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A Review of Lightweight Concrete in Civil Engineering

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ABSTRACT

Lightweight concrete, defined as concrete with a dry density below 2000 kg/m³, has become increasingly prominent in modern advanced concrete technology and constructions due to its low density, superior thermal insulation, and sustainability benefits owing to the use of industrial by-products and waste materials in the process of its production. This study presents a comprehensive overview of lightweight concrete, covering its historical development, material composition, and performance characteristics. The fresh properties, such as workability, slump, and water absorption, are discussed alongside its mechanical properties, including compressive, flexural, and tensile strength; modulus of elasticity; ductility; and fatigue resistance. The durability characteristics, such as water and chemical permeability, freeze-thaw resistance, carbonation, shrinkage behavior, and reinforcement corrosion, are also evaluated. In addition, the microstructural characteristics, including density, porosity, and aggregate-cement matrix interfacial transition zone (ITZ), are examined using SEM, XRD, TGA, and FTIR analyses. The study also considers the environmental performance of lightweight concrete, assessed through life cycle assessment, including the impact of adding waste and recycled aggregates. Various types of natural and synthetic lightweight aggregates, along with mineral admixtures, nanomaterials, and reinforcing fibers, are reviewed to evaluate their impact on the performance of lightweight concrete. Although lightweight concrete typically exhibits lower mechanical strength than normal concrete, its compressive, tensile, and flexural strength, elastic modulus, ductility, and fatigue resistance can be improved under optimized conditions. As reported in various studies, the addition of pozzolanic and nano-admixtures, along with optimized fiber reinforcement, can enhance both the microstructure and overall durability of lightweight concrete. These improvements can be achieved through the integration of industrial by-products such as fly ash, slag, or agricultural waste.

Keywords: Lightweight concrete (LWC), Pozzolanic admixtures, Lightweight aggregate, Artificial aggregate, Mechanical properties, Durability properties, Fiber reinforcement.

INTRODUCTION

Concrete is a building material widely used in the construction industry (Sağlam et al., 2022). It is a versatile construction material composed of substances with a wide variety in terms of color, density, strength, and durability. Depending on the raw materials and production methods used, lightweight, normal, and heavyweight concrete types are classified based on their density and are utilized according to the requirements of various applications (Thienel et al., 2020). As with any material, concrete has advantages as well as disadvantages, and with technological advancements, it is possible to eliminate these disadvantages. Over time, as different requirements from concrete have emerged, many types of special concretes have been developed. One of these special types is Lightweight Concrete (LWC) (Chandra & Berntsson, 2002).

Lightweight concrete is a type of concrete with a dry density of less than 2000 kg/m³. It offers significant advantages such as a high strength-to-weight ratio, low density, fire resistance, thermal shock resistance, deformation performance, and environmentally friendly characteristics. Due to its superior thermal insulation compared to normal concrete, it is especially preferred in residential construction (Agrawal et al., 2021). In addition, it reduces the dead load of structural elements, allowing load-bearing components such as columns, beams, slabs, and foundations to be designed with smaller cross-sections. The reduction in dead load reduces the total load transferred to the foundations, thus reducing the stress transmitted to the ground and the load on the soil's bearing capacity (Sldozian et al., 2023). Due to its low density, it is used in the production of pre-cast elements such as floors, panels and blocks. It can also be used in combination with on-site additives in ready-mixed concrete applications. One of the most well-known vertical structures is the Marian Tower in Chicago, which serves as an example of a modern building constructed with lightweight concrete (High-Performance Lightweight Concrete, 2007). The methods used in the production of lightweight concrete can be classified into three groups: "No-fines concrete," which is produced by removing the fine aggregate fraction to create air voids; foamed (or aerated) concrete, which forms a porous structure containing approximately 30–50% voids by incorporating gas bubbles into the cement paste or mortar matrix; and lightweight aggregate concrete, which is produced by replacing normal aggregates with lightweight aggregates that contain a high percentage of internal voids (Newman & Choo, 2003). These methods reduce the density of concrete and allow lightweight concrete to be obtained.

In the production of lightweight aggregate concrete, the lightweight aggregates used are classified into two types: natural and artificial aggregates. Due to the high production cost of artificial lightweight aggregates, natural lightweight aggregates are generally preferred in the production of lightweight concrete (Amin et al., 2020). Natural light aggregates such as pumice, volcanic tuff, volcanic slag and bentonite are aggregates obtained by crushing volcanic rocks or sedimentary stones (Chandra & Berntsson, 2002). Artificial lightweight aggregates such as clay, shale, perlite, quartzite, obsidian, slate, and vermiculite are produced either by thermal expansion of natural stones or as by-products of industrial waste. By using lightweight aggregates such as pumice and volcanic slag, semi-structural lightweight concrete can be produced, while structural lightweight concrete can be produced using aggregates such as expanded clay, shale, and slate (Chandra & Berntsson, 2002). Aggregate, which constitutes the largest volume of the composition in the concrete mix, plays a decisive role in terms of concrete strength and workability (Doğan et al., 2022). The most important reason for the low strength in lightweight concretes may be the presence of porous aggregates. Despite the advantages of lightweight concrete, the use of lightweight aggregates leads to reduced mechanical properties and durability. These reductions result in lightweight concrete exhibiting a more brittle behavior, and significant decreases are observed in mechanical parameters such as compressive strength, tensile strength, and flexural strength (Lo et al., 2004). Therefore, different fibers, nano-materials, and pozzolanic admixtures are used to enhance the strength and durability of concrete. In this study, the effects of the material composition of lightweight concrete and the addition of various fiber types such as steel, carbon, basalt, and polypropylene (PP) either single or in hybrid forms, along with nano-materials and pozzolanic admixtures, on the fresh concrete properties (e.g., workability) as well as mechanical properties including compressive strength, tensile strength, flexural strength, and flexural stiffness, were comprehensively examined. Additionally, recent research and development approaches related to lightweight concrete were also evaluated.

MATERIAL COMPOSITION AND ADMIXTURES

A) Definition and historical development of lightweight concrete

In the production of cementitious materials, the hardness, density, water permeability and thermal resistance properties of the material are developed by using chemical additives (Doğan & Dehghanpour, 2021). Lightweight concrete is a special type of concrete with reduced density, produced using cement, water, aggregate and lightweight aggregate (natural or artificial). As with normal concrete, it can contain chemical and mineral admixtures (Chandra & Berntsson, 2002). Lightweight concrete, while holding a special place in modern advanced concrete technology, has been known since ancient times. The Sumerians produced materials similar to lightweight concrete by using volcanic-origin natural aggregates such as pumice in the construction of Babylon in the 3rd millennium BC. Ancient Greek and Roman civilizations widely used lightweight aggregates such as pumice stone to reduce the load of structures, and buildings such as Hagia Sophia (A.D 537), the Pantheon (A.D 118), and the Colosseum (A.D 70-82) were constructed using this type of concrete. The Romans reduced the weight of their structures by incorporating both natural lightweight aggregates and vases made of hollow clay in their concrete, known as “Opus Caementicium” (Chandra & Berntsson, 2002). Because natural and volcanic aggregates are few and inconsistent, the use of lightweight concrete was restricted following the fall of the Roman Empire. An important turning point in material technology occurred in the 19th and 20th centuries with the creation and manufacturing of lightweight aggregate that was produced industrially (Thienel et al., 2020). Artificial lightweight aggregate production began in Germany; In 1845, Ferdinand Nebel produced blocks using pumice and lime, and in 1880, a patent was obtained by Kukenthal for the production of porous clay particles (Chandra & Berntsson, 2002). In the modern sense, according to the TS EN 206-1 (TS EN 206-1, 2002) standard, lightweight concrete has a dry density between 800 and 2000 kg/m³ and thermal conductivity ranging from 0.1 to 3 W/mK, which helps reduce the structural load and provides thermal insulation. The type of aggregate is one of the fundamental factors determining both the density and strength of the concrete (Chandra & Berntsson, 2002). Today, lightweight concrete continues to be developed in line with goals of high performance, energy efficiency, and sustainability.

B) Mineral Admixtures

Pozzolanic materials strengthen the mortar matrix and improve the microstructure. Natural pozzolans (such as Santorini soil and Trass), used since Roman times, were employed to increase the strength and durability of concrete. Today, industrial by-products such as fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume (SF), and metakaolin (MK) are commonly used. SF and MK have high pozzolanic activity and are widely used in the production of high-strength lightweight concrete (Chandra & Berntsson, 2002). In addition, as with other pozzolanic materials, rice husk ash (RHA) and palm oil fuel ash (POFA), also considered as a by-product exhibit pozzolanic properties because it contains high silica. Using RHA and POFA has two benefits: it can reduce waste while also improving the performance of concrete (Hamada et al., 2021). On the other hand, Pumice powder is a lightweight volcanic origin, while volcanic ash is formed as a result of volcanic eruptions. Therefore, both materials can be easily found in countries with intense volcanic activity (Fode et al., 2023). These mineral admixtures have fine-structure and pozzolanic activity, thus improving the pore structure and significantly increasing the strength and durability of concrete. Especially, SF contains high content of silica and improves the strength of concrete by promoting the formation of calcium silicate hydrate (C-S-H) during hydration (Ahmad et al., 2022; Fode et al., 2023). The hydration process with the mineral admixtures is different compared to pure portland cement. Moreover, pozzolanic materials such as FA, GGBS, RHA and POFA can replace a high proportion of cement to provide more sustainable and eco-friendly concrete production (Hamada et al., 2021; Mo et al., 2017). According to previous researches, SF is the most effective admixture for improving the performance of lightweight concrete; however, when appropriate curing is provided, FA and GGBS can also be used for more economical or higher cement replacement ratios.

C) Nano Admixture

Nanomaterials such as nano-silica, nano-metakaolin, nano CaO_3, nano Al_2O_3, nano Fe_2O_3, nano ZnO_2, nano MgO and carbon nanotubes (CNTs) are among the most effective components that improve the flexural, compressive and shear strength and overall durability of the cementitious composite when mixed with cement. The most commonly used nanomaterial to improve concrete properties is nano silica (SiO_2) with 51%, followed by TiO_2 with 15% and Al_2O_3 with 6% (Al-Luhybi & Altalabani, 2021). The main objectives of adding nanomaterials into concrete are to enhance workability, increase mechanical strength, improve durability and provide new functions to concrete. These materials can significantly increase the compressive, tensile and flexural strength of concrete by strengthening the cementitious matrix. In addition, they improve the microstructure of concrete by increasing its density; this reduces permeability and increases resistance to carbonation, moisture intrusion and chemical attack (Zhang et al., 2021). Many researchers have demonstrated that the addition of nanoparticles results in a more homogeneous and denser microstructure in concrete (Kurapati, 2014). In addition to enhancing the functionality of concrete, the addition of nanoparticles can also offer environmental benefits. Encapsulated healing agents integrated into concrete through nanomaterials can improve the self-healing capacity of the material, extending maintenance and repair intervals, increasing the service life of structures, and contributing to environmental sustainability. Nevertheless, there are still some issues in integrating nanomaterials into concrete. Achieving homogeneous distribution of nanoparticles, optimizing dosage, ensuring compatibility with other concrete components and addressing potential health and environmental problems are important parameters should be taken into consideration (Zhang et al., 2021).

D) Fiber-Reinforced Admixtures

In order to improve the mechanical properties and durability of lightweight concrete, fiber additives are incorporated into the mix (Wu et al., 2019). Natural fibers include asbestos, cellulose and sisal; synthetic fibers include steel, carbon, polypropylene (PP) and basalt fiber. Steel fibers are the most commonly used fiber types due to their cost-effectiveness, ease of production, and their ability to enhance mechanical properties such as tensile strength, flexural strength, toughness, impact resistance, and crack resistance. However, due to their large diameters and high specific gravity, they reduce workability and increase the density of lightweight concrete (Liu et al., 2019). Additionally, the addition of fibers in the concrete mix can negatively impact the fresh properties of concrete, making the use of superplasticizers necessary.

It has been observed that the addition of steel, carbon, basalt and polypropylene fibers either single or in hybrid forms improves mechanical properties. These fibers enhance energy absorption capacity, increases resistance to cracking and improves post-crack behavior by bridging voids. In this way, crack expansion is prevented in the early stage of curing. Furthermore, it enhances modulus of elasticity, flexural stiffness, flexural strength, splitting tensile strength, and impact resistance of concrete (Trabelsi & Kammoun, 2020). As a result; many factors such as the type of fiber, the physical properties of the fiber, and the content of fiber added to the mix have a significant impact on enhancing or diminishing the properties of lightweight concrete (Zhao et al., 2018).

FRESH PROPERTIES OF LIGHTWEIGHT CONCRETE

In the process of lightweight concrete mix design, the properties of the lightweight aggregates used are taken into consideration. These aggregates such as Pumice, Perlite, Vermiculite and Leca are characterized by high water absorption capacity and low unit weight. The most critical of these properties is the water absorption rate of aggregates. Natural or artificial aggregates exhibit water absorption behavior with a decreasing rate over time compared to normal aggregates. The content and rate of water absorption of an aggregate depends on the pore characteristics of the aggregate, such as pore volume, pore distribution and pore structure. Lightweight aggregates generally absorb more water due to high porosity (Newman & Choo, 2003). This absorption affects the fresh properties of concrete such as workability, consistency, pumpability, and density as well as the hardened properties, including thermal insulation, fire resistance, and durability against freeze-thaw effects. The water absorption rates of aggregates are typically determined based on oven-dry weight, considering absorption after 30 minutes and after 24 hours. While the 24-hour water absorption rate generally ranges between 0.5–2% for natural aggregates, it can reach up to 5–15% for lightweight aggregates (TS EN 206-1, 2002). Therefore, pre-wetting or water absorption corrections must be implemented to account for this effect in the mix design of lightweight concrete (Zhu et al., 2017).

When evaluating the slump test, the workability values for lightweight concrete are typically suitable in the range of 50–90 mm or 100–150 mm slump class for cast-in-place structures. For precast elements, drier mixes are generally required, with slump values in the range of 10–40 mm. In cases where pumping is necessary, a higher slump class of 160–210 mm is usually preferred (TS EN 206-1, 2002). However, as this value increases, issues such as segregation of the mix and the coarse aggregates floating to the surface may occur (Hassanpour et al., 2012). Therefore, since the slump test alone is not fully adequate for lightweight aggregate concrete especially for self-compacting lightweight concrete, alternative workability test methods such as the V-funnel, L-box, and slump-flow tests should be used.

According to studies, different pozzolanic admixtures exhibit varying impacts. When fine admixtures such as SF and MK are used, a decrease in the workability of lightweight concrete has been observed, regardless of the replacement ratio. This is because these fine particles require more water to become saturated (Kim et al., 2012; Sancak et al., 2011). On the other hand, when additives such as FA and GGBS which have a fineness similar to cement are used as partial cement replacements, they can enhance workability up to a certain replacement ratio. However, when the replacement ratio exceeds the optimum level, workability decreases significantly. Shafigh et al. (2013), found that the use of GGBS above 30% significantly reduced the workability and increased the viscosity of lightweight concrete made with oil palm shell aggregate. The improvement in workability achieved with low cement replacement was more pronounced for FA than for GGBS, due to FA's spherical shape, which provides a "ball-bearing" effect that facilitates the flow of fresh concrete (Demirboğa et al., 2001). When additives such as RHA, POFA, volcanic ash and pumice powder are used, a reduction in workability has been observed, even at low replacement levels, due to the porous nature of these materials (Mo et al., 2017). Islam et al. (2015), reported that when POFA content exceeded 30%, the porous nature of POFA led to decreased workability, and the addition of a superplasticizer was necessary to eliminate agglomeration issues. Kurt et al. (2015), investigated the mechanical and physical properties of lightweight concrete using pumice as lightweight aggregates and GGBS. When the GGBS content was kept constant and the content of pumice aggregate was increased, they observed a decrease in unit weight, along with increases in both water absorption and compressive strength. Additionally, the addition of nanomaterials such as nano-silica or nano-alumina can affect its workability and rheological behavior (Zhang et al., 2021). In a study by Hong et al. (2023) the effect of nano-graphene oxide on the slump value of lightweight concrete was investigated. The slump value of concrete without nano-graphene oxide decreased from 95 mm initially to 50 mm over time. The addition of high dosage of nano-graphene oxide reduced workability by approximately 40% compared to the reference mix. Similarly, Xu et al. (2012), reported that the addition of nano-calcium carbonate (nano-$CaCO_3$) improved the workability of concrete. They reported that the addition of 2% nano-$CaCO_3$ increased the workability of concrete by 8.5%, which was attributed to the effective dispersion of the nanoparticles. While Sulaiman et al. (2019), reported that as the nano-silica dosage increases, the workability of lightweight concrete decreases, due to the higher water demand of the mix. Joanna et al. (2019), stated that the workability primarily depends on the content of lightweight aggregate, despite the addition of NS, micro-silica, and nano-CO_2, the highest slump value observed at 80% replacement of lightweight gravel. According to various studies, by optimizing the dosage and dispersion of nanomaterials, it is possible to enhance the flowability of the mix while reducing the segregation and bleeding tendencies.

Some researchers have observed that the addition of various fiber types such as steel, polypropylene (PP), carbon and basalt to lightweight concrete mixtures reduces workability and results in lower slump values compared to fiber-free samples (Liu et al., 2019; Omar & Hassan, 2019). This reduction is mainly attributed to fiber clumping and blockages within the lightweight concrete matrix (Amin et al., 2020). The extent of workability reduction depends on the type and dosage of the fibers used. Li et al. (2017) studied the effect of 0.5%, 1%, 1.5%, 2% and 2.5% steel fibers on workability of lightweight concrete containing Lytag. They showed that adding 0.5% and 2.5% steel fiber to lightweight concrete decrease the workability up to 14% and 56% respectively, compared to fiber-free concrete. Moreover, slump loss over time was more pronounced in concretes containing steel fibers. Similarly, Iqbal et al. (2015), emphasized that while fibers reduce concrete consistency, they enhance mechanical strength and shrinkage behavior in the long term. In fiber-reinforced concrete mixtures, superplasticizers are used to enhance workability and reduce fiber clumping (Hassanpour et al., 2012). Domagala et al. (2011), showed that even when the steel fiber content is low (<1%), a higher dosage of superplasticizer is necessary to ensure good workability and to prevent fiber blockage in the mix. However, a low water-to-cement (w/c) ratio is generally considered unfavorable, as it may lead to decreased workability and compromise the homogeneity of the concrete. Güneyisi et al. (2015), prepared lightweight concrete samples using fly ash aggregates with varying w/c ratios, and found that increasing the w/c ratio significantly improved the concrete's passing ability and filling capacity. Similarly, improvements in the workability of lightweight concrete have been reported by many researchers (Kurt et al., 2015; Lotfy et al., 2015).

MECHANICAL PROPERTIES OF LIGHTWEIGHT CONCRETE

A) Compressive, Flexural, and Tensile Strength

The following segment discusses the mechanical properties of lightweight concrete after a 28-day curing period. These mechanical properties include compressive strength, flexural strength and splitting tensile strength. While many types of lightweight aggregates are sufficient for producing lightweight concrete with a compressive strength of 35 MPa or higher, only a limited number of lightweight aggregates can be used to produce concrete with compressive strength in the range of 50–70 MPa. Lightweight concrete with a compressive strength of 20–35 MPa is commonly used in cast-in-place applications. While higher-strength lightweight concretes are used in precast bridges and offshore applications. The compressive strength of lightweight concrete can be affected by factors such as aggregate strength and stiffness, cement content, and the age of the concrete (Newman & Choo, 2003). The use of lightweight materials reduces the mechanical properties of lightweight concrete, such as compressive, flexural, and tensile strength, compared to normal concrete. Moreover, these properties decrease further as the proportion of lightweight materials increases (Nadh et al., 2021). Tedjditi et al. (2020), reported that concrete containing 25% virgin cork exhibited compressive and flexural strengths that were 73% and 42% lower, respectively, compared to the control concrete. As the virgin cork content increased, the reductions in these mechanical properties became more pronounced relative to control concrete (Tedjditi et al., 2020). Similarly, Jedidi et al. (2015), investigated the compressive strength of lightweight concrete at various ages by replacing sand with expanded perlite aggregate (EPA) and found that compressive strength decreases as the EPA content increases. Alqahtani et al. (2018), conducted an experimental study using synthetic aggregates to replace two types of coarse aggregates (Lytag and pumice). They observed a reduction in split tensile strength with both replacements.

Mineral admixtures are widely used to reduce the negative effects of lightweight materials on the mechanical properties of concrete. Among these admixtures, pozzolanic materials are particularly important for improving the strength and microstructure of concrete (As shown in Table 1). SF, stands out as one of the most effective additives due to its high fineness, which not only promotes a strong pozzolanic reaction but also provides a filling effect within the concrete. As a result, lightweight concrete containing SF exhibits higher compressive strength even at an early age compared to control concretes without SF. Kılıç et al. (2003), reported that lightweight concrete with 10% SF showed higher compressive strength at all ages from 3 days to 90 days compared to the control concrete without SF. Similar improvements were also observed in other mechanical properties. Youm et al. (2016), stated that the use of 0%, 3.5%, and 7.0% SF in lightweight concrete with slate and expanded clay aggregates increased compressive strength by 8–10% compared to control concrete. However, they noted no significant effect on splitting tensile strength or modulus of elasticity. When admixtures such as FA and GGBS are used in lightweight concrete, the early-age strengths are generally lower compared to control concrete; however, at later ages, such as after 28 days, the strength of these modified concretes can exceed that of the control mix due to the delayed hydration characteristic of these additives' materials. Kılıç et al. (2003), reported that the use of 20% C-class FA in lightweight concrete with slate and expanded clay aggregates caused a decrease in splitting tensile strength and flexural strength in the early ages up to 7 days, but an improvement was observed in later ages. Similarly, Subaşı (2009), found that adding 10% FA to lightweight concrete made with expanded clay increased the 28-day splitting tensile strength by 6–10%. In contrast, increasing the FA content to 20% and 30% resulted in a 20% decrease in strength compared to the control mix without FA. Concrete containing GGBS generally exhibits higher early-age strength compared to those containing FA, due to the self-cementing property of GGBS. Akçaoğlu and Atış (2011), reported that the compressive strength of PET lightweight concrete containing 50% GGBS was lower than that of the control concrete up to 7 days, but exceeded that of the control concrete on the 28th day. Chen and Liu (2008), observed that adding up to 40% GGBS to expanded clay lightweight concrete increased compressive strength at 7 and 28 days.

Researchers have observed a decrease in the mechanical properties of lightweight concrete when GGBS is used at rates exceeding 20%. Mo et al. (2015), reported that increasing GGBS from 20% to 70% caused a 29% and 15% reduction in the 28-day flexural and tensile strength of oil palm shell lightweight concrete, respectively. Similarly, other pozzolanic additives such as MK, RHA, POFA, pumice powder, and volcanic ash also exhibited low early-age strength abut high long-term strength gains. Mo et al. (2018), stated that the inclusion of 10% MK in oil palm shell lightweight concrete provided the most favorable improvement in terms of compressive strength, splitting tensile strength, flexural strength, elastic modulus, and Poisson's ratio. Al-Sibahy and Edwards (2012), also reported that using 10% MK in lightweight concrete containing expanded clay increased compressive strength, splitting tensile strength, Poisson's ratio, and elastic modulus after 7 days. Ofuyatan et al. (2021), conducted mechanical tests on lightweight concrete mixtures containing POFA after 7, 14, and 28 days of curing; they reported that samples containing 10% and 50% POFA showed a regular increase in compressive strength compared to the control concrete during the early curing period.

Based on 28-day compressive strength, the optimum replacement ratio of pozzolanic additives in lightweight concrete is generally found to be in the range of 10–20%. When these ratios are exceeded, the dilution effect becomes dominant, leading to a decrease in strength. Kelestemur and Demirel (2015), reported that for pumice aggregate lightweight concrete, a 15% MK content was the most suitable level, resulting in a compressive strength that was 23% higher than that of the control concrete. However, increasing the MK content to 20% led to a reduction in strength due to the dilution effect. Similarly, Foong et al. (2015), found that the optimal RHA content for oil palm shell lightweight concrete is 15%. The increase in compressive strength correspondingly increased the elastic modulus, splitting tensile strength, and flexural strength by 25%, 28%, and 15%, respectively. This strength enhancement was attributed to the filling effect and pozzolanic reaction of RHA. However, increasing the RHA content to 20% caused a reduction in compressive strength. On the other hand, the addition of nanomaterials can enhance the compressive strength, tensile strength and flexural strength of lightweight concrete Nanometric particles fill the voids between larger aggregate particles, resulting in improved density and increased interfacial bond strength. Furthermore, the pozzolanic reactivity of certain nanomaterials contributes to increased density, thereby improving mechanical performance. It has been found that the incorporation of nanoparticles such as GO, CNT, and NS into lightweight concrete increases its compressive strength. In Hong et al.'s (2023) study, the compressive strength of high-strength lightweight concrete was significantly increased by adding a various content 0.02%, 0.04%, 0.05%, 0.06%, and 0.08% of GO. The optimum enhancement was observed at 0.05% GO. Similarly, Narasimman et al. (2020), achieved a maximum compressive strength of 107.2 MPa by adding 1% NS and 2% CNT, based on 28-day results. Al-Luhybi and Al-Talabani (2021), also stated that the addition of NS improved the compressive strength of lightweight concrete Additionally, Wang et al. (2018), observed an increase in the compressive strength of lightweight concrete with the addition of 3% NS. Sekhavati et al. (2019), reported that a combined addition of 5% NS and 5% nano-lime increased compressive strength by 53%.

Table 1. The Impact of various mineral admixtures on mechanical properties of lightweight concrete.

Reference	Mineral admixture	Replacement ratio (%)	Type of aggregate	Key observation
(Kiliç et al., 2003)	SF	10%	Slate and expanded clay aggregates.	Higher compressive strength at all ages from 3 days to 90 days
(Youm et al., 2016)	SF	0%,3.5% and 7%%	Slate and expanded clay aggregates.	Increased compressive strength by 8–10%, and no significant effect on splitting tensile strength or modulus of elasticity.
(Kiliç et al., 2003)	C-class FA`	20%	Slate and expanded clay aggregates.	A decrease in splitting tensile strength and flexural strength in the early ages up to 7 days, but an improvement was observed in later ages.
(Subaşı & Subaı, 2009)	FA	10%,20% and 30%	Expanded clay.	Increased the 28-day splitting tensile strength by 6–10%. But when 20%and 30% content used, the splitting tensile strength decreases by 20%.
(Akaözolu & Ati, 2011)	GGBS	50%	Waste Poly-ethylene Terephthalate (PET).	The compressive strength was lower than that of the control concrete up to 7 days, but exceeded that of the control concrete on the 28th day.
(Chen & Liu, 2008)	GGBS	40%	Expanded clay.	Increased compressive strength at 7 and 28 days.
(Mo et al., 2015)	GGBS	20% - 70%	Oil palm shell.	Caused a 29% and 15% reduction in the 28-day flexural and tensile strength.
(Mo et al., 2018)	MK	10%	Oil palm shell.	Improvement in compressive strength, splitting tensile strength, flexural strength, elastic modulus, and Poisson's ratio.
(Al-Sibahy & Edwards, 2012)	MK	10%	Expanded clay.	Increased compressive strength, splitting tensile strength, Poisson's ratio, and elastic modulus after 7 days.
(Ofuyatan et al., 2021)	POFA	10% and 50%		A regular increase in compressive strength compared to the control concrete during the early curing period.
(Keleştemur & Demirel, 2015)	MK	15% (Opt.) and 20%	Pumice.	Increase in compressive strength by 23% than the control concrete. When the content increased to 20%, a reduction was observed in strength due to the dilution effect.
(Foong et al., 2015)	RHA	15% and 20%%	Oil palm shell.	Increase in compressive strength, elastic modulus, splitting tensile strength, and flexural strength by 25%, 28%, and 15%, respectively. But when the content increased to 20% a reduction in compressive strength was observed.

Similar results have been reported in other studies. Zhang et al. (2018), evaluated five different mixtures containing 0.05–1% NS. At a dosage of 0.1%, a 41% increase in flexural strength was observed, while doses above 0.5% led to reduced strength. The 28-day results showed improvements at all dosages compared to 7-day results. Othman et al. (2023) investigated dosages of 1–6% nano-calcium carbonate ($CaCO_3$). The highest increase

64% was observed at a 4% dosage; beyond that dosage, strength reduced due to particle agglomeration and disruption of the microstructure. In another study, Othman et al. (2022), tested six different mixes with 0.10–0.30% nano-Fe_3O_4. The highest tensile strength was achieved with 0.25% nano-Fe_3O_4, showing a 51% increase at 56 days. This was attributed to the acceleration of calcium hydrate formation by nano-Fe_3O_4. Ghanbari et al.(2020) evaluated 24 different mixes containing 2–6% NS and 0.25–1.5% fiber. At 28 days, tensile strength increased by 3–55%, with the highest value achieved using 4% NS and 1.5% fiber. The combination of NS's pozzolanic effect and the reinforcing contribution of fibers resulted in significantly improved strength, which could not be achieved when each material was used alone.

Fiber reinforcement is also used to improve the mechanical properties of concrete. The most notable effect of fibers on the mechanical performance of lightweight concrete is the significant enhancement in tensile strength, flexural strength, and flexural toughness. This transforms lightweight concrete from a brittle material into a more ductile material (Choi et al., 2016). In a previous study, Shah et al. (2024) investigated the effects of adding 2% and 4% steel fibers to concrete containing 0%, 15%, 30%, and 45% expanded polystyrene (EPS) along with 10% micro-silica. The use of 45% EPS reduced the concrete density by 53%. However, the mix with 15% EPS and 2% steel fibers provided the best weight-to-strength ratio. It was also concluded that adding 2% steel fibers improved crack resistance and increased flexural strength by 5%. Chen et al. (2024) it was reported that the use of hybrid fibers consisting of micro-steel and PP enhanced tensile strength, improved crack resistance and ductility, and effectively controlled crack propagation. Furthermore, it increased the concrete's self-healing capacity and overall strength.

According to most studies, the addition of various fibers to lightweight concrete mixtures has been reported to have a limited effect on improving compressive strength. Some researchers have even stated that when the amount of fiber used in the lightweight concrete mixture exceeds the optimal level, it can lead to a reduction in compressive strength and negatively affect the material (Leong et al., 2020). Nahhab et al. (2020), reported that adding steel fibers to lightweight concrete produced with expanded clay aggregate (LECA) reduces workability and did not result in a significant increase in compressive strength. However, compared to the fiber-free specimen, it increased flexural strength by 55%. They also noted that increasing the LECA content further weakens the mechanical properties of lightweight concrete. Altalabani et al. (2020), stated that adding 0.22% PP fiber to LECA-based lightweight concrete increased compressive strength by 0.12%, tensile strength by 4.5%, and elastic modulus by 2.55%. However, increasing the fiber content to 0.33% caused a 5.30% decrease in compressive strength, while tensile strength and elastic modulus still increased by 4.7% and 3.9%, respectively. Similarly, Saradar et al. (2020), reported that the addition of basalt fiber to LECA-based lightweight concrete increased compressive strength to a limited extent, but at higher dosages, it actually reduced compressive strength compared to fiber-free concrete. Kadela et al. (2023), used recycled steel fibers obtained from scrap tire wires and found that the addition of these fibers into lightweight concrete increased compressive strength by up to 48%, tensile strength by 52%, and flexural strength by 41%. Ma et al. (2023), reported that adding 0.5%, 1%, and 1.5% of 9 mm long basalt fibers to lightweight concrete containing calcium carbonate-reinforced epoxy spheres increased compressive strength by 22.8% compared to the control concrete. They also noted that basalt fibers had a negligible effect on the concrete's density. Xue et al. (2023), also stated that 0.3% of 12 mm long basalt fibers enhanced compressive and tensile strength as well as toughness, effectively preventing crack propagation.

Behera et al. (2022) investigated the performance of single and hybrid steel and PVA fibers in ultra-high-strength lightweight concrete produced using fly ash aggregate, oil palm shell, and supplementary binders. It was reported that the addition of fibers improved the compressive strength and tensile strength compared to the control concrete, however, the cost of LWHFRC was 16.46% higher than that of the fiber-free mixture. Wang et al. (2023), stated that the addition of 1% steel fibers increased the strength and stiffness of columns made from such concrete, which reduced damage and deterioration of the columns and prevented excessive displacement and acceleration. Mirza and Soroushian (2002) examined the effect of glass fibers (L = 12 mm, D = 135 μm) on the flexural strength of perlite-based lightweight concrete. They reported that increasing the glass fiber content in the range of 0.125–0.75% enhanced flexural strength by approximately 64–120%. On the other hand, one of the most critical parameters determining the strength and durability of lightweight concrete is the water-to-cement (w/c) ratio. However, due to the high-water absorption capacity of porous aggregates, the actual (w/c) ratio is generally lower than the nominal value and is difficult to determine accurately. Factors influencing the actual water-to-cement ratio in lightweight concrete include the aggregate's water absorption capacity, its existing moisture content, the physical state of the moisture, the volume fraction of the porous aggregate within the concrete, and rheological properties of the cement paste (Domagała, 2015).

A low (w/c) ratio results in a denser and less permeable cement matrix, which enhances mechanical properties such as flexural and compressive strength (Adhikary et al., 2022). Nassar et al. (2018), found that a lightweight concrete mix with a w/c ratio of 0.45 provided the highest compressive and flexural strength. They also reported a significant reduction in the fresh concrete density as the aggregate volume increased. Güneyisi et al. (2016), stated that higher w/c ratios significantly reduced the compressive strength of lightweight concrete. However, they found that the addition of small amounts of nano-silica was effective in improving the strength of lightweight concrete. Lotfy et al. (2015), also observed that high water content in lightweight concrete mixtures led to strength reduction. On the other hand, bond strength (adhesion) is an important structural property of reinforced concrete, defined as the bond between the steel reinforcement and the surrounding concrete (John Robert Prince & Singh, 2013). According to Bogas et al. (2014), the w/c ratio is one of the most critical factors affecting bond strength in concrete, regardless of the type of aggregate used, and its influence is reported to be greater than that of compressive strength.

B) Modulus of elasticity

The modulus of elasticity can vary by ±25% depending on various factors, such as binder and aggregate type, moisture content (Newman & Choo, 2003). When comparing mixtures with the same compressive strength, the elastic modulus of lightweight concrete (12.6–27.34 GPa) is 25–50% lower than that of normal concrete. This is because the modulus elasticity of normal aggregates is higher than that of lightweight aggregates; thus, as the content of lightweight aggregates increases in lightweight concrete, the overall modulus of elasticity decreases (Chandra & Berntsson, 2002). Tedjditi et al. (2020), found that concrete containing 25% virgin cork exhibited a modulus of elasticity that was 78% lower than the control concrete. Additionally, according to the stress–strain curves, concrete with a high virgin cork content demonstrated good inelastic deformation capacity by exhibiting plastic deformation before failure (Tedjditi et al., 2020).

Experimental studies show that fiber reinforcement is not always a reliable method for increasing the modulus of elasticity of lightweight concrete. Especially at low fiber content, its effect on the modulus of elasticity is often negligible (Hassanpour et al., 2012). Some studies report that steel fibers can increase the modulus of elasticity of lightweight concrete by 6% to 30% (Campione et al., 2001; Domagala, 2011). However, depending on the content of steel fiber and the type of lightweight aggregate used, reductions of up to 12% in the modulus of elasticity have also been observed (Kayali et al., 2003). In some studies, increasing the volume of crimped steel fibers from 0% to 0.8% led to a 29% reduction in the modulus of elasticity of lightweight concrete (Zhao et al., 2019). In contrast, the use of hooked-end steel fibers tends to increase the modulus of elasticity as the fiber volume content increases (Esmaeili et al., 2023). Badogiannis et al. (2019), found that pumice aggregate lightweight concrete reinforced with steel and PP fibers showed improved mechanical strength. However, the addition of fibers had no significant effect on the Poisson’s ratio or elastic modulus. Behera et al. (2022), observed that the addition of fibers to ultra-high-strength lightweight concrete produced using fly ash aggregate, oil palm shell, and binders increased the modulus of elasticity by 55.98% compared to the reference concrete. On the other hand, Domagała (2011), demonstrated that the most significant factor affecting the modulus of elasticity of fiber reinforced lightweight concrete is the bond strength between the aggregate and the cement matrix. For example, the modulus of elasticity of lightweight concrete with expanded clay aggregate containing 2% steel fibers is approximately 18% higher than that of concrete without fibers (Kayali et al., 2003). In contrast, using the same content of steel fiber in pumice aggregate lightweight concrete resulted in about a 12% decrease in the modulus of elasticity (Hassanpour et al., 2012). In the case of PP fibers, the highest increase in the modulus of elasticity is approximately 4%. However, at higher volume fractions, the use of PP fibers led to reductions in modulus of elasticity of up to 12% (Badogiannis et al., 2019). In addition, the incorporation of certain pozzolanic additives can also influence the modulus of elasticity of lightweight concrete. According to Shannag (2011), using 15% SF resulted in a slight increase in the modulus of elasticity of tuff-based lightweight concrete. Mo et al. (2018), identified 10% as the optimal replacement level of MK to enhance the modulus of elasticity of lightweight concrete made with oil palm shell aggregate. Furthermore, Muthusamy and Zamri (2016) also, reported that a 20%

POFA increases the modulus of elasticity of oil palm shell lightweight concrete.

C) Ductility

Ductility is a crucial indicator of structural performance. In general, lightweight concrete exhibits a more brittle behavior compared to normal concrete, which leads to sudden and explosive failure after reaching its maximum load (Mohamed et al., 2023). Campione et al. (2001), reported that lightweight concrete produced with expanded clay aggregates up to 17 mm in size displayed significantly more brittle behavior than normal concrete with the same compressive strength. This brittle structure is one of the main disadvantages of lightweight concrete. To overcome this disadvantage, an appropriate content of fibers is added to lightweight concrete. Among various fiber types, the addition of steel fibers increases the ductility of lightweight concrete; however, the rate of increase decreases as the fiber content increases (Hosen et al., 2022). Caratelli et al. (2016), observed that adding 30 kg/m³ of hooked-end steel fibers increased the load-carrying capacity by approximately 20% and ductility by approximately 65% under monotonic loading. Similarly, Altun and Aktaş (2013), reported that using 30 kg/m³ and 60 kg/m³ of steel fibers in lightweight concrete containing 350 kg/m³ of cement, the ductility increased values by 18% and 9%, respectively. For mixtures with 400 kg/m³ of cement, the ductility increased by 21% and 69%. While for mixtures with 450 kg/m³ of cement, the ductility increased by 64% and 98%, respectively. Hosen et al. (2022), in their study on palm oil clinker (POC)-based lightweight concrete incorporating 0–1.5% steel fibers, found significant improvements in ductility compared to control specimens without fibers. Specifically, they reported that compressive ductility increased by 472%, displacement ductility by 140%, and energy ductility by 568%. These findings clearly indicate that POC-based high-strength fiber-reinforced lightweight concrete exhibits significantly superior ductility performance under extreme loading conditions compared to conventional concrete (Hosen et al., 2022).

D) Fatigue Performance

Fatigue refers to the failure of a material under repeated stress levels that are below its maximum static strength. Several factors can impact a material's fatigue strength, including the ratio of applied stresses, the rate of loading, the composition of the matrix, mechanical properties, boundary and surrounding environmental conditions (Sohel et al., 2018). Clark (1993), reported that lightweight concrete with a density exceeding 1,500 kg/m³ behaves similarly to normal concrete under repeated compressive loads. Lightweight concrete exhibits lower fatigue resistance than normal concrete due to its low aggregate strength and weak cohesion between mortar and aggregate particles. Additionally, the fatigue life of lightweight concrete decreases due to its low tensile strength and crack resistance. Therefore, improving the fatigue resistance of lightweight concrete is crucial for ensuring the durability and stability of structures subjected to cyclic loads. Fiber reinforcement can enhance the dynamic properties of lightweight concrete such as fatigue behavior by increasing ductility and reducing both crack width and crack propagation (Choi et al., 2016). Cachim et al. (2002), conducted fatigue tests on steel fiber-reinforced concrete under compression and reported that the superior fatigue life of fiber-reinforced concrete compared to plain concrete is associated with ability of fibers to control initial defects such as microcracks and voids. Similarly, Choi et al. (2016), investigated the fatigue performance of steel and PVA fiber-reinforced lightweight concrete containing high content of mineral admixtures. The study applied cyclic compressive loads at 0.75, 0.80, and 0.90 f'c and found that fiber-reinforced mixes exhibited a significantly longer fatigue life compared to plain concrete. Notably, PVA fibers were more effective than steel fibers in limiting microcrack propagation. However, the best fatigue performance was achieved when both fiber types were used together in a hybrid form (Choi et al., 2016). To ensure the targeted fatigue life of concrete, the type, dosage, and content of fibers must be carefully considered during mix design.

DURABILITY AND ENVIRONMENTAL RESISTANCE OF LIGHTWEIGHT CONCRETE

A) Water Permeability

Porosity, along with the size, distribution and continuity of pores, significantly affect the water permeability of concrete. Since lightweight aggregates generally have higher water absorption compared to normal aggregates, the permeability coefficient and water absorption by weight of lightweight aggregate concrete are higher. While water absorption decreases with concrete age in normal concrete, Lo et al. (2006), observed that water absorption increases with concrete age in low-strength lightweight concrete with air-entraining agents. Şahin et al. (2003), found that when the pumice aggregate ratio is 100% the water absorption rate of concrete reached 16.7%. Gündüz et al. (2005), found that the water absorption rate of pumice lightweight concrete varies between 12.41% and 26.37%, and it increases as the pumice aggregate-to-cement ratio increases. Moreover, an increase in water absorption led to a decrease in compressive strength. Chia and Zhang (2002), showed that at the same water-to-cement ratio, lightweight concrete could be less permeable compared to normal concrete. They found that as the w/c ratio decreased, the permeability of lightweight concrete became even lower. Furthermore, the addition of SF to both normal and lightweight concretes was found to reduce water permeability by refining and densifying the porous structure of the cement matrix. However, the type and content of admixtures used, as well as the fibers incorporated, are factors that affect water movement in lightweight concrete. Bogas et al. (2015), found that when 8% SF was used in lightweight aggregate concrete containing expanded clay, the capillary water absorption coefficient and water permeability decreased significantly in comparison to the increase in compressive strength. In the same study, they found that replacing 40% of the cement with FA increased the capillary water absorption coefficient, but only a slight effect was observed at a 22% FA replacement level (Bogas et al., 2015). Real et al. (2015), noted an increase in the capillary water absorption coefficient when 20% FA was added to lightweight concrete containing slate and expanded clay. On the other hand, in lightweight aggregate concrete with expanded clay, when 25% and 40% of the cement was replaced with GGBS, water permeability decreased, and curing methods such as accelerated curing, water curing, and air curing were found to have no effect on water permeability. Similarly, Mo et al. (2016) found that when the cement was replaced with 40% GGBS in concrete containing oil palm shell, water absorption and capillary absorption decreased. The pore refinement effect of GGBS is attributed to its ability to reduce the size and connectivity of pores in the concrete. It was also discovered that the pore refinement effect of GGBS was particularly more pronounced in the improvement of the cement matrix (Mo et al., 2016). Kelestemur and Demirel (2015), found that when up to 20% MK was used in lightweight aggregate concrete containing pumice, capillary absorption and porosity decreased. This was attributed to the fine MK particles, which fill the voids in the interfacial transition zone (ITZ) between the aggregate and the cement, and the pores in the cement matrix, thereby creating discontinuities in the capillary pores (Keleştemur & Demirel, 2015).

In fiber-reinforced concrete, the mechanical obstruction caused by fibers affects the pathways of water movement. Dawood et al. (2018), stated that the inclusion of 0.5%, 1%, and 1.5% carbon fibers reduced the water absorption rate by 18.7%, 38.5%, and 40%, respectively, compared to fiber-free concrete. Zinkaah et al. (2014), noted that the water absorption rate of lightweight concrete containing steel fibers was 10% higher than that of fiber-free samples. Some researchers have stated that fibers such as carbon, basalt, and PP preserve the structure of lightweight concrete by bridging cracks and filling voids, thereby reducing water absorption and permeability. Loh et al. (2021), reported that adding 0.285% PP and PVA fibers, respectively, to lightweight concrete made with oil palm shell (OPS) reduced the water absorption rate by 17.2% and 21.5%, respectively, compared to fiber-free concrete. Furthermore, due to the synergistic effect of hybrid PP and PVA fibers, the water absorption rate decreased by 24%. Furthermore, the addition of steel fibers can reduce water absorption. According to research, steel fibers were found to decrease the depth of water penetration. The bridging effect of steel fibers reduces micro-cracks and improves the microstructure, thus resulting in a significant decrease in the water absorption capacity of lightweight concrete when the steel fiber content is increased from 0.25% to 1.5% (Hosen et al., 2021; Kaplan et al., 2021).

B) Chemical Attack Resistance

Aggressive groundwater, polluted air and reactive liquids often cause chemical effects. Lightweight concrete is more porous than normal concrete and therefore more vulnerable to such chemical attacks. In particular, acids attack lightweight concrete in different ways. Here, the type of acid (such as hydrochloric acid, sulfuric acid, and lactic acid) and the type of lightweight concrete used affect the extent and nature of the attack (Chandra & Berntsson, 2002). Lightweight aggregates with a porous structure create both micro and macro-scale voids within the concrete matrix. This porosity increases the water absorption capacity of concrete and facilitates the ingress of harmful substances, such as chloride ions into concrete, thereby negatively affecting the durability of lightweight concrete (Lo et al., 2004). Hasan et al. (2021), conducted an experimental study examining water absorption rate and rapid chloride penetration (RCP), which are important indicators of concrete durability. The study reported that, due to the high porosity of lightweight concrete, the water absorption and chloride ion penetration were 12.5% and 0.35% higher, respectively, compared to normal concrete.

Pozzolanic additives such as SF, FA, GGBS, and MK have a more pronounced effect on the chemical durability of lightweight concrete, specifically in enhancing resistance to chloride penetration, chloride diffusion, and increasing electrical resistivity, compared to their influence on mechanical properties or water absorption. These additives enhance durability by refining the microstructure of the cementitious matrix (Youm et al., 2016). According to research, the resistance to chloride permeability in lightweight concrete containing slate and expanded clay can be improved by up to 7% with the use of SF. In rapid chloride permeability test, the total load and chloride diffusion coefficient decreased by approximately 10 times and 3–6 times, respectively, at 90 days of concrete age (Lothenbach et al., 2011). Youm et al. (2016), reported that increasing the content of SF enhances resistance against chloride ingress. This improvement is mainly attributed to the densification of the hardened cement paste's microstructural composition due to the addition of SF. Also, Wang et al. (2005), found that a 10% SF addition in lightweight concrete reduces the chloride diffusion coefficient by approximately three times. This improvement is achieved due to the pozzolanic effect of SF, which enhances the pore distribution and cement microstructure of the concrete. In the same study, it was noted that the use of 10% FA and GGBS in lightweight concrete with slate aggregate reduces the chloride diffusion coefficient; however, the effect of GGBS is lower compared to FA, due to the nature of GGBS's secondary hydration products (Wang et al., 2005). Real et al. (2015), observed that using 20% FA led to a trend of increased chloride diffusion coefficient in shale and expanded clay lightweight concretes. On the other hand, Kawabata et al. (2012), found that using 10% RHA improved the resistance of expanded clay lightweight concrete against chloride ion permeability. Similarly, the use of pumice powder and volcanic ash was found to improve the chloride permeability resistance of pumice lightweight concrete. This improvement driven by the pozzolanic reaction of pumice powder, became particularly more evident at later ages (Mo et al., 2017).

Moreover, nanomaterials have also shown positive effects on the durability of lightweight concrete. Nanomaterials improve the microstructure of concrete by reducing the size of pores. This limits the ingress of chloride ions and improves resistance against environmental threats such as carbonation and sulfate attack. As a result, the concrete’s performance against aggressive environmental effects improves, enhancing its durability and extending its service life. Sun et al. (2020), reported that the addition of 1% nano-calcium carbonate and 20% fly ash additive reduced chloride ion penetration and improved the concrete’s microstructure, thereby enhancing durability. Hong et al. (2023), demonstrated that the incorporation of 0.05% nano-graphene oxide significantly reduced chloride penetration. However, the effectiveness diminished at higher dosages due to agglomeration of the nanomaterial. Garg et al. (2023), observed that a mix containing 7.5% nano-metakaolin and fly ash achieved the best performance in terms of strength and sulfate–chloride resistance. Similarly, Vargas et al. (2018), studied the behavior of lightweight concrete exposed to sulfate attack with varying NS contents ranging from 0–10%. They found that the addition of 10% NS significantly reduced the effects of magnesium sulfate attack compared to lower NS content mixtures. This improvement was attributed to the reaction of NS with calcium hydroxide to form additional C-S-H gel, which improves the microstructure, reduces pore size, decreases permeability, and increases durability (Garg et al., 2023).

C) Thermal Properties and High-Temperature Resistance

Lightweight concretes have lower thermal expansion coefficients compared to normal-weight concretes. Due to their low thermal expansion and high deformation capacity under tensile stress, lightweight concretes are less susceptible to damage caused by thermal stresses compared to normal concrete. Due to their porous structure, the air in the voids of lightweight aggregates reduces the rate of heat transfer. Therefore, lightweight concretes can be used for thermal insulation in many structures (Newman & Choo, 2003). Since there is a significant relationship between density and thermal conductivity, studies have shown that the thermal conductivity of lightweight concrete is roughly half that of conventional concrete (Zhang et al., 2021). The thermal insulation coefficient of lightweight concrete depends on its density, type of aggregate, and moisture content (Newman & Choo, 2003). Demirboğa and Gül (2003), reported that the thermal conductivity of concrete made %100 with pumice aggregate is approximately 0.3 W/mK. They also found that replacing pumice with expanded perlite further reduces thermal conductivity. Additionally, the addition of mineral additives such as 30% SF reduced thermal conductivity by up to 13%. Similar results were obtained when Class-C FA was used (Demirboğa & Gül, 2003). Real et al. (2016), determined in thermal conductivity tests that replacing cement with FA resulted in an 18% reduction in thermal conductivity. In one study, due to its low density, the thermal conductivity of expanded perlite lightweight mortar was reduced by 13% with the use of 20% GGBS. Al-Sibahy and Edwards (2012), also reported that the thermal conductivity of lightweight concrete decreased with the use of MK. Hawa et al. (2013), stated that when 20–30% of the cement was replaced with RHA, the electrical resistivity of lightweight concrete containing expanded polystyrene and pumice increased.

By forming cementitious components that are resistant to thermal conductivity, the addition of nanomaterials can affect the thermal conductivity of lightweight concrete (Zhang et al., 2021). Saleh et al. (2021) reported that adding 3% NS to concrete significantly enhanced its thermal insulation. The thermal conductivity of concrete containing NS was measured between 0.5–0.92 W/m·°C, whereas that of normal concrete ranged from 1.22–2.05 W/m·°C. The main reason for the 41% reduction in heat diffusion is the microstructural air voids, which block heat transfer and increase heat storage capacity. This indicates that NS enhances thermal performance and provides environmental benefits by reducing heat-related emissions (Saleh et al., 2021). In terms of fire resistance, materials can be categorized into combustible and non-combustible based on their burning potential. Concrete, stone, brick, and other inorganic materials are non-combustible. The impact of fire on a building's structural elements depends on the temperature reached, the duration of the fire, and the thermal properties of the structural component. Lightweight aggregates maintain their stability under high temperatures, thus experiencing less strength loss and offering better thermal insulation. Furthermore, due to their low thermal expansion, lightweight concrete is more fire-resistant compared to normal concrete (Newman & Choo, 2003).

When concrete is exposed to high temperatures, both free and chemically bound water evaporate, generating significant internal pressure within the concrete that may lead to explosive spalling. Researchers have proposed several practical solutions to reduce this issue, such as reducing the amount of free water in the concrete and incorporating fibers into the mix (Liao et al., 2024). Cai et al.(2021), found that under high temperatures, PP fibers showed fewer edge bursts and surface cracks. Arel et al. (2018), reported that steel fibers can improve the compressive strength of concrete at temperatures of 50, 150, 300, and 450 °C. While PP fibers help prevent cracks and spalling at high temperatures by forming voids upon melting, which lowers vapor pressure, these voids may also reduce compressive strength. On the other hand, due to their high melting point and bridging effect, steel fibers contribute to increased compressive and splitting strength at elevated temperatures (Liao et al., 2024).

D) Freeze-thaw Resistance

One of the most critical factors affecting the service life and durability of concrete is freeze-thaw damage (Zeng et al., 2023). The performance of lightweight concrete under freeze-thaw cycles depends on mix proportions, type of aggregate, moisture content, and the amount of entrained air. Laboratory test results have shown that non-air-entrained lightweight aggregate concretes exhibit greater resistance to freeze-thaw effects compared to non-air-entrained normal concretes with the same strength level (Newman & Choo, 2003). According to most studies, lightweight concrete exhibits higher freeze-thaw resistance compared to standard concrete, primarily due to its porous microstructure, which allows for greater volumetric expansion (Du et al., 2021). Despite a reduction in mechanical properties caused by freeze-thaw action, lightweight concrete demonstrates stronger resistance to freezing. Tan et al. (2013), reported that as the number of freeze-thaw cycles increases, the compressive strength of lightweight aggregate concrete decreases. Karagöl et al. (2018), found that incorporating 10% lightweight aggregate significantly improves the freeze-thaw performance of lightweight concrete. Gao et al. (2002), emphasized that microcracks are the most critical factor influencing the durability of lightweight concrete under freeze-thaw conditions. The primary causes of cracking in concrete exposed to freeze-thaw cycles include the expansion and stress generated by water freezing within the pores. A secondary cause is the thermal stresses that develop during repeated freeze-thaw cycling. The performance of lightweight concrete is reduced due to freeze-thaw effects, which limits its use in cold regions.

Therefore, various mineral admixtures and fibers are often incorporated to enhance its freeze-thaw resistance. Demirboğa and Gül (2004), reported that using up to 30% SF improved the freeze resistance of pumice lightweight concrete, and after 25 freeze-thaw cycles, compressive strength increased by 89% with 20% SF content. Nanomaterials can also enhance the freeze-thaw resistance of concrete by improving its microstructure. By filling pores in the cement matrix, they reduce permeability and limit the ingress of water and harmful ions. Tarangini et al.(2022), found that the addition of NS increased freeze-thaw resistance by 70%. Liu et al. (2022), also demonstrated that nano-silicon emulsion improved durability against freeze-thaw cycles by forming a hydrophobic structure. The effectiveness of nanomaterials depends on various parameters, including type, dosage, dispersion, and mix design. On the other hand, fibers are also used to improve the mechanical properties of concrete. Due to their crack-bridging capabilities, fibers can reduce freeze-thaw damage in concrete (Zeng et al., 2023). After 250 freeze-thaw cycles, Zeng et al. (Zeng et al., 2023a), showed that freeze-thaw damage was significantly reduced with the addition of BF and PANF fibers. According to Rustamov et al. (2021), the use of PVA and steel fibers provided good resistance against freeze-thaw damage. After 300 cycles, the specimens subjected to freeze-thaw testing exhibited 18.5% and 3.4% higher strength, respectively, compared to control concrete before the cycles.

E) Carbonation Resistance

When the concrete exposed to the atmosphere, it interacts with carbon dioxide present in the environment. This interaction occurs primarily with the calcium hydroxide produced during the hydration of cement. Additionally, C-S-H can also react with carbon dioxide. This process is known as carbonation (Chandra & Berntsson, 2002). In lightweight concrete, the use of porous aggregates allows for greater diffusion of gases such as carbon dioxide. However, if the aggregate particles are homogeneously distributed within a well-compacted matrix, the carbonation rate may not differ significantly from that of normal concrete (Newman & Choo, 2003). Gao et al. (2013)**,** found that adding 20% FA reduced the carbonation depth of shale lightweight concrete by approximately 22% compared to FA-free lightweight concrete, due to the pozzolanic reaction and fine particle size of FA, which enhanced the pore structure of the concrete and blocked the pathways for water and air penetration. However, increasing the FA content to 30% resulted in a greater carbonation depth in the same type of concrete. The same study showed that 20% GGBS increased carbonation depth within the first 14 days but resulted in lower carbonation depth than the control concrete after 14 days (Gao et al., 2013). Lo et al. (2009), also reported that when the FA content was below 25%, the increase in carbonation depth was not significant, whereas at higher levels such as 40% and 55%, a considerable increase in carbonation depth was observed. Similarly, Akçaözoğlu and Atiş (2011) noted that after 28 days, the carbonation depth increased in PET-based lightweight mortar containing 50% GGBS. Kawabata et al. (2012), found that the resistance of expanded clay lightweight concrete to carbonation was enhanced with the use of 10% RHA. Huberorá and Hela (2013), studied the durability of expanded clay lightweight concrete exposed to a carbonation environment for 12 months. The concretes had a water-to-binder ratio of 0.33–0.35 and strength classes of LC30/33–LC35/38. In this study, mixtures containing 40% FA were found to be more resistant to carbonation compared to those with 5% SF or 40% LF.

Lightweight concrete reinforced with PP and/or steel fibers exhibits good resistance to carbonation. This is primarily due to the high crack resistance provided by the fibers, which can reduce the penetration of carbon dioxide into the concrete. In addition, PP fibers due to their impermeability to water enhances the carbonation resistance of lightweight concrete compared to natural fibers (Liao et al., 2024). On the other hand, when the fiber content is increased from 0.5% to 2%, the carbonation resistance of pumice-based lightweight concrete containing steel fibers decreases (Kaplan et al., 2021).

F) Shrinkage Behavior

In general, the type and hardness of fine and coarse aggregates in the concrete significantly affect shrinkage Concretes with a higher aggregate content shrink less rapidly. Additionally, concrete made with aggregates that have a high elastic modulus is more resistant to shrinkage (Maghfouri et al., 2022)**.** Due to the porous nature and lower elastic modulus of lightweight aggregates, the shrinkage of lightweight concrete is 1.0 to 1.5 times higher than that of normal concrete (Chandra & Berntsson, 2002; Maghfouri et al., 2022). Excessive shrinkage of concrete can lead to the formation of microcracks and the propagation of cracks, allowing chemicals such as acids and chloride ions to pass into the concrete, which can cause reinforcement corrosion and reduce the durability of the concrete. According to a study, the properties of lightweight expanded polystyrene (EPS) concrete were investigated by replacing sand and gravel with 25%, 40%, and 55% EPS. When the concrete mixtures contained 25%, 40%, and 55% EPS, it was shown that the 90-day drying shrinkage strain of the control concrete mixture was approximately 33%, 42%, and 78% lower than that of the EPS concrete mixtures, respectively (Chen & Liu, 2004). In another study, it was shown that in low-strength pumice concrete, drying shrinkage decreased as the pumice aggregate/cement ratio increased, and shrinkage was below 0.08% (Gündüz & Uğur, 2005). Al-Alusi et al.

(2024), demonstrated that incorporation 5%, 10%, 15%, 20%, 25%, and 30% of EPS in lightweight concrete led to an increase in drying shrinkage as the EPS content increased. However, the addition of waste plastic fibers (WPFs) reduced drying shrinkage by approximately 0.25% to 1.25% compared to the reference concrete. The drying shrinkage with added EPS and WPFs developed quickly between 40 and 60 days and stabilized thereafter (Al-Alusi et al., 2024). Pozzolanic materials have contributed to the reduction of crack area and crack propagation in lightweight concrete. When 22% FA was added Bogas et al.(2014), found that the drying shrinkage of expanded clay lightweight concrete increased, due to the porous structure that accelerates the drying rate. However, when FA content was increased to 40%, the FA particles acted like "micro aggregates," reducing drying shrinkage. Akçaözoğlu and Atış (2011), reported that the drying shrinkage of PET lightweight concrete containing FA was lower than that of the FA-free control concrete. In the same study, the drying shrinkage of 50% GGBS PET lightweight concrete was unaffected up to 90 days, but after 90 days, it was shown to be reduced compared to the concrete without GGBS. Additionally, the addition of 20% pumice powder and volcanic ash to pumice lightweight concrete showed positive results in reducing drying shrinkage (K. M. A. Hossain et al., 2011).

Nanomaterials have also shown positive results. Federowicz et al.(2021), stated that the internal curing effect of lightweight aggregates reduces total shrinkage, but the addition of NS had no significant effect on shrinkage. While concrete with NS and concrete without NS exhibited similar behavior during the first 7 days, a 3% NS addition caused a 5.4% increase in total shrinkage at 90 days. Nevertheless, NS reduced surface cracks by up to 25%. Mansour et al.(2022), observed that the addition of nano-metakaolin increased shrinkage, but showed that this effect could be mitigated by using expanded materials and that strength could be improved under non-cured conditions. The effect of nano-metakaolin on shrinkage was also investigated by He et al.(2023) which found that using 20% MK reduced drying shrinkage by 39.6% compared to the control concrete. According to most studies, the addition of various fibers especially steel fibers improves shrinkage resistance and provides control against long-term drying shrinkage cracking. Chen and Liu (2005), reported that shrinkage was reduced by 24–30% with fiber use, and noted that shrinkage was almost completely prevented after the 60th day. In another study, steel fibers with a density of up to 1800 kg/m³ were added to EPSC, and it was found that the steel fibers significantly improved the drying shrinkage of EPSC specimens (Chen & Liu, 2004). Gong et al. (2018), also found that the bridging action of PPFs could reduce the drying shrinkage with adding short PPFs to concrete mixes. Yousefieh et al. (2017), found that shrinkage performance strongly depended on the fiber’s elastic modulus, with steel fibers which having the highest modulus, providing greater tensile strength before initial cracking.

G) Reinforcement Corrosion Resistance

In lightweight concrete, the cement dosage is generally high, which results in high alkalinity and creates an environment that helps prevent reinforcement corrosion. This alkaline environment, provided the concrete is properly placed, can significantly reduce the risk of reinforcement corrosion. However, at low cement dosages (e.g., 300 kg/m³), early-stage corrosion may occur. According to national standards, the concrete cover thickness should be greater in lightweight concrete; however, many practical applications have shown that this requirement is not necessary (Newman & Choo, 2003). Corrosion of reinforcement can negatively affect the bond strength, durability, and service life of the concrete. In steel-reinforced concrete, when high-quality cement is used, it typically exhibits good long-term durability due to the alkaline environment. However, in the case of lightweight concrete, the use of porous aggregates may lead to the penetration of aggressive ions and harmful substances, gradually deteriorating this protective environment (Keleştemur & Demirel, 2015). To improve the microstructure and reduce permeability, pozzolanic additives are commonly used. Keleştemur and Demirel (2015), reported that when 20% MK was used in pumice aggregate lightweight concrete, the pozzolanic reaction of MK enhanced the microstructure and increased the density of the concrete, thereby improving its corrosion resistance.

MICROSTRUCTURAL CHARACTERIZATION OF LIGHTWEIGHT CONCRETE

A) Density and Porosity

The density of fresh lightweight concrete typically ranges between 1400 – 1800 kg/m³. After curing, the dry density is approximately 5–10% lower. According to TS EN 206-1 (TS EN 206-1, 2002), concrete mixtures with a density below 2000 kg/m³ are classified as lightweight concrete, while those with a density below 800 kg/m³ are categorized as ultra-lightweight concrete. Several factors influence these density values such as environmental conditions and the surface-area-to-volume ratio of the concrete element. The use of natural sand as fine aggregate significantly increases the concrete's density. Additionally, when aiming to achieve compressive strengths above 35 MPa, it is often necessary to increase the cement content. However, this also leads to an increase overall density (Newman & Choo, 2003). Lightweight concretes are materials characterized by a high volume of pores or voids within their structure. These pores can constitute between 10% and 67% of the total concrete volume due to the use of lightweight and porous aggregates. As a result, porosity is a critical parameter that significantly influences the mechanical properties and durability of the concrete. Moreover, factors such as the shape and size of aggregate particles, the void ratio between them, and the content of cement paste all affect porosity. Increasing the content of paste helps fill these voids, thereby reducing porosity. Therefore, porosity and density are essential parameters for production control and quality assurance in lightweight concrete (Kurpińska & Ferenc, 2017).

When fine particles such as FA and MK are used, the pozzolanic reaction products help fill the pores within the cement matrix and the interfacial transition zone (ITZ) between the cement paste and aggregates, thereby reducing the overall porosity. Subaşı (2009), reported that lightweight concrete containing 10% FA and expanded clay aggregates exhibited lower porosity compared to the mix without FA. However, when the FA content was increased to 30%, the porosity increased. Similarly, Kelestemur and Demirel (2015), demonstrated that incorporating 20% MK into lightweight concrete with pumice aggregate reduces the porosity of the concrete. On the other hand, nanomaterials contribute to the formation of a denser microstructure and smaller pore sizes by influencing the nucleation and growth of hydration products. These changes have a positive impact on the mechanical and durability properties of lightweight concrete (Zhang et al., 2021). Zhang et al. (2018), observed that even very small content of NS added to lightweight concrete altered the structure of the cement paste's hydration and improve the ITZ between lightweight aggregate and cement paste. Du et al. (2015), investigated the effects of 1%, 2%, and 3% NS additions, concluding that the filling effect of nano-NS reduced porosity, leading to enhanced durability. Similar findings were reported by Sun et al. (2020), using nano-calcium carbonate; and Hong et al. (2023), using nano-graphene oxide. However, to maximize these beneficial effects, it is crucial to ensure the uniform dispersion and homogeneous distribution of nanomaterials within the concrete matrix.

B) Interfacial Transition Zone (ITZ)

Concrete is a heterogeneous material consisting of three phases: the cement paste, the aggregate, and the interfacial transition zone (ITZ) between the cement paste and the aggregates. Although the ITZ occupies only a small volume of the concrete, it has a significant influence on both the mechanical strength and durability of the concrete (Zhu et al., 2017). The behavior of aggregates, cement paste, and the interface transition zone (ITZ) between aggregates and cement paste determines the mechanical properties of concrete (Erdem et al., 2012).

In lightweight concrete, the aggregates have lower strength than the cement paste thus contributing more significantly to failure (Li et al., 2017). Consequently, the ITZ in lightweight concrete is often considered stronger than in normal weight concrete (Wu et al., 2019). Kong et al. (2015), reported that the thickness and stiffness of the ITZ surrounding lightweight aggregates are higher compared to those surrounding normal aggregates Both physical and chemical interactions between lightweight aggregates and the cement paste enhance the mechanical strength of the ITZ. Similarly, Vargas et al. (2017), found that lightweight aggregates help form a denser and thinner ITZ compared to conventional concrete. This improvement is due to their physical and chemical properties, which reduce porosity, minimize the wall effect, and promote C-S-H formation that interlocks well with the cement matrix.

C) SEM, XRD, TGA and FI-IR

In studies conducted on lightweight concrete, various analytical techniques are employed to investigate its microstructure and to identify the chemical changes induced by the incorporation of sustainable or mineral additives (Zhang et al., 2021). Vargas et al.(2017), used XRD, SEM, and XRF analyses to investigate the ITZ characteristics of lightweight aggregates such as pumice, and found that these aggregates formed denser and thinner ITZs compared to conventional aggregates. This improvement was attributed to the surface porosity, chemical composition, and morphology of the lightweight aggregates. In particular, the pozzolanic reactivity of pumice aggregates contributed to stronger bonding with the cement matrix, The ITZ thickness was also influenced by the aggregate shape index; more angular aggregates formed a thinner and denser ITZs. However, while the improvement in ITZ enhances compressive strength, the ultimate strength of the concrete is limited by the strength of the lightweight aggregates used. Additionally, it was observed that increasing the water-to-cement ratio leads to a thicker ITZ (Vargas et al., 2017). Fahmy et al. (2022), investigated the microstructure of lightweight self-compacting concrete incorporating Nano waste class and Nano waste ceramic using SEM and XRD analyses. They found that when two nanomaterials were added, the texture became more compact, small voids decreased, and large crystals were formed. Also, the highest calcium hydroxide (CH) content and the lowest peak intensities were observed, indicating that pozzolanic reactions between the nanoparticles and CH led to the formation of calcium silicate hydrate (C–S–H) gel (Fahmy et al., 2022). Du et al.(2015), studied the effect of nano-metakaolin on the microstructure of concrete through SEM imaging, demonstrating the dispersion of nanoparticles and the relationship between C–S–H crystals and the nanomaterial. In some studies, the cement hydration process was interrupted with acetone or alcohol (Dehghanpour et al., 2022). In the microstructure of lightweight concretes, C-S-H formations are the main phases that determine the density and strength of the cement matrix. This contributes to the improvement of both mechanical properties and conductivity (Dehghanpour, 2023).

After 250 freeze–thaw cycles, Zeng et al.(2023a), examined the microstructure of lightweight concrete after freeze-thaw cycles using SEM analysis and reported that the number of pores and microcracks increased as the number of cycles increased (as shown in Fig. 1). Initially, a dense structure was observed, but after 100 and 200 cycles, crack propagation in the ITZ regions became evident. Furthermore, it was noted that freeze-thaw damage was significantly reduced with the addition of BF and PANF fibers (as shown in Fig.2). Balgourinejad et al.(2022), demonstrated in SEM analysis of lightweight concrete with 0.4% PP fibers that fire resistance increased with porosity and permeability above 400°C, while the microstructure became denser at 200°C. At 400°C, moderate cracks formed in the cement mortar, which were caused by thermal curing and mechanical damage. The reduction in strength was attributed to the weak ITZ between the lightweight aggregate, PP fiber, and cement.

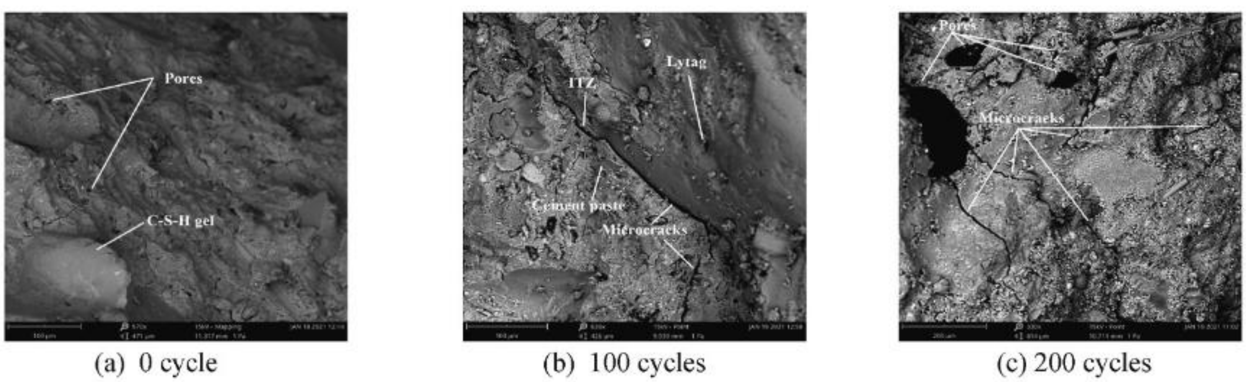

Fig. 1. SEM of Lightweight concrete after 0,100,200 freeze-thaw cycles (Zeng, Li, et al., 2023a).

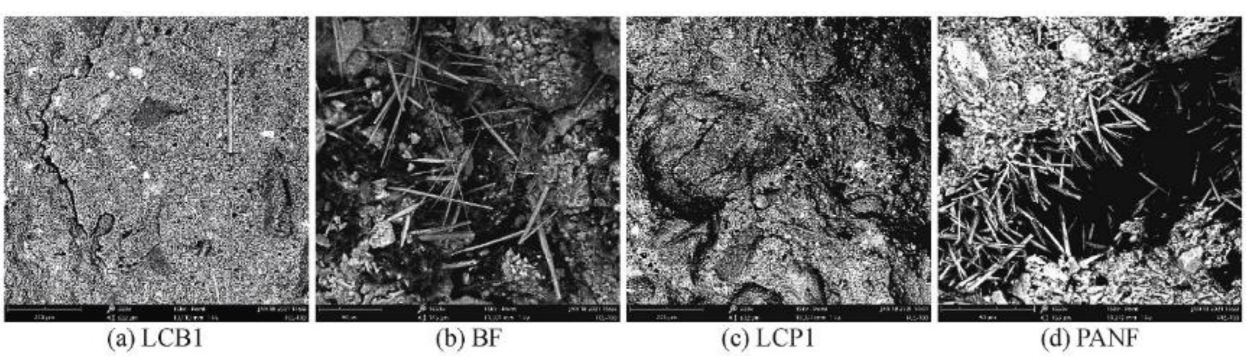

Figure 2. SEM of Fiber Reinforced Lightweight concretes after 300 freeze-thaw cycles (Zeng, Li, et al., 2023a).

PRODUCTION AND APPLICATION TECHNIQUES OF LIGHTWEIGHT CONCRETE

A) Rheological Properties

The rheology of concrete describes the flow behavior of fresh concrete, and this behavior is primarily evaluated through rheological parameters such as plastic viscosity and yield stress (Adebakin et al., 2018). In lightweight concrete, the high pressure generated during pumping of fresh concrete can cause water to press into the porous lightweight aggregates within the concrete. This water absorption can negatively affect the homogeneity and workability of the concrete. To prevent this issue, thickening agent admixtures that reduce water movement are used, followed by the addition of appropriate superplasticizers to restore workability. The type of lightweight aggregate, sand type, and mineral admixtures directly influence the rheological behavior of fresh concrete under high pressure. In this context, mineral admixtures and natural pozzolans are especially utilized in self-compacting concrete (SCC) systems to enhance cohesion and resistance to segregation (Chandra & Berntsson, 2002). Adebakin et al. (2018), demonstrated that the addition of 15% and 20% FA generally had positive effects on the passing ability, stability, and flowability of fresh SCC.

B) 3D Printing Applications

3D printing technology is presented as one of the innovative methods supporting low-carbon development in the construction industry. This technology appealing in the design of low-energy, passive, and zero-energy buildings, where there is a growing need for high-performance thermal insulation (Jaysawal et al., 2022). Due to its favorable thermal insulation properties, the integration of lightweight concrete with 3D printing technology aligns with the objectives of reducing carbon emissions (Sifan et al., 2023). In the literature, 3D-printed lightweight concrete applications primarily fall into two main categories: 3D-printed foamed concrete and 3D-printed lightweight aggregate concrete. In this context, Alghamdi et al.(2019), developed alkali-activated lightweight foamed concrete with a density ranging from 600–1000 kg/m³ using 3D printing technology. Rahul et al. (2020), prepared 3D-printed lightweight concrete by replacing 30% of the sand with expanded clay aggregate. Mohammad et al. (2020) produced 3D-printed lightweight concrete using expanded perlite aggregate and achieved a 67% reduction in thermal conductivity. Similarly, Cuevas et al. (2021), developed 3D-printed lightweight concrete using expanded microspheres and achieved a remarkable 40% reduction in both density and thermal conductivity compared to reference concrete.

Pasupathy et al. (2022), used a combination of expanded perlite and pre- produced foam in 3D-printed lightweight aggregate concrete to minimize the need for foam and achieved a density below 1000 kg/m³. However, the excessive water absorption of lightweight aggregates during the fresh concrete mixing process negatively affects the rheological properties. To address this issue, Deng et al. (2022), used ceramist sand coated with cement paste to reduce surface water absorption of the aggregate. Nevertheless, achieving lower densities in 3D-printed lightweight aggregate concrete remains challenging, and the water absorption issue of lightweight aggregates remains a significant problem.

SUSTAINABILITY AND ENVIRONMENTAL ASSESSMENT

A) Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is an effective method used to evaluate the environmental impacts of a product throughout its entire life cycle, from raw material extraction to production, use, and disposal. The LCA approach is increasingly being applied today to assess the sustainability of construction materials and products such as concrete, brick, cladding, and aggregates. It is recommended that materials consumed in large quantities and directly associated with environmental impacts such as cement, aggregates, concrete, fly ash, and incineration residues be evaluated within the scope of this analysis (Rigamonti et al., 2009).Napolano et al. (2016), conducted a life cycle assessment (LCA) for lightweight concrete made with recycled aggregates. The study involved four different lightweight aggregates (three derived from waste materials and one from raw clay). The lightweight concrete mixtures containing recycled waste aggregates demonstrated lower environmental impacts compared to those using natural lightweight aggregates. In all environmental impact categories, the concrete made with natural lightweight aggregates showed the highest negative effect. Hossain et al. (2016), analyzed the environmental impacts of recycled aggregate production from construction and demolition (C&D) waste and waste glass using the life cycle analysis (LCA) method. Their findings indicated environmental benefits, especially in the production of recycled fine aggregates from C&D waste.

While Yazdanbakhsh et al.(2018), showed that replacing natural aggregate with recycled aggregate in concrete did not have a significant environmental impact based on LCA results. In contrast Rosado et al.(2017), noted that mixed recycled aggregates presented a more environmentally favorable option. Ersan et al. (2022) , investigated the life cycle impact of lightweight concrete incorporating recycled plastic waste and fly ash. In their study, a green lightweight concrete mix containing 20% fly ash as a replacement for cement and 30% recycled plastic waste instead of natural lightweight aggregate was compared to conventional natural lightweight aggregate concrete. The results showed that the green lightweight concrete exhibited a lower environmental impact in the LCA compared to the natural lightweight aggregate concrete.

B) Use of Waste and Recycled Materials

Sustainable buildings play a crucial role in the construction industry, particularly as concrete is scrutinized for its high carbon dioxide (CO_2) emissions, mainly due to cement consumption. Among concrete components, cement has the highest environmental footprint. Cement production is responsible for approximately 5–8% of global CO_2 emissions (Win et al., 2022). In this context, lightweight concrete is preferred in large projects such as high-rise buildings and bridges to ensure structural sustainability and reduce costs and environmental impacts. By replacing natural aggregates with various industrial by-products and waste materials, adverse environmental effects can be significantly minimized (Agrawal et al., 2021). Agrawal et al.(2021), demonstrated that low-density lightweight aggregates and waste materials can be used in structural applications while exhibiting strength comparable to normal concrete.

Today, in addition to natural lightweight aggregates such as expanded clay, shale, and pumice; various waste materials such as C&D waste, crushed clay bricks, rubber, plastic, palm oil shells, and other agricultural residues are also successfully utilized in the production of lightweight concrete (**Bogas, De Brito, et al., 2014)**. These practices make significant contributions to the sustainability of lightweight concrete. While Ahmad et al. (2019) produced concrete with a density range of 800 to 1300 kg/m³ using expanded clay aggregates. He et al. (2016), reported that, compared to conventional concrete, lightweight concrete made with clay ceramist exhibited superior mechanical properties and enhanced fire resistance. Yang et al. (2015), replaced sand with recycled plastic waste at 10–30% in self-compacting concrete. Compressive strength increased up to 15% replacement, as the plastic waste helped fill voids and densify the mix. In addition, various industrial wastes such as FA, GGBS, clinker, rubber, and recycled plastics can potentially be used in the production of lightweight concrete. Adhikary and Rudzionis (2019), observed an increase in the slump flow of fresh concrete when rubber was used as a replacement for fine aggregate along with the addition of fly ash. Ahmad et al.(2020), reported that replacing 10% of sand with palm oil fuel ash in lightweight concrete resulted in higher compressive strength compared to control concrete. Similarly, Muthusamy and Zamri (2016), investigated palm oil fuel ash as a partial cement replacement in oil palm shell lightweight concrete. Its pozzolanic reaction formed secondary C-S-H, improving matrix–aggregate bonding, reducing porosity, and enhancing compressive strength. While Lv et al. (2019), indicated that as the replacement ratio of sand with rubber particles increased, both the slump value and flexural strength of lightweight concrete decreased. This loss in strength was attributed to the poor bond between the rubber particles and the cement paste. Shafigh et al. (2012), investigated the effect of adding palm oil shell (OPS) into lightweight concrete containing expanded clay. Ahmmad et al. (2016) and Zhang and Poon (2015), demonstrated the potential environmental and structural benefits of using higher proportions of industrial wastes, such as palm oil clinker and bottom ash, as alternatives to natural aggregates in concrete production.

APPLICATIONS OF LIGHTWEIGHT CONCRETE

The use of lightweight concrete has been an integral part of the construction industry for many years. Today, due to the development of various types of lightweight aggregates, lightweight concrete is widely used in construction projects such as high-rise buildings due to its density reduction properties, which offer advantages in terms of design and economy (Yun et al., 2013). This characteristic has enabled the construction of numerous bridges in Norway using lightweight concrete with compressive strengths of 55–60 MPa (Youm et al., 2016). Due to its lower thermal conductivity compared to normal concrete, energy-efficient homes constructed with lightweight concrete can reduce heating energy consumption by over 30% during the winter season (Yun et al., 2013). Additionally, it has been found suitable for offshore platforms as it helps prevent excessive displacement (Haug & Fjeld, 1996). According to Jo et al. (2007), alkali-activated fly ash lightweight aggregate concrete can be used as a retaining structure, low-strength concrete filling material, paving material, and in the construction of bridge deck pavement and structural blocks. Oreshkin et al. (2016), used lightweight concrete in the production of window lintels and cottage construction. Bicer and Kar (2017), demonstrated that expanded polystyrene lightweight concrete can be used in buildings as an insulation material, flooring, partition walls, and ceiling applications. Various studies have reported that lightweight concrete can also be used to produce lightweight structural concrete, thermal insulation and road pavements, crash barrier, curbs, and concrete drains (Kiliç et al., 2003; Libre et al., 2011; Yasar et al., 2003).

CONCLUSION

This study is a comprehensive review that investigates the properties, performance, and sustainability aspects of lightweight concrete through analysis of recent research findings. Lightweight concrete has found widespread application in modern construction, particularly in high-rise buildings and precast elements such as floors, panels, and blocks, due to its reduced density, which offers advantages in terms of structural efficiency and cost-effectiveness. However, the use of porous lightweight aggregates typically leads to lower mechanical strength and reduced durability compared to normal-weight concrete. To address these limitations, the incorporation of mineral admixtures such as silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBS), metakaolin (MK), palm oil fuel ash (POFA), and rice husk ash (RHA) has shown promising results. These admixtures contribute through their pozzolanic activity, fine particle size, and pore-filling effect, which together refine the microstructure, reduce porosity, and improve resistance to chemical attack, chloride ingress, and other aggressive environmental conditions.

Nanomaterials such as nano-silica, nano-graphene oxide, and nano-metakaolin further enhance the performance of lightweight concrete by improving fresh properties, densifying the matrix, and increasing durability and mechanical strength. These materials effectively reduce pore size and optimize the pore structure, thereby significantly enhancing resistance to permeability, carbonation, and long-term deterioration. In parallel, the use of fiber reinforcements—especially in hybrid combinations—enhances the flexural and tensile performance, ductility, and toughness of lightweight concrete. Fibers also play a vital role in crack control and fatigue resistance, contributing to longer service life and structural integrity. Although the inclusion of fibers may negatively affect workability, this drawback can be mitigated through optimized mix designs and the use of superplasticizers.

From a sustainability perspective, the integration of recycled materials, industrial by-products, and other waste-based additives plays a critical role in reducing the environmental footprint of lightweight concrete. Life Cycle Assessment (LCA) studies indicate that green lightweight concrete made with recycled or alternative aggregates exhibits significantly lower environmental impacts compared to conventional lightweight concrete. Furthermore, the reduced density of lightweight concrete offers additional benefits such as improved fire resistance and superior thermal insulation. The lower thermal conductivity associated with lightweight mixtures contributes to enhanced energy efficiency by minimizing heat transfer through structural components, making it an ideal material for sustainable and energy-conscious building design.

DECLARATIONS

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Competing interests

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