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# INFRA-LIGHTWEIGHT CONCRETE: A COMPREHENSIVE REVIEW OF STRUCTURAL AND THERMAL PERFORMANCE WITH SUSTAINABLE AGGREGATES

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***Abstract***
With the increasing concern on the issue of climate change and the increasing energy consumption within the built environment, there is the increasing need to come up with building materials that not only meet the structural requirement but also the thermal performance of the built environment. The conventional concrete, though effective structurally, has a poor thermal conductivity and thus, it consumes a lot of energy and gives discomfort especially where the ambient temperatures are very hot. Infra-lightweight concrete (ILC) is a fledgling trend in the field of sustainable building, with decreased density and better thermal insulation capacity and still possess adequate mechanical strength to be utilized as a structural material. In this review, the recent advances in ILC are thoroughly discussed with a focus on the utilization of sustainable and waste-based aggregates including palm kernel shells (PKS) and expanded polystyrene (EPS). The paper will analyze the two performance parameters of ILC involving thermal conductivity and compressive strength and the effects of their determination by the type of aggregate used, binder content, and mix design. As has been shown by previous studies, the incorporation of lightweight materials tends to decrease the strength, but with proper mix optimization, it is possible to obtain concrete with a fair structural performance and improved insulation capacity. Specifically, PKS and EPS which are agricultural and industrial by-products have potential promising low-cost and greener alternatives to traditional aggregates. Concrete incorporating PKS have demonstrated thermal conductivity values as low as 0.19 W/mK and 6MPa to 26 MPa compressive strength depending on the particle size and replacement level while concrete incorporating EPS have achieved densities as low as 300 kg/m³, thermal conductivity as low as 0.12-0.6 W/mK, and compressive strengths of 10MPa to 36 MPa at optimum replacement levels. The possible potential of ILC in fulfilling the structural requirements and energy-efficiency in contemporary buildings, particularly in hot climates, are also presented in this review. The gaps in the current studies are outlined, such as long-term durability research, optimization of mix design to use it in large amounts, and the usage of ILC in whole building energy modeling. It will be concluded that the paper has highlighted the future research directions in respect to the larger implementation of ILC as a multipurpose building substance in the environmentally friendly constructions.

**Keywords:** *Infra-lightweight concrete, thermal insulation, sustainable aggregates, palm kernel shells, expanded polystyrene.*

## Introduction

Concrete is a construction material with high usage that is made up of aggregate, cement, water, and other additives. The most common type, which is normal weight concrete (NWC), has a density of between 2240 and 2450 kg/m³ (Neville *et al.,* 2012). This dense structure can result in a high dead loading on structures which requires greater foundation size and reinforcements leading to higher costs of construction (Mehta and Monteiro, 2014). Also, NWC has a relatively high thermal conductivity with a range of 1.4 to 3.3 W/m.k that makes it easy to transfer a lot of heat via the building envelopes (Mehta and Monteiro, 2014; Zhao *et al.,* 2020). Such heat conduction in hot or cold climates increases energy requirements in indoor temperature regulation, which has proven to be a problem in energy-saving and sustainable design (Mehta and Monteiro, 2014; Al-Salloum *et al.,* 2015). These disadvantages have increased the desire to seek other alternative concretes which can be less self-weight, and enhance thermal performance.

Among the such options is lightweight concrete that has different types having lower densities than NWC (Hedjazi, 2019). The decrease in the density may be obtained by means of lightweight aggregate (LWA), foamed concrete (FC), autoclaved aerated concrete (AAC), or density-saving methods (Tay *et al.,* 2022). Overall, lightweight concrete has a weight of between 500 and 2000 kg/m³ (Hedjazi, 2019; Danso and Appiah-Agyei, 2021; ACI, 2003). A higher level of infra-lightweight concrete (ILC) is characterized by the fact that the dry density of the concrete is below 800 kg/m³ (Elshahawi *et al.,* 2021; Falliano *et al.,* 2019). There are usually two types of lightweight concrete which include structural and non-structural. Lightweight aggregate concrete (LWAC) may be applicable with regard to structural purposes, as per the American Concrete Institute (ACI, 2003). To be termed as structural lightweight concrete (SLWC), the concrete should be characterized by a highest possible density of 1840 kg/m³ and a lowest possible compressive strength at 28 days of 17Mpa (Hedjazi, 2019; Danso and Appiah-Agyei, 2021) as indicated in Table 1. Those concretes that fall short of this strength requirement or are mainly used as an insulator type are considered as non-structural lightweight concrete (NSLWC) (Tay *et al.,* 2022). The benefits of the LWAC are better thermal insulation, better fire resistance and less dead loads and it creates cost saving in transportation, labor, and formwork, especially in precast construction. The decreased density however changes important properties. LWC also has weaker tensile strength, ultimate strain, and shear strength and higher creep and shrinkage as compared to NWC of the same compressive strength. LWC is neither as rigid as NWC but can provide thinner structural members because of less dead loads, which partly counter the lower modulus of elasticity.

There are many natural and inorganic lightweight aggregates that can be used in LWAC, such as volcanic pumice, expanded glass (e.g., Poraver), expanded clay (e.g., LECA), and Lytag (fly ash-based aggregates). The nature, structure and the physical properties of these aggregates have a great effect on the thermal and mechanical properties of the concrete (Tay *et al.,* 2022). Especially, density and internal voids of concrete matrix are key considerations of thermal conductivity. Thermal conductivity may change by as much as 25 at the same density due to changes in mineralogy of the aggregate.

The structural and thermal performance of ILC are studied in this review with the focus on the application of environmentally friendly and easily accessible materials (e.g., palm kernel shell, PKS, and expanded polystyrene, EPS). It presents prior studies, discusses thermal and mechanical performance of LWAC using these materials, and suggests gaps in knowledge that can be used to conduct a further study.

## Structural and nonstructural lightweight concrete

Lightweight aggregate concrete (LWAC) is an acknowledged material used in the structural applications according to the American Concrete Institute (ACI, 2003). A concrete that is considered a structural lightweight concrete (SLWC) must be able to reach a compressive strength of 17 MPa over the course of 28 days and must have a density up to 1840 kg/m³ (Hedjazi, 2019; Danso and Appiah-Agyei, 2021). Concretes that fail to meet this strength condition are typically classified to be non-structural lightweight concrete (NSLWC). These concretes usually have more air voids in the cement matrix and lower densities and are therefore applied in cases where lower weight and insulation is required. Compressive strength lower than 17 Mpa Lightweight concrete is thus classified as NSLWC (Tay *et al.,* 2022) as shown in Table 1. Using LWAC has a number of benefits such as increasing fire resistance, thermal performance and reducing structural dead load by a significant level. Reduced self-weight is also able to cut down costs of transportation, formwork, labor and handling, especially in precast concrete construction. The mechanical properties of concrete vary with the decrease in the density of the concrete. In the case where LWAC and normal weight concrete (NWC) are selected to have comparable compressive strengths, LWAC tends to have lower tensile strength, shear capacity and ultimate stress. It is also more prone to creep and shrinkage and reduced stiffness. However, smaller depths of beam or slabs are possible due to the reduction in dead load. Even though it is true that LWAC has a lesser modulus of elasticity compared to similar NWC, the self-weight of the latter usually balances the difference when comparing the deflection of structure.

Table 1: Comparison of SLWC, NSLWC, and ILC

| **Property** | **Structural Lightweight Concrete (SLWC)** | **Non-Structural Lightweight Concrete (NSLWC)** | **Infra-Lightweight Concrete (ILC)** | **Reference** |
|---|---|---|---|---|
| Primary Application | Load-bearing structural elements such as beams, slabs, and columns | Non-load-bearing elements: insulation panels, partition walls, screeds | Load-bearing exterior walls with integrated thermal insulation | Hedjazi, 2019, Tay *et al.,* 2022, Elshahawi *et al.,* 2021, Falliano *et al.,* 2019 |
| Target Dry Density (kg/m³) | ≤ 1840 | Typically, < 1600 | ≤ 800 | Hedjazi, 2019, Tay *et al.,* 2022, Elshahawi *et al.,* 2021 |
| Target 28-day Compressive Strength (MPa) | ≥ 17 | < 17 | 6–12 (may vary based on mix design) | Hedjazi, 2019, Tay *et al.,* 2022, Elshahawi *et al.,* 2021, Alengaram *et al.,* 2013, Yu *et al.,* 2015 |
| Thermal Conductivity (W/m·K) | 0.3 – 1.0 (depending on aggregate type and porosity) | 0.2 – 0.5 | 0.12 – 0.25 | Daza-Badilla *et al.,* 2024, Real *et al.,* 2016, Alengaram *et al.,* 2013, Yu *et al.,* 2015 |
| Typical Aggregates (additives) Used | Expanded clay, shale, pumice, sintered fly ash (Lytag), expanded glass | Perlite, vermiculite, EPS, rubber particles, waste plastics | Waste-derived aggregates such as PKS, EPS, recycled glass, wood shavings | Tay *et al.,* 2022, Alengaram *et al.,* 2013, Jayanth and Sowmya, 2018, Yu *et al.,* 2015 |
| Fire Resistance | High | High | High | Tay *et al.,* 2022, Elshahawi *et al.,* 2021 |
| Thermal Insulation Benefit | Moderate | High | Very high | Tay *et al.,* 2022, Elshahawi *et al.,* 2021, Alengaram *et al.,* 2013, Yu *et al.,* 2015 |
| Preferred Climate Use | Temperate and seismic zones (weight reduction critical) | All climates where insulation is more important than strength | Tropical and hot climates where both structure and thermal efficiency are required | Tay *et al.,* 2022, Elshahawi *et al.,* 2021, Falliano *et al.,* 2019 |

### Lightweight aggregate concrete (LWAC)

Lightweight aggregate concrete (LWAC) is a concrete which has found a wide range of applications and thus has received a lot of research. There are numerous uses for LWAC in construction, including long span bridges, high rises, buildings with weak foundations, and highly specialized uses like floating and offshore constructions. Lightweight concrete density and the occurrence of voids in the matrix are the main factors that govern the thermal conductivity of lightweight concrete (Tay *et al.,* 2022). Under similar density conditions, however, the thermal conductivity of LWC can be affected by the mineralogical properties of the aggregate material by up to 25%.

LWAC may be created with a broad spectrum of lightweight aggregates (LWA) which may consist of natural materials like volcanic pumice and processed materials like expanded shale, clay and glass. Examples are LECA, which is based on expanded clay, and Poraver, which is based on expanded glass aggregates. Lytag aggregates, which are made out of fly ash among other industrial by-products, are also in use. The ensuing qualities of lightweight concrete will mostly be dependent on the form of aggregate chosen and its mechanical properties in the mix (Tay *et al.,* 2022).

### Type of Thermally-insulated Concrete Materials

The performance of insulation systems in buildings requires the use of thermal insulation materials. When it comes to building science, there are a number of variables concerning the building envelope, which affect the thermal performance. They are the size of the building, the materials that were utilized, the nature of the insulation system, the ratio between the window and the wall, the building orientation, and the nature and the number of glazing layers. Of these components, walls and roofs are more often exposed to heat transfer as compared to other building envelope components. It has been indicated that building energy performance is very dependent on the configuration and material make-up of wall systems (Silva and Ssekulima, 2011). Traditionally, thermal insulation systems are formed by adding insulating layers to provide a high level of energy efficiency and indoor thermal comfort. Lightweight concrete has thermal conductivity values of a range between 0.2 and 1.9 W/mK, and conventional concrete has a range of 0.6 to 3.3 W/mK (Daza-Badilla *et al.,* 2024; Real *et al.,* 2016; Yun *et al.,* 2013; Newman and Owens, 2003). The main job of the insulation materials is to minimize the heat transfer; they limit the conduction, convection, and radiations processes.

**Palm kernel shell**

Plate 1 illustrates that Palm kernel shell (PKS) is a by-product that is produced when oil palm trees are being extracted. Oil palm (Elaeis guineensis) has a number of similarities with coconut palms because they are in the same genus and are normally found in Africa (Pantzaris and Ahmad, 2001). They are also prevalent in America, Asia and Africa with grand bases in Nigeria (Olanipekun *et al.,* 2006). The thermal conductivity of PKS is low, 0.19 W/m 2 K, which is very lower than 1.4 W/m 2 K in stone aggregates (Alengaram *et al.,* 2013). Hence, it is possible to use lightweight concrete (LWC) with PKS to provide an enhanced insulation barrier and reduce energy use, which would facilitate a healthier environment. Density of PKS with compaction and particle size is 500-600 kg/m³ (loose) and 600 740 kg/m³ (compacted) (Alengaram *et al.,* 2013). Since PKS is lightweight, concrete that is made using it usually weighs between 1600 and 1900 kg/m³ (Alengaram *et al.,* 2013).

The impact of the replacement of coarse aggregate by PKS as a partial replacement was studied by (Azunna, 2019). In order to create lightweight concrete, PKS was recommended as a partial substitution for coarse aggregate based on the results obtained. For possible applications in construction, a replacement percentage of no more than 25% is recommended. It was also discovered that as the percentage of PKS increases from 25%, the compressive strength decreased significantly.


Plate 1: PKS as a waste material in oil palm factory (Gapki, 2022)

In their study, Fanijo and Arowojolu, (2020) examined the behaviour of laterised concrete in which the coarse aggregate was substituted by PKS. They noted that the more the PKS the better the workability of the concrete. The increase in the PKS content however resulted in a decrease in mechanical properties of the concrete. The researchers came up with the conclusion that concrete with as much as 20 percent PKS and laterite have the potential of being a feasible substitute to conventional concrete in general construction. At this dose level, it is possible to produce concrete at a low cost using these two locally sourced components while minimizing the adverse effects of these waste products.

A study by Ogunwemimo *et al.* (2019) aimed at determining the prospects of palm kernel shells (PKS) as a partial replacement of coarse aggregates in concrete. They substituted the coarse aggregate with PKS in different proportions, 0, 5, 10, 15 and 20 percent. The obtained results demonstrated that when coarse aggregate was partially substituted by PKS (5 percent) the compressive strength was maximum among all the obtained values of compressive strength, as compared to the control. On the basis of this finding, they determined 5 percent replacement by weight as the best percentage content of PKS to be used in the concrete. Also, it was found that the overall cost of concrete production with the use of PKS decreased as compared to the situation when crushed granite was used.

Khankhaje *et al.* (2016) also examined the properties of lightweight concrete that is sustainable and uses palm kernel shell (PKS) instead of coarse aggregate. In their research, they found that as the percentage content of the smaller-sized PKS was raised to 75% it was observed that the compressive strength dropped to 6 Mpa, 28 days into the curing process. The maximum compressive strength occurred at the 25 percent replacement level with small sized PKS. It was also reported that the size of the particles of PKS was a key factor in defining the granular structure of the concrete thus shown to affect compressive and tensile strength. PKS size of 4.75-6.30 mm was discovered to provide a balanced mix composition. This reduced size enabled the PKS particles to fill in voids, and this decreased the porosity. Conversely, bigger particles (6.30- 9.50 mm) interfered with the uniformity of the granular structure, which caused the drop in mechanical strength.

The study conducted by Danso and Appiah-Agyei, (2021) investigated the impact of palm kernel shell (PKS) size change on the use of such a material as a substitute of coarse aggregate in the production of lightweight concrete. In the experiment, the authors aimed at assessing the applications of concrete prepared using various PKS sizes of 6 mm, 8 mm, 10 mm, 12 mm, and a combination of mixed size. Such properties as density, compressive strength, flexural strength, and microstructural characteristics (through SEM analysis) were explored. The findings revealed that the densities of all the concrete samples were less than 2000 kg/m³, which means that they have conformed to the structural lightweight concrete requirements, as reported by Hedjazi, (2019). Of the samples, the concrete that used 12 mm PKS showed the best compressive strength after 28 days with a value of 10.2 MPa which is 4 percent to 15.9 percent higher than the compressive strength of the concrete that had been made using other sizes of PKS. Similarly, it had higher flexural strength at the same curing age; it had a flexural strength of 2.85Mpa that was improved by between 3.2 to 57.07 percent as compared to other size categories at the same age. The SEM analysis also proved that the bond between the PKS and the mortar around it is a strong interfacial bond. The application of lightweight concrete in structural use is recommended to be performed using 12 mm PKS based on these findings.

Indeed, Ifeanyi *et al*. (2023) examined the structural performance of concrete with palm kernel shell (PKS) as a partial substitution of coarse aggregate. Compressive strength was to be assessed using a total of 48 cubes of concrete each weighing 150 mm x 150mm x 150 mm with a mix ratio of 1:1.5:3 (cement: sand: aggregate). PKS replaced the coarse aggregate at the replacement levels of 0, 10, 20 and 30 percent. All specimens of concrete cubes were cured in 7, 14, 21, 28 days and then tested. The purpose of this investigation was to determine the possibility of the decrease of the weight of concrete without diminishing its structural properties. Upon results of comparing the test outcome with the control samples, it was revealed that a 10 percent replacement of the PKS provided a favourable balance that led to weight reduction without compromising on satisfactory compressive strength.

**Expended polystyrene (EPS) beads**

Expanded Polystyrene (EPS) is a plastic-based compound that is made up of almost 98 percent of air and 2 percent of polystyrene (Kuhail, 2003). It is a light, fine and spherical particle as shown in Plate 2a. EPS is closed cell structured and therefore, is not water absorbing, has high thermal insulation, soundproofing, and impact resistance attributes. It is however non-biodegradable. One of the environmental issues that is caused by the packaging industry is EPS waste (Jayanth and Sowmya, 2018). In this regard, Babu *et al*. (2005) discussed the application of granulated EPS in place of traditional coarse aggregates in the production of concrete. This approach does not only offer a good means of EPS waste management, but also offers the production of the lightweight EPS concrete with desirable qualities. As stated in Igba *et al*. (2020) the polystyrene particles are of a homogeneous shape and size and the concrete that is obtained can have densities ranging between approximately 300 kg/m³ in no-fines mixes to more than 1000 kg/m³ in full compacted concrete.

Salih *et al*. (2023) carried out experimental research to establish the best substitution ratio of coarse gravel in concrete by expanded polystyrene (EPS) beads. Their results found out that compressive strength decreased by 0 to 91 percent of the control mix which was comprised of no EPS. On the basis of their analysis that took into account the balance between the reduction in concrete density and the equal reduction in compressive strength, they have reached a conclusion that a volumetric substitution of coarse aggregate at 22 percent of the total with EPS produced the most optimal performance within the confines of their study.

An experimental study on the properties of concrete was conducted by Kulkarni and Shete, (2022) by partially replacing coarse aggregate with the use of expanded polystyrene (EPS) beads. They observed that the higher the percentage of EPS beads, the higher the workability of fresh concrete. Regarding flexural strength, positive effect was observed till a replacement level of 5 percent beyond which flexural strength started to decrease particularly at 15 percent. Also, they indicated that the compressive strength increased to 33.93 N/mm² to 36.41 N/mm² with replacement of 5% EPS, but further addition of EPS content led to a decrease in compressive strength. On the basis of these results, the research found 5 percent EPS replacement as the best level in order to reach a balance between strength and workability.

An experimental investigation was made by (Jayanth and Sowmya, 2018) into the use of expanded polystyrene (EPS) beads as a partial substitute of coarse aggregate to make up lightweight concrete. They also carried out a number of tests in fresh and hardened concrete to determine physical and mechanical properties of concrete at 7, 14 and 28 days of curing. The findings indicated that the density of the concrete and compressive strength of the concrete was found to decrease with the percentage of EPS beads. Interestingly they also observed an improvement in compressive strength due to a low concentration ratio of EPS beads in the mix. Suggestions of their findings was that EPS could substitute up to 5% of coarse aggregate without a high degree of failure to the strength of concrete.

The study by Verma and Jain, (2020) examined the behaviour of partially replacing coarse aggregate with expanded polystyrene (EPS) beads in concrete. Their research found out that the higher the percentage of EPS the greater the workability of the concrete mix. Nevertheless, they found increased percentage of EPS beads resulted in decreases in compressive strength, split tensile strength and flexural strength. Nevertheless, their findings demonstrated that the use of coarse aggregate substitution with EPS at 2.5 percent and 5 percent did not affect the mechanical properties of M50 grade of concrete significantly. On the basis of the results, they found the replacement level of 2.5 to 5 percent provided a good solution in terms of weight reduction and mechanical performance due to lightweight concrete application.

The effect of expanded polystyrene (EPS) on the strength parameters of concrete was investigated by Patidar *et al.* (2019) as one of the partial replacements of coarse aggregates. The investigation established that workability of the concrete mixture improved with the addition of an increased percentage of polystyrene beads. Nevertheless, an increase in the content of EPS caused compressive strength to decrease.

Due to the use of EPS beads as a partial substitute of fine aggregates in concrete, Abd *et al.* (2016) conducted a study on this application. The more the EPS beads content in the concrete mixes, the less the density of concrete. They also noted that an increase in the level of EPS beads increases the workability of the concrete mix.

The study of Adeala and Soyeni, (2020) focused on the structural performance of concrete to which the expanded polystyrene (EPS) was added as an alternative to fine aggregate in part. The outcome found out that the maximum percentage of replacement in regard to compressive strength is 5%. The experiment has also showed that the maximum flexural strength of the concrete was obtained when 10 percent of the fine aggregates had been substituted with EPS beads.

A study conducted by Gambo (2023) involved experimental research on substituting fine aggregate in concrete with EPS beads. Their findings indicated that replacement percentage of 1.5 resulted in increase in compressive strength and the strength started decreasing at 3% replacement. The maximum compressive strength at 28 days with 1.5% replacement of EPS was 31.2 N/mm². It was also found out that 1.5 replacement of EPS in concrete gives the highest flexural strength and greater replacement gives the strength a downward trend. At 28 days, flexural strength of 6.1 N/mm² was recorded using 1.5% EPS replacement. The research was able to come up with a conclusion of 1.5 percent as the best and optimal replacement percentage of EPS of fine aggregate to obtain an optimal compressive and flexural strength.

Igba *et al.* (2020) discussed the potential of utilizing expanded polystyrene (EPS) in part of fine aggregate in concrete as in Plate 2a. Also, the study found that the slump and compaction factor values declined with the increasing percentage of EPS replacement. The compressive strength of EPS containing 0.25% replacement of fine aggregate produced the optimum result. However, the strength of the concrete decreased at higher percentage replacement of EPS.

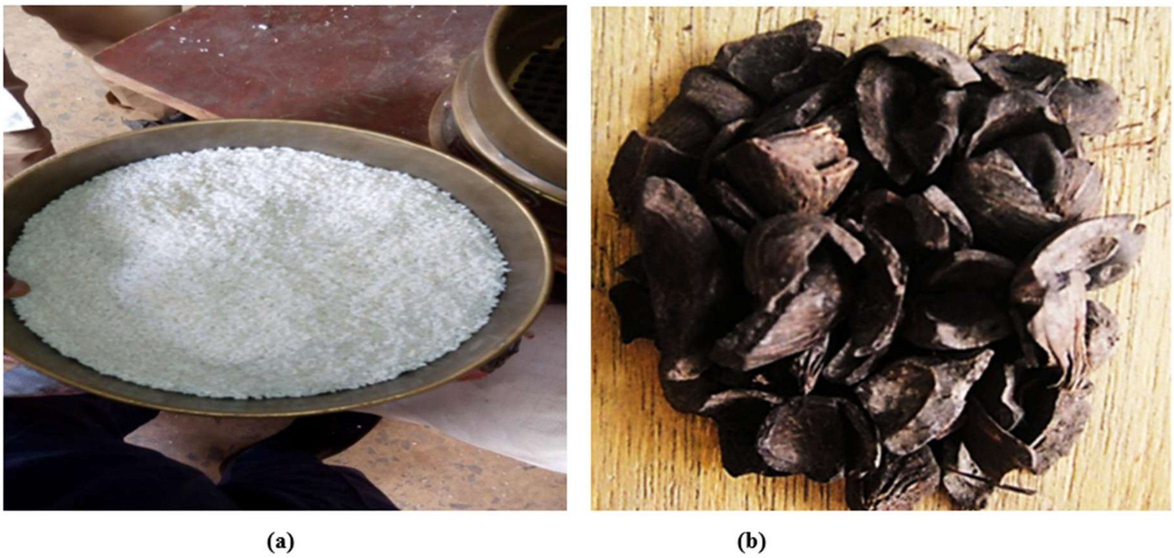

Plate 2: Concrete admixture (a) EPS beads (b) PKS (Igba *et al.,* 2020)

**Review of Existing Studies**

Lightweight aggregate concrete (LWAC) has its strength greatly affected by the physical and chemical properties of lightweight aggregates (LWA), especially because of the effects that take place at the interfacial transition zone (Wasserman and Bentur, 1996). In the LWA case, Alduaij *et al.* (1999) tested the lightweight concrete within hot coastal conditions and found that the compressive strength continued to increase with additions of cement from 350 kg/m³ to 350 kg/m³, but the total density of the concrete was approximately 1500 kg/m³.

Through the studies of thermal conductivity and compressive strength, Demirboga and Gül, (2003) underscored the impacts of the mineral admixtures in the expanded perlite aggregate concrete. Their results indicated that by substituting part of the cement with silica fume and fly ash they could not only decrease thermal conductivity by up to 15 percent but also decrease the concrete density and compressive strength by up to 30 percent.

Production of lightweight concrete blocks with diatomite as the aggregate was investigated by Unal *et al*. (2007), with the compressive strengths of 3.5-6.0 N/mm² at 28 days and densities of 950 to 1200 kg/m³. They also noted that as cement content increase by 250 to 400 kg/m³, the thermal conductivity also increased by 0.22 to 0.30 W/mK.

An experimental lightweight concrete obtained by Liu *et al*. (2010) with a cement content of 500 kg/m³, and a unit density of 1400 kg/m³ using expanded clay and expanded glass as aggregates yielded a high water and chloride-ion resistance and a compressive strength of 24 N/mm² after 28 days. Likewise, Wang and Tsai, (2006) experimented with dredged silt as a light weight aggregate, where the density of the particles was between 800 and 1500 kg/m³ and the binder contents were 364, 452, and 516 kg/m³. Their findings also showed compressive strengths of 18-42 N/mm² and thermal conductivities of 0.5-0.7 W/m K within 28 days. The research revealed that compressive strength is more heavily governed by the density of the aggregate when the contents of cement and water are kept the same with thermal conductivity being determined by a number of factors such as the nature and quantity of the lightweight aggregate, as well as binder mix.

A study was also carried out by Ling and Teo, (2011) on lightweight concrete bricks using expanded polystyrene (EPS), and rice husk ash (RHA) as lightweight aggregates. The analysis found that cement substitution with RHA at a percentage of 10 gave the best results and water curing was identified as the best way of curing.

As a study on the effect of the addition of zeolite to the nature of autoclaved concrete, Karakurt *et al.* (2010) used the aluminium powder as the pore-forming substance. Zeolite was used by replacing quartz aggregates in their study at a total dosage of 535 kg/m³. The best performances were found at 50 percent replacement and the compressive strength was 3.2 N/mm² and thermal conductivity value 0.19 W/mK.

Wongkeo *et al.* (2012) examined the behaviour of autoclave concrete in which bottom ash was used as a partial replacement of cement with the pore-forming agent being aluminium powder. Compressive strength at 1400 kg/m³ bulk density rose to 11.6 N/mm² at bottom ash replacement of 30 percent compared to 9 N/mm² at bottom ash replacement of 0 percent. Yet, in this increase in strength there was a minor increase in thermal conductivity of 0.5 to 0.61 W/mK.

Deo and Pofale, (2015) Experimented on the partial substitution of sand to fly ash to strengthen the packing of the particles and internal curing of concrete. Their results showed that the compressive and flexural strengths of the modified concrete in the absence of a superplasticizer were about 15 percent greater than the control mix. The strength gains were further enhanced when a superplasticizer was added up to a maximum of 28 percent compared to the control.

Akcazglu *et al.* (2013) researched on lightweight concrete which used waste PET as the lightweight aggregate (LWA). The unit dry density of concrete that was produced during the research was between 1530 and 1930 kg/m³, the thermal conductivity of 0.4 to 0.6 W/mK, and the compressive strengths of 28 days was 9.5 to 25.3 N/mm². A lightweight model created in the course of the study showed good thermal insulation, the dry density reached 650-700 kg/m³, and the thermal conductivity was about 0.12 W/mK. It had an average mechanical performance, with compressive strengths of 28 days between 10 and 12 N/mm². Nevertheless, this mixture was very water permeable, which implied an improved level of durability (Yu *et al.,* 2015).

In a separate study, perlite aggregate was expanded and it was applied in concrete at different ratios of 20, 40, 60, 80, and 100 percent to substitute natural aggregates. Heat conductivity, compressive and flexural strength tests were conducted to test the six different concrete mixes. The mix of 100 percent expanded perlite reduced the heat conductivity (to 0.69 W/mK), which is 62 percent lower than conventional concrete but after 28 days of curing, it had still attained a high compressive strength of 42 MPa (Malek *et al.,* 2020).

A study was conducted by Marthong and Agrawal, (2012) on the effect of replacing Ordinary Portland Cement (OPC) of different grades by fly ash, as a partial replacement. Their study was conducted on the fly ash replacement level that was the key parameter, which was varied at levels of 10, 20, 30, and 40 percent. They considered durability, shrinkage and compressive strength. The findings revealed that fly ash-blended concrete was more durable with all the OPC grades and higher fly ash concentration to 40 percent enhanced the performance especially with higher grade cement mixes.

The use of fly ash as a partial replacement of sand in concrete mixtures was studied by Mujiburrakhman and Widodo, (2020). They evaluated the mechanical behaviour and cost efficiency of four sets of concrete specimens with different proportions of fly ash 0, 20, 35 and 50 percent. Water to binder ratios were calculated through the pozzolanic cementing efficiency method. Results indicated that the addition of fly ash ensured that the density was reduced as well as the overall cost of the concrete, without much reduction in the compressive strength. As a result, fly ash-enriched concrete was considered to have better mechanical properties with cost-saving advantages.

In another study, plain concrete and lightweight reinforced concrete (RC) that included natural fibre was tested using thermal conductivity in comparison with scanning electron microscopy (SEM) and microscopic examination to analyse fibre-concrete interfacial bonding. Results showed that increasing the proportion of natural fibers (such as basalt, jute, coconut, sugarcane, and sisal) led to enhanced thermal insulation but a reduction in compressive strength. Thermogravimetric analysis revealed that concrete reinforced with jute, sugarcane, and basalt fibers exhibited superior thermal stability up to 50 °C suitable for the climate in South Asian regions. In contrast, samples containing sisal and coconut fibers displayed slightly lower thermal stability. Nevertheless, at a 2.5% fiber content of coconut and jute, a balance was achieved with notable gains in both compressive strength and thermal performance (Muhammed *et al.,* 2020).

The paper Yu *et al.* (2015) examined the impact of substituting cement partially with secondary cementitious material, such as limestone powder and nano-silica. In this way, lightweight concrete with a dry density of about 650 700 kg/m³ was developed and insulated, which has a thermal conductivity of 0.12 W/mK and an average compressive strength of 10-12 Mpa after 28 days as summarized in Table 2.

A study by Yu *et al.* (2016) examined the effect of polypropylene fibers on the mechanical and thermal characteristics of insulated lightweight concrete (ILC). The experiment has indicated that ILC attained an average compressive strength of 15 Mpa. In an example of a mixture of dry density 745 kg/m³, the thermal conductivity of the mixture was 0.17 W/mK, which underscores that the nature of the aggregate, as well as the inclusion of a fiber, influences the mechanical and thermal properties of ILC, especially in mixtures with dry densities lower than 500 kg/m³.

Table 2: Previous Work Done with some of the Materials

| **Reference** | **Composition** | **Density of concrete kg/m³** | **Thermal conductivity W/ (m.K)** | **Compressive strength MPa** |
|---|---|---|---|---|
| Jamal *et al.* (2024) | Geopolymer concrete using pumice-derived sodium silicate solution, alkaline/precursor ratio 0.4, no OPC | 1746–1815 | 0.119–0.131 | 13 |
| Yang and Lee (2015) | OPC, silica fume, gypsum, superplasticizer, surfactant. | 491–694 | 0·118–0·199 | 2·4–6·9 |
| Yu *et al.* (2015) | OPC, limestone powder, nano-silica. | 650–700 | 0.12-1 | 10-12 |
| Akcaozoglu *et al.* (2013) | OPC, shredded waste PET granules (0 - 4 mm), blast furnace slag (50% replacement of cement) | 1530–1930 | 0.4–0.6 | 9.5–25.3 |
| Alengaram *et al.* (2013) | OPC, palm kernel shell (PKS) silica fume, 5% fly ash, | 1600–1900 | 0.19 | ~26 |
| Chen and Liu (2013) | OPC, silica fume, high alumina content cement, polypropylene fibres, superplasticizer, surfactant LWA. | 400–800 | 0.07-0.3 | 1·58–11 |
| Yang *et al.* (2013) | OPC, gypsum, quick lime, ground granulated slag, sodiumsulfate, water glass, aluminium powder. | 590–740 | 0.15 | 2·2–6·4 |
| Awang *et al.* (2012) | OPC, sand, fly ash, lime, polypropylene fibres, surfactant. | 600–1400 | 0.35-0.6 | 0·3–11·8 |
| Benazzouk *et al.* (2008) | OPC, rubber particles, surfactants. | 1150 | 0.47 | 10.50 |
| Demirdag and Gunduz (2008) | OPC, fine volcanic slag aggregate, coarse volcanic slag aggregate. | 1185-1472 | 0.43-0.64 | 0.49-6.8 |
| Wang and Tsai (2006) | OPC, dredged silt, variable binder contents | 800–1500 | 0.5–0.7 | 18–42 |

Bderina *et al.* (2007) explored how incorporating wood shavings influences the mechanical behavior and thermal conductivity of sand-based concrete. The study found that increasing the proportion of wood shavings enhanced the thermal insulation of the concrete by decreasing its heat conductivity. It was observed that dune sand concretes generally exhibited slightly higher thermal conductivity than river sand concretes at lower shaving content. However, this variation became less noticeable as the amount of wood shavings increased. Despite the improvement in thermal insulation, higher shaving content led to a decline in the mechanical strength of the concrete.

Thermal performance of a lightweight cement-based composite with rubber waste particles was studied by Benazzouk *et al.* (2008). The research was meant to determine the insulation capability of this material and it was revealed that the inclusion of rubber minimized thermal conductivity. In a mixture with 50 percent rubber particles, the properties were measured to have a thermal conductivity of 0.47 W/mK, compressive strength of 10.50 MPa and flexural strength of 3.25 Mpa. The use of this type of composite was suggested where there is need to minimize heat transfer and also where energy saving is required especially in low load bearing structures, as highlighted in Table 2.

Becchio *et al.* (2009) examined how incorporating wood aggregates affects both the thermal and mechanical behavior of concrete. Their findings indicated that although the inclusion of wood aggregates significantly enhanced the thermal insulation by reducing density, it also adversely affected the material's mechanical performance due to the lower overall compactness of the composite.

Yu *et al.* (2013) examined the production of lightweight cement-based composites that provide a balance between thermal insulation and structural performance. They used the recycles of glass as a lightweight aggregate (LWA). The material that was produced had low thermal conductivity (0.485 W/mK) because of the existence of closed pores in the lightweight aggregates and still had sufficient mechanical strength. This is a combination that renders the composite applicable as a monolithic material that can provide load bearing and insulating services. Also, the use of olive stone in another study was carried out to improve the thermal performance and decrease the ultimate density of mortar made of cement-lime.

Research on thermal and mechanical properties of lightweight geopolymer concrete prepared using pumice aggregate was carried out by Jamal *et al.* (2024). The concrete mixtures had varying dry density between 1746 and 1815 kg/m³, and the thermal conductivity of the mixtures was between 0.119 and 0.131 W/mK. In spite of such positive thermal characteristics, mechanical strength was relatively low, and its highest values were 13 Mpa in compressing, 2.2 Mpa in flexural, and 1.64 Mpa in tensile breakage. These findings suggest that concrete has some good insulation quality although it might not be applicable in structural loading purposes.

The report by Haba *et al.* (2013) indicated that the thermal conductance and density of cement-lime mortar reduced with the percentage content of olive stone. In particular, the addition of the olive stone to a dry weight of up to 70% caused a decrease in the thermal conductance by more than 76 percent and in the density of the material by, on average, 30 percent, which shows its prospects in terms of enhancing thermal insulation.

The thermal and hybrid characteristics of a new cement-sand-water composite with date palm fibers as a reinforcement, which is 15% of the mix weight, were investigated by (Haba *et al.,* 2017). This experiment compared performance of the material with regard to water vapour permeability, sorption isotherm, moisture diffusivity, and thermal conductivity. Findings showed that adding date palm fibers was used to improve the overall performance of the material by lowering the resistance to the water vapor and easing the movement of moisture. The thermal insulation property of the composite in the dry state was found to be strong and therefore it could be used in areas with extreme environmental conditions.

In Hussain and Sastry (2014), the mechanical performance of M40 and M50 grade concretes where cement was partially substituted with micro silica (5, 7.5, 10, 15%) and nano silica (1, 1.5, 2, 2.5%). The experiment was performed to measure compressive strength, split tensile strength, and flexural strength of modified concretes. They found that a 7.5 and 2 percent ratio of micro silica and nano silica gave maximum increase, the compressive, tensile, and flexural stress increased by 25.807, 25.766, and 18.067 percent, respectively, over the control mixes of both M40 and M50 concretes.

In a study by Nili *et al.* (2010), the concrete mixtures consisted of water-cement ratio of 0.45, which was partly substituted with micro silica and colloidal nano silica. Their experiment revealed that the compressive strength and electrical resistivity were significantly improved with the addition of 6% micro silica and 1.5% nano silica but the capillary absorption was decreased. These were the most intense effects of 7 and 28 days of the curing period. Out of the mixtures that have been tested, the blend of 6% micro silica and 1.5% nano silica gave the best compressive strength.

## Conclusion

Infra-lightweight concrete (ILC) will provide a sustainable and efficient alternative in present day construction, particularly in situations that require structural load-bearing and thermal insulations (Elshahawi *et al.,* 2021; Yu *et al.,* 2015). The review has shown that the use of waste materials like PKS and EPS in addition to reducing environmental footprint of concrete production (Danso and Appiah-Agyei; Alengaram *et al.,* 2013) results in improved thermal insulation properties of concrete (Alengaram *et al.,* 2013; Alcaozoglu *et al.,* 2013). Nonetheless, there is a significant concern in trade-offs between strength and insulation which needs to be optimized especially in structures (Tay *et al.,* 2022). It is very important in selection of proper type of aggregates, percentage of binder, and mix of concrete design in order to have desirable results (Liu *et al.,* 2010; Wang and Tsai, 2006). Although progress has been encouraging in numerous studies, a long-term performance assessment, field study of implementation, and incorporation of ILC in energy modeling frameworks is required (Falliano *et al.,* 2019; Demirdag *et al.,* 2016). The future studies need to narrow down on perfect mix compositions, hybrid systems, and the aspect of durability, to ensure that ILC can be widely adopted in building construction that is sustainable and resilient.

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