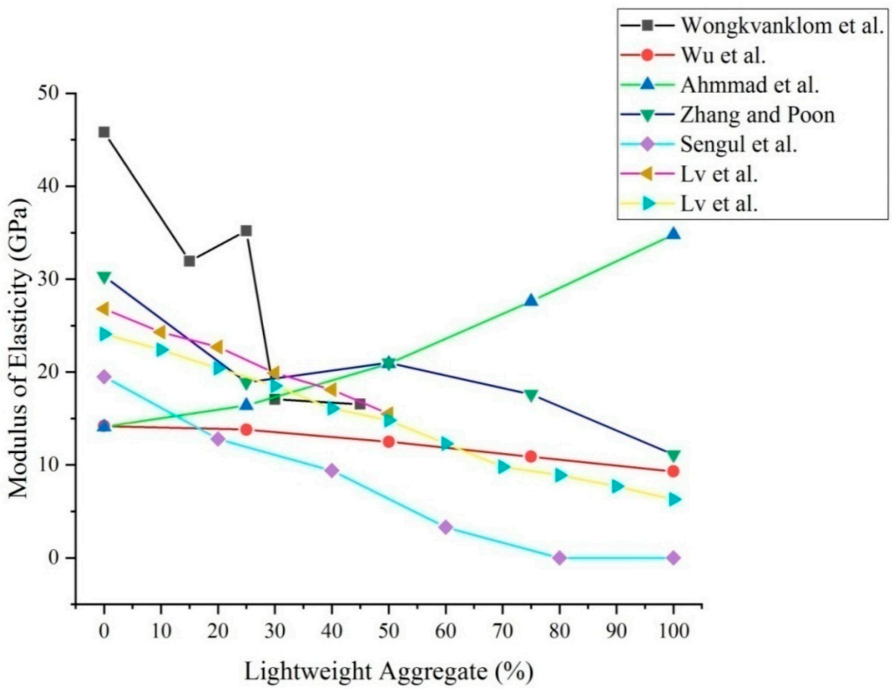

Figure 9. Modulus of elasticity of lightweight concrete [46,80,82,84,85,90,96].

3.5. Ultrasonic Pulse Velocity

Ultrasonic pulse velocity (UPV) is a non-destructive testing technique to check the class of quality and strength of concrete. The influence of various lightweight aggregate on concrete is summarized below.

Hamada et al. [98] carried out a UPV test to study the effect of palm oil clinker (POC) aggregate in lightweight concrete quality. The results showed that the UPV values were found 5% to 14% lower for LWAC concrete mixes than the control mix due to the POC aggregate, which increased air content in concrete. The negative effect of supplementary cementitious material (rice husk ash and fly ash) as replacement of cement was found in palm oil shale lightweight aggregate concrete [99].

Liu et al. [100] studied the effect of UPV on foamed and non-foamed oil palm shell geopolymer concrete. The non-foamed geopolymer concrete showed a higher value of UPV as compared to foamed geopolymer concrete. Polyvinylchloride (PVC) waste was used by Senhadji et al. [51] to replace the natural aggregate (fine and coarse). This study showed that the UPV values decreased with the increase of PVC granules in the concrete. Akcaozoglu et al. [101] carried out a test on waste PET lightweight aggregate (WPLA) replaced with normal weight aggregate in concrete. The decreasing trend was observed in UPV values of specimens with the increase of WPLA in the mixture.

4. Durability Properties

The durability of concrete is defined as the ability of concrete to resist the deterioration caused by the intrusive and extrusive environment. The durability reduces the serviceability of concrete before its service life span [4,102]. In this study, we review lightweight concrete durability properties like drying shrinkage, water absorption, water permeability, chloride penetration, carbonation, and fire resistance.

4.1. Drying Shrinkage

Drying shrinkage in concrete occurs with the water evaporation and moisture loss on the exposed surface; the cracks develop on the concrete surface decreases the concrete durability with time.

Various studies showed that the lightweight aggregate concrete showed a higher drying shrinkage than the normal weight concrete [103,104]. Bogas et al. [103] noticed a higher drying shrinkage in the lightweight concrete containing 20%, 50%, and 100% coarse recycled lightweight aggregate. Shafighet al. [104] reported that the lightweight concrete made with the crushed oil palm shell aggregate had a higher drying shrinkage than normal concrete. Alqahtani et al. [72] carried out a study on the synthetic aggregate coarse aggregate in LWC. The test results showed that drying shrinkage in LWC increased with the replacement of the lytag and coarse pumice aggregate at a different percentage. The lower water absorption and weak bonding between the paste and aggregate resulted in higher drying shrinkage than the control LWC. The drying shrinkage was mainly affected by the aggregate properties and their amount in the lightweight concrete.

Aslam et al. [105] replaced the oil palm shell with the oil palm shell boiler clinker in the drying shrinkage test study of lightweight concrete. They found that the drying shrinkage of oil palm shell boiler clinker concrete was found similar to the oil palm shell concrete at all replacement levels at all ages. The drying shrinkage of oil palm shell concrete and normal concrete for up to 90 days was found by Mannan and Ganapathy [106]. They reported 14% higher drying shrinkage in the oil palm shell concrete than the normal weight concrete.

4.2. Water Absorption

The water absorption test is performed to check the penetration rate of harmful chemicals and water in terms of the durability of concrete to the exposed surface water absorption of LWA concrete influenced by different lightweight aggregate and waste [107,108].

The study conducted by Rossignolo and Agnesini [109] observed a decreasing trend in the water absorption of LWAC with increment in polymer/cement ratio. Wongkvanklom et al. [96] found that water absorption of concrete containing recycled lightweight concrete aggregate at 0%, 15%, 25%, 35%, 45%, respectively, showed an increasing water absorption trend with the increase with RLCA content in concrete. Piyaphanuwat and Asavapisit [52] studied the effect of ceramic wastes a coarse aggregate in lightweight aggregate concrete (LWAC). The ceramic waste was used as a coarse aggregate of deteriorated working mould (DWM) form. The coarse aggregate was replaced with DWM at 0%, 25%, 50%, 75%, and 100% respectively. The test results showed that an increase in water absorption for all LWAC depends upon DWM.

Recently Alqahtani et al. [72] studied the influence of synthetic aggregate on water absorption in LWC. The test results showed that synthetic aggregate concrete made with normal aggregate replacement had a lower water absorption percentage. Sengul et al. [85] reported that the incorporation of expanded perlite as a natural sand substitute in concrete increased the water absorption percentage of concrete. They pointed out the porous nature of the perlite aggregate for an increase in water absorption of concrete. Thus, it can be seen from Figure 10 that the water absorption of concrete increased with the use of LWA.

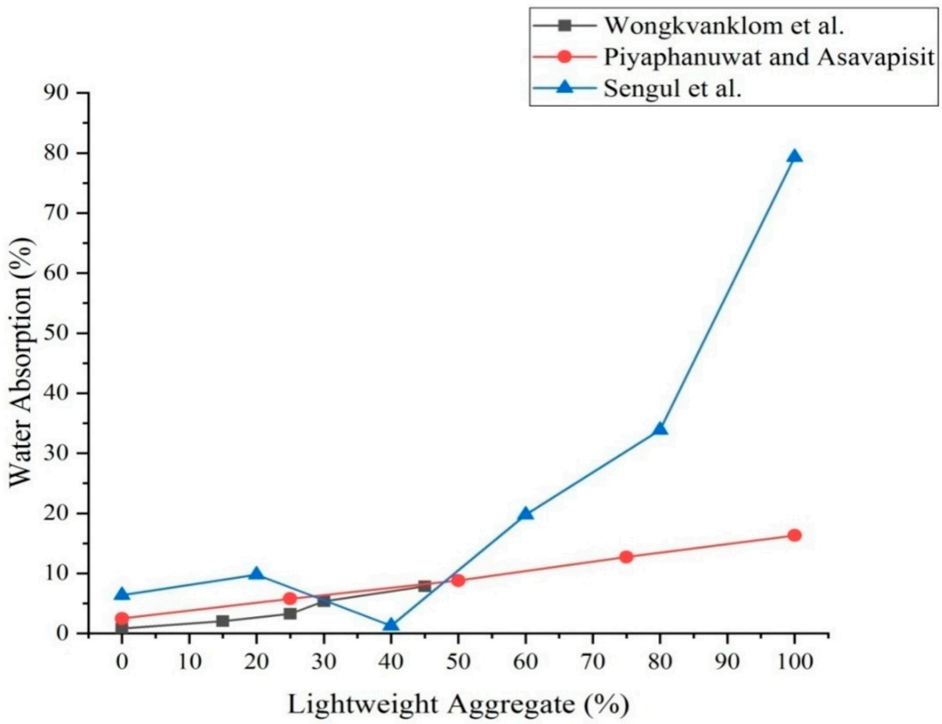

Figure 10. Water Absorption of lightweight concrete [52,85,96].

4.3. Water Permeability

The permeability of concrete is a vital durability property, which resists the porous penetration of fluids. The permeability of normal concrete is affected by the w/c ratio, age and curing of concrete, and compaction.

Chia and Zhang [45] reported that the addition of expanded clay type commercially manufactured aggregate in lightweight concrete has a lower permeability value than normal concrete. Hossain et al. [110] assessed pumice aggregate impact as partial replacement of both fine and coarse aggregate with natural aggregate on lightweight concrete. The water permeability after 12 weeks of volcanic pumice concrete (VPC) mixtures was found to be less than that of normal concrete. The lightweight aggregate concrete showed a higher water penetration than the normal concrete at the same w/c ratio due to the porous nature of lightweight aggregate [107].

Ge et al. [111] studied the effect of the prewetting of the lightweight aggregate on the concrete permeability. The prewetted aggregate had an improved durability property than the without wetted aggregate in the lightweight concrete. Fazhou et al. [112] carried out a study on the mineral admixture effect on the lightweight aggregate concrete. They used the ground granulated blast furnace slag, fly ash, and silica fume as a mineral admixture in lightweight concrete production. They reported that the incorporation of the mineral admixture decreased the permeability of lightweight concrete. The fly ash and silica fume showed better results than the ground granulated blast furnace slag mineral admixture in the lightweight concrete. The literature studies revealed an increase in the water permeability due to the porous nature of the LWA. However, water permeability was reduced by the pre-treatment and the use of mineral admixture.

4.4. Chloride Penetration

The chloride penetration test is done to check the resistance of chloride ions penetration in concrete as part of the durability assessment. The depth of chloride penetration is measured through the RCPT apparatus. Kockal and Ozturan [47] studied the behavior of concrete containing lightweight fly ash aggregate with glass powder (LWGC), bentonite (LWBC), and cold bonded (LWCC) on chloride penetration. LWBC showed good results among all in the chloride permeability test. Islam et al. [53] carried out a study to find the effect of palm oil shells as coarse aggregate and palm oil fuel ash as binder replacement in LWC. They found chloride ion penetration of the oil palm shell concrete (OPSC) without palm oil fuel ash (POFA) was higher than the OPSC with 70% POFA. Zhang and Poon [46] studied the influence of furnace bottom ash as fine aggregate and expanded clay as coarse aggregate on chloride ion penetration of LWC. They reported that high volumes of furnace bottom ash (FBA) inclusion harmed concrete durability properties. Bogas et al. [18] found that the chloride diffusion coefficient was more for a concrete sample containing recycled lightweight aggregate than normal-weight concrete.

Alqahtani et al. [72] used synthetic aggregate as a substitute of lytag and coarse pumice aggregate. They noted the reduction of 9–17% in the chloride ion permeability test results with coarse aggregate replacements from 25 to100%. The impervious nature and lower ion conductivity of synthetic aggregate reduced the chloride ion permeability. Senhadji et al. [51] also reported that the chloride ion penetration of concrete increased with the incorporation of the PVC lightweight aggregate.

Overall, from the above literature studies mentioned in this section and from Figure 11, it can be seen that the chloride penetration in LWAC reduced with the use of non-porous lightweight aggregate. However, with the incorporation of porous LWA, the chloride penetration of concrete increases.

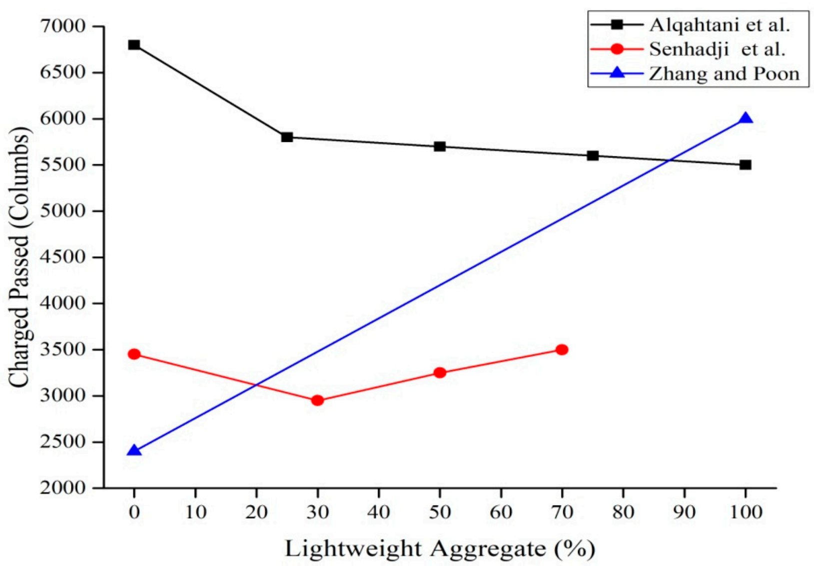

Figure 11. Chloride ion permeability of lightweight concrete [46,51,72].

4.5. Carbonation

The corrosion of steel occurs mainly in concrete structure subjected to carbonation. Due to the carbonation in concrete, the pH of the concrete gets reduced with time.

Gao et al. [113] studied the effect of the mineral admixture on carbonation characteristics of LWC. In the study, they used fly ash, pulverized fly ash, granulated blast furnace slag, and silica fume as a mineral admixture. They observed that the lightweight concrete made up with a 20% mineral admixture had a higher carbonation depth than the normal concrete. The increment in carbonation depth was found to be 129.3%, 179.9%, 77.6%, and 86.2%, respectively, for LWC containing fly ash, pulverized fly ash, granulated blast furnace slag, and silica fume at 28 days. Bogas et al. [18] showed that the carbonation depth of the concrete increased with the incorporation of the LWA. The porous nature of the LWA increased the carbonation depth on exposure to CO_2. Parra et al. [21] reported that the lightweight concrete containing the polypropylene and cork waste aggregate showed increased carbonation depth. In another study, the incorporation of pulverized fly ash in normal-weight concrete showed better carbonation resistance than the LWC because of the pore refinement in concrete [65]. The increase in the water to binder ratio increased the carbonation depth of both normal weight and lightweight concrete [114].

The depth of carbonation in sand-dune lightweight concrete was found parallel with the normal weight concrete after12 months [115]. Zhao et al. [22] used the waste clay brick in the production of lightweight concrete. They reported that lightweight concrete carbonation resistance made with waste clay bricks as fine aggregate and coarse aggregate at different water to binder ratios satisfied the Chinese (JGJ 51) guidelines [116]. The test results of the carbonation section indicated that the carbonation depth of the LWAC increased with the exposure time (Figure 12). Thus, extensive investigations are required on the carbonation of the LWAC to find the effective dosages of supplementary cementitious material.

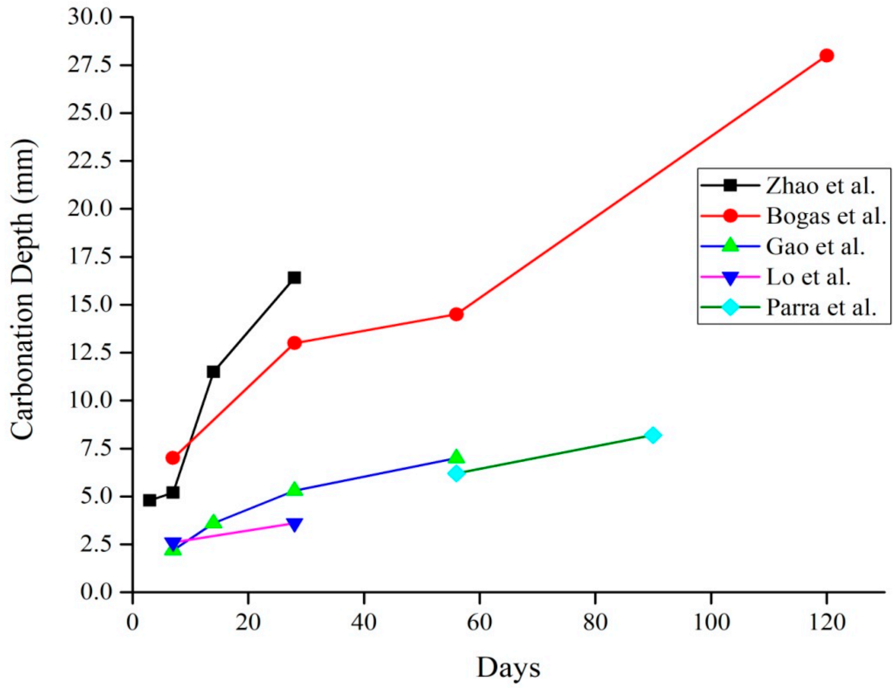

Figure 12. Carbonation depth of lightweight concrete [18,21,22,113,114].

4.6. Fire Resistance

During the lifetime of the reinforced concrete structure, the one of the most adverse condition related to the environment is fire, which results in a loss of stiffness and bearing capacity, caused mainly by the deterioration in the mechanical properties of concrete and steel bars subjected to high temperature.

Andic-Cakır and Hizal [101] examined the influence of elevated temperature on different self-consolidating lightweight aggregate pumice concrete properties. The test results showed that mass loss increased with the increase in temperature for all mixtures. A negative correlation (R: 0.8770) was observed in the concrete mixtures' compressive strength with relative mass loss values. (Figures 13 and 14).

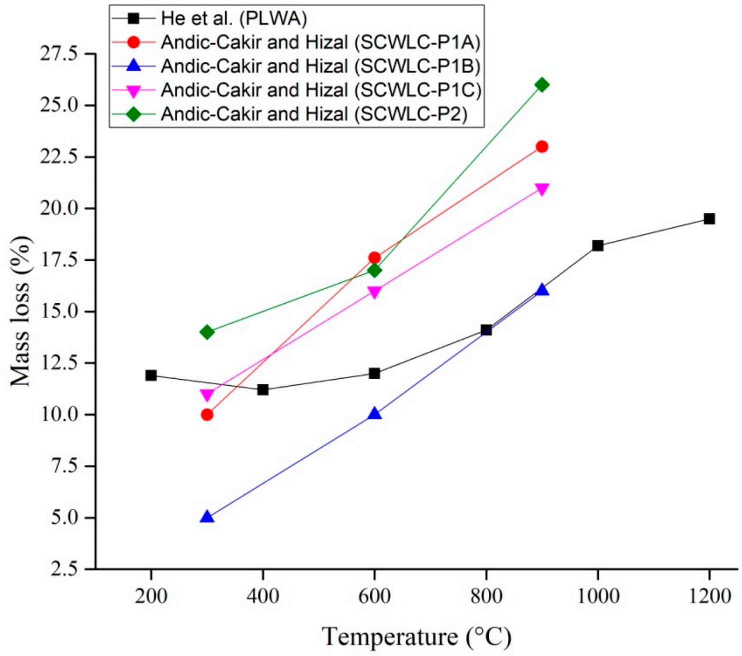

Figure 13. Weight loss in different mixes subjected to elevated temperatures [38,101].

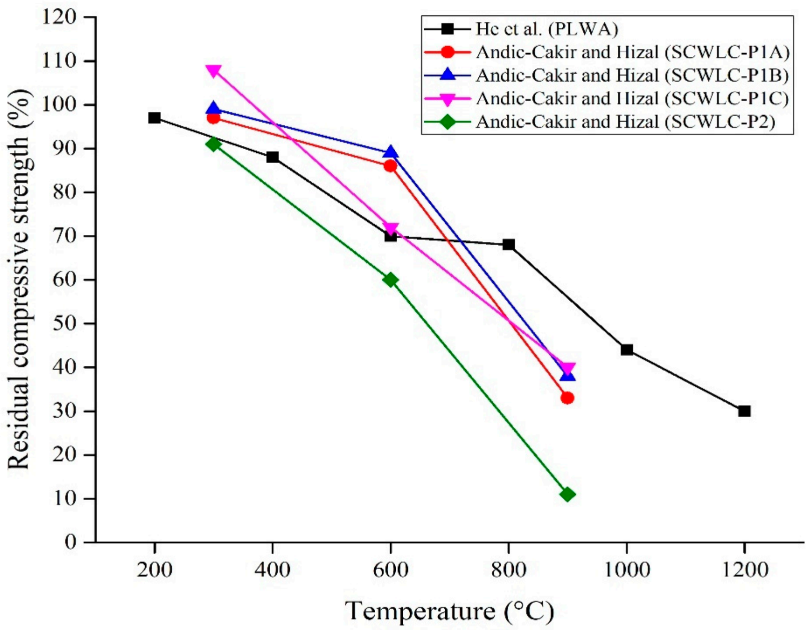

Figure 14. Compressive strength of different mixes subjected to elevated temperatures [38,101].

He et al. [38] carried out a study on the lightweight concrete subjected to the different elevated temperature. Four different type of aggregate were used to produce concrete, i.e., normal aggregate (NC), lightweight aggregate (LWAC), modified-I lightweight aggregate (PLWAC) and modified-II lightweight aggregate (GLWAC). They reported that the modified lightweight aggregate concrete (PLWAC) sample had superior mechanical properties and resistance of spalling compared to other concrete samples. Due to the modification of lightweight aggregate, the water absorption capacity of concrete reduced which resulted in lower spalling as compared to other aggregate concrete.

Tanyildizi and Coskun [117] carried out a study on lightweight pumice aggregate concrete performance with silica fume (SF) subjected to high temperature. In this study, they replaced cement with the silica fume at 5%, 10%, 20%, and 30%. They found that pumice LWAC with 20% of silica fume showed slightly better performance in compressive strength loss at 800 °C temperature exposure (Figure 15). The studies mentioned above along with Figures 13–15 clearly show that different elevated temperatures and the supplementary cementitious materials affect the fire resistance properties of LWAC.

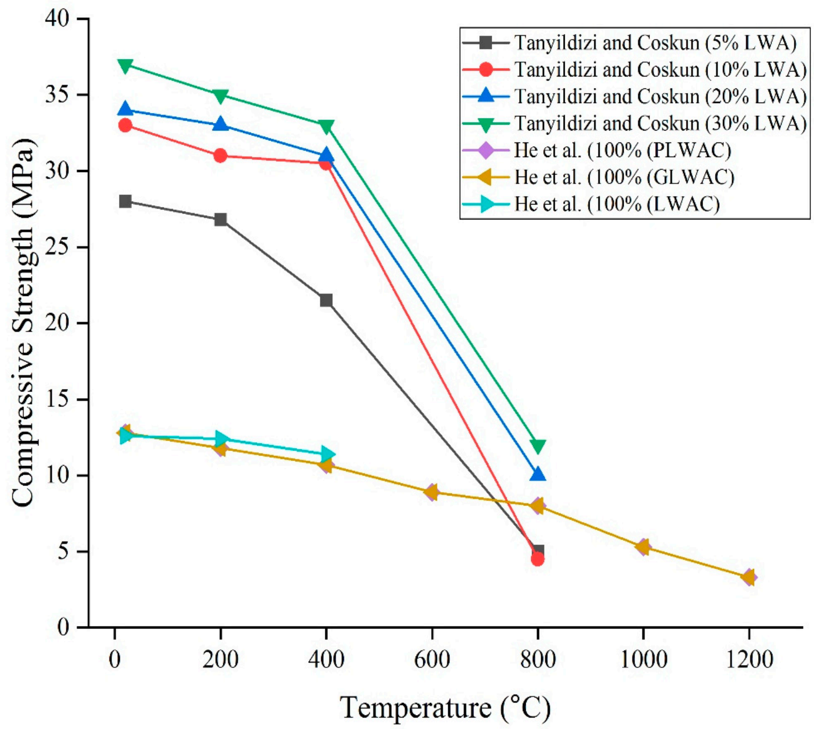

Figure 15. Compressive strength at high temperature [38,117].

4.7. Freeze-Thaw Resistance

The freeze-thaw resistance of concrete is a crucial durability property that occurs with the drop in temperature and freezing of pore water in concrete.

Mau and Ayuta [118] used fine perlite powder to make the lightweight aggregate in their study to evaluate the freeze-thaw effect of the concrete. The 100 × 100 × 400 mm prism specimens were used, and the impact of the lightweight aggregate in the concrete was found after the 300 freeze-thaw cycles. They showed that the mass and dynamic modulus of elasticity decreased after the 300 cycles of freeze-thaw. They reported that the mass and dynamic modulus of lightweight concrete elasticity decreased due to the formation of pores in the lightweight aggregate. The effect of the freeze-thaw cycles on the Aeolian lightweight aggregate concrete was investigated by Dong et al. [119]. They noticed that Aeolian sand promoted the freeze-thaw damage to the concrete.

Kan and Demirboga [120] studied the effect of the recycled waste expanded polystyrene foam as lightweight aggregate subject to the freeze-thaw. They replaced the natural aggregate at 25%, 50%, 75%, and 100% with expanded polystyrene foam lightweight aggregate. The compressive strength after the freeze-thaw cycle decreased to 67%. The higher frost resistance was noticed after the 300 freeze-thaw cycles which were attributed to the porous nature of light aggregate. Thus, with an increase in the content of the LWA and freeze-thaw cycles, the LWAC properties decrease.

4.8. Summary of Durability Properties

In terms of the different durability properties, various types of lightweight aggregate have a significant effect on lightweight aggregate concrete. The drying shrinkage of the various LWAC concrete increased with the inclusion of the LWA in concrete. The drying shrinkage of the different LWAC is mainly affected by the LWA properties and their quantity in the LWAC [72,103]. The water absorption of the lightweight concrete increased in most of the literature studies with the incorporation of the different LWA in concrete; this was due to the porous nature of the lightweight aggregate and high water absorption of the LWA [52,85,96]. In some cases, the lightweight concrete water absorption was found to be lowered than traditional concrete due to the lower water absorption of the LWA [72]. In general, the water permeability of the LWAC increased with the replacement levels of natural aggregate, this was due to the porous nature of LWA [107], and a decrease in the water penetration depth was noticed in limited LWAC because of the lower w/c ratio, pre-treatment, and improved bonding between the porous aggregate and cement paste [45,111].

The chloride penetration of the LWAC increased with the substitution of the natural aggregate due to the porous nature of the LWA. However, the reduction in the chloride penetration was observed in some literature studies, which was mainly attributed to the replacement of the LWA with the other less/non- porous LWA such as lytag and pumice [72]. The carbonation of the LWAC gets affected due to the natural aggregate's replacement, use of the admixture, and w/c ratio. Fire resistance performance of LWAC was found to be influenced by the increase in elevated temperature. However, the use of the supplementary cementitious material improved the fire resistance of LWAC. Freeze-thaw resistance of the LWAC was found to be lower for the different LWA than the normal aggregate due to the porous nature of the lightweight aggregate and the number of cycles of freeze-thaw.

In general, the durability of LWAC (drying shrinkage, water absorption, water permeability, chloride penetration, carbonation, fire, and free-thaw resistance) showed a negative effect. Generally, the alteration in the LWAC internal structure with the LWA and the physical properties (porous nature) of the LWA negatively influenced the durability.

5. Environmental Life Cycle Assessment

Napolano et al. [121] carried out a life cycle assessment (LCA) on the lightweight concrete containing recycled aggregate. Four different lightweight aggregates were used. Three types of lightweight aggregate were made from the waste and one from the raw clay material. LCA of the lightweight recycled waste concrete mixture showed a lower environmental impact than the natural lightweight aggregate concrete. The environmental impact of the natural light aggregate concrete was found higher in all impact and damage categories.

Ersan et al. [122] studied the effect of recycled plastic waste and fly ash on the LCA of lightweight concrete. The comparative analysis between the natural lightweight aggregate concrete and green lightweight aggregate concrete was carried out. The green lightweight concrete contained 20% fly ash as a cement replacement and 30% plastic waste aggregate as a natural lightweight aggregate replacement. They observed a decrease in the LCA of the green lightweight concrete than the natural lightweight aggregate concrete.

6. General Application of Lightweight Concrete

The use of LWC blocks has been a part of construction activities for quite a few decades. Today, the development of new different types of LWA makes it possible to use LWC in structural work where a reduction in the density of concrete is needed to consider design and economy. Bicer and Kar et al. [6] reported that the light weight expanded polystyrene concrete can be used for producing partition wall in the building, insulation material, flooring, and ceiling. Jo et al. [13] stated that the alkali-activated fly ash lightweight aggregate (AFLA) concrete could be used for the earth retaining structure, low strength concrete filling material, and paving material. The lightweight concrete can also be used for the construction of the bridge deck pavement and building blocks [13]. Oreshkin et al. [16] used lightweight concrete in the production of the lintel of the windows and cottage construction. Long-span bridges and floating structures were also made using lightweight aggregate concrete in the past [17]. Various studies reported that the lightweight concrete can also be implemented to produce lightweight structural concrete, thermal insulation, and masonry blocks road pavement, sidewalks, crash barrier, kerbs, and concrete drain [19,24,41,65]. The various application of LWC is shown in Figure 16.

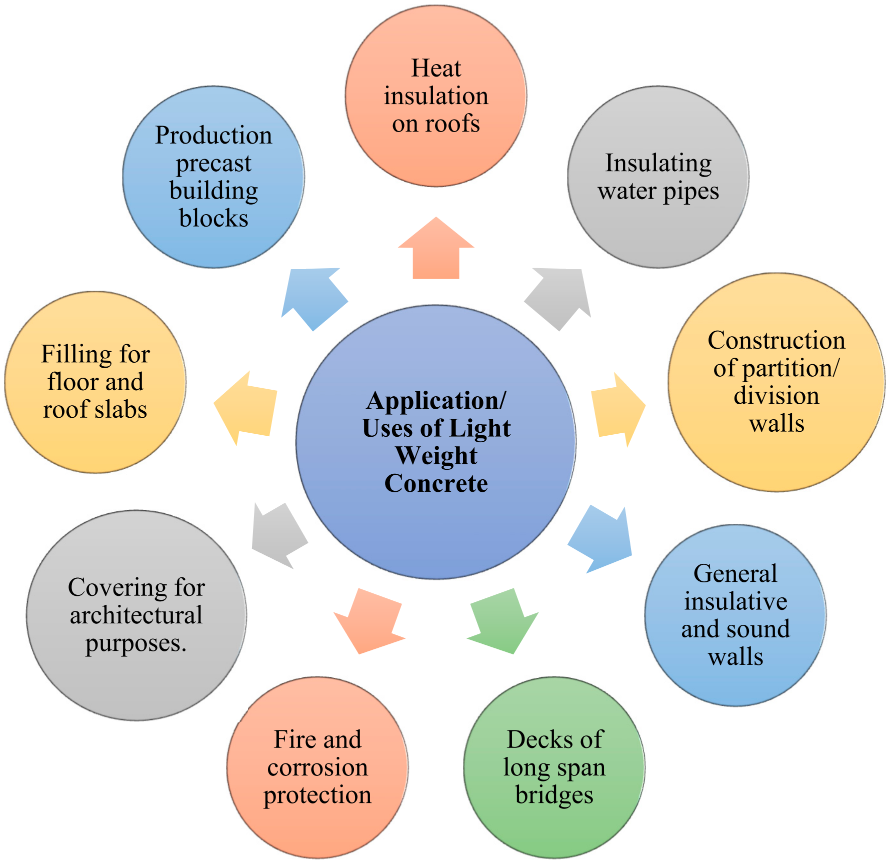

Figure 16. Application of lightweight concrete.

7. Concluding Remarks

Today, to ensure the survival of the construction sector, sustainability is a factor that must be considered in construction activities. In the past, various studies were conducted on the different types of LWA in lightweight concrete. However, lightweight aggregate had some adverse effects on the different properties of lightweight concrete. In this study, the effect of incorporation of various lightweight aggregate on concrete properties like fresh, mechanical, and durability are presented. The attempt has been made to review a different type of lightweight aggregate and its influence on the lightweight aggregate concrete (LWAC) in a normal and special type of concrete. Factors such as porous nature, soft particles, and high water absorption properties of most of the lightweight aggregate influenced the lightweight aggregate concrete properties. Therefore, it is challenging to use different types of LWA in the production of LWAC. It has been suggested to carry out a pre-treatment before using light aggregate in LWAC production.

The following conclusion can be drawn based on the findings of the literature review:

- Based on the various research article results subjected to varied aggregates in use of LWAC, it can be concluded that the utilization of different aggregate or waste demonstrates incredible results in terms of sustainable lightweight aggregate concrete production. The density of the normal concrete will be reduced with the use of the different lightweight aggregate. The addition of the lightweight aggregate in normal concrete significantly reduces the dead load of the structure.

- The fresh properties of the lightweight concrete showed that the inclusion of the different lightweight aggregate appears to be reduced, but it may also be seen that the fresh properties of the lightweight concrete can be improved by using the different admixtures and pre-treatment on the various lightweight aggregate.
- According to the study, it can also be concluded that the use of a different type of lightweight aggregate and waste material in LWAC decreases the mechanical properties of concrete. With the inclusion of supplementary cementitious material and modification/pre-treatment of lightweight aggregate, the mechanical properties can be improved.
- The incorporation of the different lightweight aggregate in the lightweight concrete generally decreased the concrete's durability properties.
- The use of lightweight aggregate in structural concrete will help in productivity and in improving the initial and long-term performance of concrete and service life of the structure with environmental sustainability.
- Finally, the use of different waste materials in lightweight concrete production will lower the lightweight aggregate concrete cost.

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