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An ultra-lightweight cellular concrete for geotechnical applications – A review

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ABSTRACT

For decades, lightweight concrete has been used in various civil engineering applications. Cellular concrete is a type of lighweight concrete that is an emerging composite in materials engineering still. However, due to its low weight, it can be integrated with industrial by-products to develop more advanced composites such as ultra-lightweight cellular concrete (ULCC). ULCC is sustainable and regarded as a potential candidate due to its simplicity of use and other benefits. A systematic review of the potential applications of ULCC in geotechnical construction are presented in this review article. Due to technological breakthroughs and changes in environmental conditions, and their material property is one of the variables that influence the degradation of roadway. Several investigations have been conducted by incorporating different materials into pavement structures to achieve longer-lasting and better pavement infrastructures than those at present. Sustainability benefits, workability, low prices, time, and structural capacity are factors that have been widely focused. This study focuses on the raw materials, production techniques, types, and properties of the ULCCs. The boundary densities of the ULCCs were considered from 400 to 1600 kg/m^3. Structures all across the globe have benefited from the usage of cellular concrete in some form or another. However, much work in this field should be focused on, particularly in geotechnical applications. Geotechnical applications need specific attention to develop this kind of concrete with enhanced qualities. In order to address this need, this review

Abbreviations: CAC, calcium aluminate cement; CSA, calcium sulfoaluminate cement; DSP, dense silica particle; FA, Fly ash; FRC, fiber-reinforced concrete; GGBS, ground granulated blast furnace slag; HSC, high-strength concrete; MDF, concrete, and macro-defect-free; MK, metakaolin; OPC, Ordinary Portland cement; RHA, rice husk ash; SCM, supplementary cementitious material; SF, silica fume; UHPC, ultra-high performance concrete; UHSC, ultra-high-strength concrete.

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paper has extensively focused on raw materials, manufacturing procedures, cellular concrete characteristics, types and uses of ULCC, particularly in geotechnical applications. Furthermore, several limitations and gaps in ULCC application in highway construction are highlighted, and recommendations on further improving its use and performance are provided.

1. Introduction

After introducing lightweight concrete in 1920 [1], Axel Eriksson developed the first cellular concrete in 1923 [2]. In 1934, Siporex was introduced; it is a patented Swiss product made using an Eklund-invented vapor curing technique [3]. Lightweight foamed concrete (LFC) was used in the Soviet Union from 1938 onwards, during which Kudriashoff's production procedures were utilized but only for non-structural elements [4]. In 1950, coal slag from thermoelectric facilities was used to create aerated concrete for load-bearing components in the United Kingdom. Valore conducted the first scientific investigation on lightweight cellular concrete (LCC) in 1954 [5]. With considerable success, cellular concrete was being utilized in oil wells and in excavation as a cementing agent and filler by 1970 [6]. In the 1980 s, LFC was adopted as a subgrade fill for road construction in Japan [7]. The low weight, good fluidity, high strength and thermal insulation properties of LCC have led to find a new class of geotechnical engineering materials [8, 9]. LCC has been used in construction for decades, with volcanic ash as fine aggregate [10].

Advancements in concrete technology and novel materials have improved strength, placement capacity, consistency, and durability [11]. When air bubbles form in a cement paste due to mixing water and proprietary admixtures, ultra-lightweight cellular concrete (ULCC) develops a vesicular structure [12]. LCC is commonly used in geotechnical applications due to its lower weight than soil, extreme flowability and capability to fill cavities of any size and shape and lower cost than most other solutions. ULCC has been used in the landfilling and cavity filling of underground pipelines and filling of highway embankments [13], with respectable construction applications [14]. Experimental investigations have largely emphasized the ULCC's compressive strength, thermal insulation, pore structure, wet density, service life, and material durability [15–17]. ULCC is made with unit weights ranging between 97 and 488 kg/m^2 [18], with pores having sizes between 0.01 and 1 mm and being consistently distributed in the cement paste [10]. These pores are created by injecting a synthetic- or protein-based foaming agent into the material, which reacts physically and chemically with other elements to abduct the air [6,19].

It is possible for these materials to have unit weights as low as 2.3 kN/m^3 [11] due to the fact that they may include between 10% and 70% air voids [6], depending on the quantity of foaming agent applied to the combination. When using ULCC, it is possible to create LCC with very low permeability, with water absorption levels ranging from 3% to 7% and shrinkage of less than 0.3% [20].

Incorporating foam into the cement-based ULCC creates a microstructure with pores, and its mechanical properties vary practically linearly with unit weight [21]. The mechanical and physical properties of ULCC are influenced by porosity and pore structure. Thus, compressive strength improves when the average porosity is reduced [22]. The influence of foam content on the interior pore structure has also been investigated [23]. Thermal insulation and hygroscopic characteristics are improved when foam and micropore content is high, but compressive strength is decreased when the interior pores widen [23]. It has been shown that the microstructure of pore dispersion in river silt bubble-mixed soil [24] has a significant influence on local stress distribution and the eventual mechanism of failure. The durability and the strength of ULCC influences the characteristics of internal pores. Meanwhile, adding multi-walled carbon nanotubes to foamed cement can improve foam distribution consistency and decrease foam size [25]. The studies as mentioned earlier, have shown that pores affect the characteristics of ULCC. Additionally, aerogel concrete (Fig. 1) has thermal

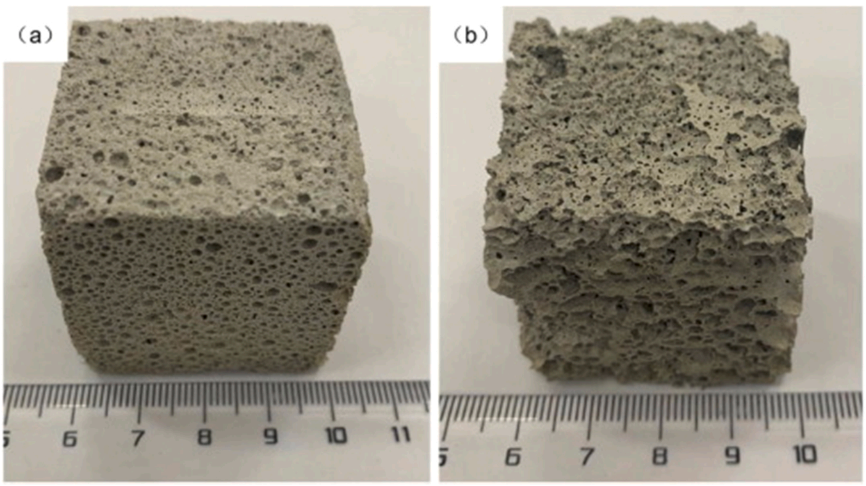

Fig. 1. ULCC samples: (a) with aerogel and (b) without aerogel
Adapted from [26].

conductivity and higher density [26]. As a result, although super-insulative aerogels can exhibit thermal conductivity and reduced density in concrete, the reduction is less than that achieved by inclusion with foam. The higher aerogel content also raises the cost of the material and restricts its use in technical applications.

The influence of the skeleton structure on the strength mechanism of ULCC has also been investigated. A study reported that adding calcined gypsum leads to an increase the strength of ULCC initially and then decrease [24]. Another work conducted an unconfined compressive strength test and a direct shear test on sludge lightweight soil specimens hardened by cement and foam [27]. Strength and failure modes were examined in relation to curing time, cement content, and curing time-dependent failure mode [28–33]. An electron microscope was used to study the microstructure of ULCC samples with different water-cement ratios in order to verify the microstructure and compressive strength properties of the material [34] (see Table 1). The main findings revealed that the water-cement ratio significantly impact the ULCC's compressive strength and microstructure of ULCC. The effects of foam content and the addition of fly ash and silica fume on several mechanical and foam concrete's physical properties have also been studied under different curing conditions [35]. Another research proposed a ULCC durability assessment approach and found that the cement skeleton structure is the primary source of ULCC strength [36]. Concerning the mechanical characteristics Kearsley [37] reported that the compressive strength of foamed concrete drops exponentially with the loss in density. In spite of this, it's important to point out that the existence of this attribute is dependent on a wide range of circumstances, including the size and shape of the element, the technique used to make foam, the route taken by the load and the amount of water present [2]. Kearsley [70] also discovered that as the bubble diameter increased, the compressive strength decreased for dry densities ranging between 500 and 1000 kg/m^3. When the density is more than 1000 kg/m^3, the paste composition is what determines the strength. Fig. 2 shows how the predicted qualities of foamed cellular concrete are linked to the density of the concrete.

Since the turn of the century, fly ash has been one of the most easily salvaged industrial waste products available [42,43]. Fly ash has been progressively incorporated with ULCC as a key admixture to increase strength and fluidity, minimize the amount of cement, and reduce costs and energy use. High-ash foamed concrete may take longer to harden than foamed concrete produced of cement alone [44]. The thermal resistance of cellular concrete is improved by the addition of alkali-activated fly ash [45]. According to studies [46, 47], fluidity wetting strength and durability may be improved by introducing some fly ash to the ULCC. Bridge backfill systems might benefit from the usage of fly ash [48]. Regardless of rolling or water permeability, its weight is half that of fly ash, making it an ideal backfill material [49]. However, the global interest in further exploring the performance of ULCCs has surged. Thus, the most influential factors that have permitted the development of novel technologies connected to ULCCs are comprehensively reviewed, summarized, and elaborated in the current study. This work also highlights the use of numerous active additives and fillers to increase the performance of modified ULCCs for different uses, such as for general and geotechnical applications.

ULCC has grown in recent years. The strength-to-weight ratio has improved and novel cementitious raw materials, foaming agents, and fillers for specialized cellular concrete applications have been developed. However, there is still much work in this unexplored area. It needs special attention to promote this type of concrete with improved properties towards technological advancement in the construction industry. To fill this vacuum, this review article has focused extensively on the raw materials, production techniques, properties of cellular concrete, types and applications of ULCC, especially in geotechnical applications.

2. Ultra-lightweight cellular concrete

Ultra-lightweight cellular concrete (ULCC) is a developing construction material that could be made by the addition of unique functional aggregates, such as micro-silica [52] and expanded recycled glass [53], to the concrete mixture. These aggregates have a grain size that allows them to be used to alternative sand or gravel. Approximately two-thirds of the overall volume is made up of air trapped in the microscopic hollow grains. High air content in the concrete allows for a density of 800 kg/m^3, a thermal conductivity of

Table 1
Difference between ULCC and normal concrete.

Properties	ULCC	Normal concrete	Refs.
Compressive strength	48 MPa	55.2 MPa	[38] [39]
Density	320–1842 kg/m^3	2083–2403 kg/m^3	
Modulus of elasticity	Ultra-lightweight (448 MPa) Medium lightweight concrete (20,684 MPa)	13,790–20,684 MPa for normal concrete	
Shrinkage	Vermiculite: 0.1–0.7% Perilite: 0.1–0.2%,Shale and clay: 0.02–0.08% Slag: 0.04–0.06%	0.04–0.08%	
Thermal conductivity	British thermal unit (BTU) per hour/m^2/degree F/ mm^{2}Vermiculite: 0.1–0.7% Perilite: 0.1–0.2%, Shale and clay: 0.02–0.08% Slag: 0.04–0.06%	BTU, per hour/m^2/degree F/mm^2 Gravel's and sand's thermal conductivity ranges between 8.0% and 12.0%	
Fire resistance	Four-hour rating for 114 mm Slabs with lightweight aggregate	Three-hour rating for 152.4 mm^2 slabs produced from crushed, trap rock, gravel, and limestone aggregate	
Adsorption	1.2%	All mixtures' strength improves greatly as a result of compressive strength and elastic modulus.	[40, 41]
Porosity	3.1%		
Mass loss	10.5%		

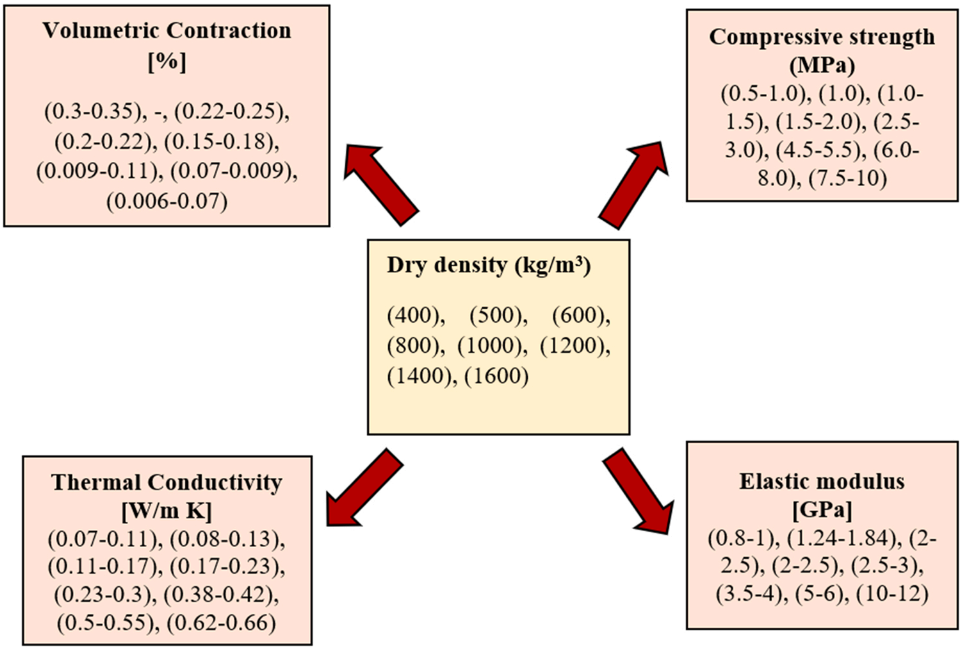

Fig. 2. Properties of ULCC with respect to density [12,50,51].

0.14 W/(mK), and a compressive strength of about 10 N/mm^2 (Fig. 1). ULCC is similar to aerated autoclaved concrete (AAC) blocks, widely utilized in several European and Asian nations [51,54]. AAC and ULCC attempt to combine thermal and structural characteristics in single building material. This attempt provides advantages in terms of recyclability and raw material usage. Both have superior sound insulation and fire protection. AAC can achieve thermal conductivities as low as 0.08–0.12 W/mK with bulk densities of 300–500 kg/m^3 [55]. However, Compressive strength of AAC blocks is generally less than 5 N/mm^2. (Fig. 1). AAC blocks can only be used for two-story low-rise structures due to their lack of reinforcing. AAC's low heat conductivity has been the subject of recent research aimed at increasing structural performance. When specific additives are used, AAC blocks with compressive strengths of up to 7 N/mm^2 are achievable, but the thermal conductivity is shifted to the same range as ULCC [56]. ULCC has the lowest thermal conductivity, density (800 kg/m^3) and the compressive strength (more than 10 N/mm^2) [57]. Another distinction between ULCC and AAC is that ULCC, because of its enlarged recycled glass aggregates, the surface doesn't need to be finished to prevent significant moisture strain and condensed water freezing. [58]. The unusual mix of insulating and structural properties of ULCC materials, it can be used to create a novel architectural concept: monolithic walls. With only 70 cm of ULCC, a load-bearing structure with an RC value of 5 m^{2}K/W can be achieved. This results in an unusual construction that embodies the following paradox: the material ULCC has low thermal inertia (volumetric heat capacity, $\rho \times cp = 700$ k.J/m^3. K). In contrast to multi-layered construction, monolithic applications have a distribution of thermal capacitance and thermal resistance comparable to those of building structures with high thermal inertia. A single-layer building envelope offers numerous promising alternatives of design integration, production methods, and ULCC technologies. In addition to reducing the impact of thermal bridges, ULCC's minimal connections and joints enable for airtight structures.

3. Raw materials for ULCC

The raw materials for creating ULCC as a special engineered concrete are Portland cement, fly ash, sand, water and pre-formed foam in different amounts; they are combined to make a solidified material with an oven-dry density of not more than 400 kg/m^2.

3.1. Portland cement, binders, and sand

Portland cement, sulphoaluminate cement, and calcium cement are the most common binders in the production of cellular concrete [21]. Micro-silica, lime, fly ash, and demolition/construction debris are examples of additional materials that could be utilized to replace cement partially. These materials can serve a distinct function, such as improving consistency and long-term resistance or lowering production costs.

Several experimental advancements that contemplate replacing cement have concentrated on evaluating the use of fly ash, which is recognized for its pozzolanic activity that aids the hydration process [59]. Fly ash reduces cement consumption by 50% and hydration temperature by 40% when used in concrete [60], and increased compressive strength as a result of early reductions in bubble size [61]. The aforementioned implies light densities ranging from 1100 kg/m^3 to 1500 kg/m^3 [62] and after 28 days of curing, the flexural and compression strengths were significantly reduced. [63]. A microstructure investigation has revealed the possible application of fly ash, particularly its use in casting parts. Fly ash has been used as an alternative to sulphoaluminate and other quick-setting cementitious materials by mixing it with hydrogen peroxide, cellulose, and dispersants, among other additives and dispersants. As a result, concrete with ultralow densities ranging between 850 and 1100 kg/m^3; compared with sulphoaluminate combinations, it has a lower thermal conductivity and better durability [63].

Researchers are looking at the possibility of substituting up to 30% of cement with blast furnace slags. When ultrafine particle size is utilized, this waste material improves compressive and flexure strength [64] and helps minimize cracking [65]. It has also been used in conjunction with Portland cement to generate cellulosic concrete, a byproduct of the phosphoric acid manufacturing process, as shown in Fig. 2.

It was shown that just a little amount of this substance might operate as a cementing agent, enhancing compressive strength by stimulating the development of calcium silicate and ettringite [66]. Meanwhile, many experimental studies related to mineral mixes as alternative binders or as replacements for Portland cement have reported that 23% blast furnace slag + 15% fly ash + 12% micro silica of cement weight produces cellular concretes with compressive strengths ranging from 1.1 MPa to 23.7 MPa. Furthermore, superplasticizers increase the compressive strength to 44.1 MPa with good workability, making the material ideal for on-site casting [67]. A simple combination of fly ash and microsilica increases the paste–aggregate interlinks, increases workability,compression strength at densities ranging from 1300 kg/m^3 to 1900 kg/m^3, and improves thermal isolation [68]. Additionally, experiments that adopted a lime + microsilica combination demonstrated that microsilica has a significant effect on the physical characteristics of cellular concrete based on soils. The inclusion of microsilica increases the breadth and regularity of the pores and makes them more rounded in shape, resulting in increased thermal isolation and strength. By adding up to 20% microsilica, the density is reduced to 800 kg/m^3 with a compressive strength of 7.5 MPa. In another research, a combination of fly ash (80%) and blast furnace slag (20%) (with hydrogen peroxide as a foaming agent) was tested for its capability to produce cellular concretes with a density of 270 kg/m^3 [68].

Cellular concretes built completely of geopolymers, rather than Portland cement, are a new development. By combining the advantages of cellular concrete with the use of environmentally friendly geopolymers, this method also has the potential to reduce construction's carbon impact [69]. It is possible to attain compressive strengths of up to 18 MPa at a curing temperature of 60 °C after 28 days of curing using type C fly ash and an alkaline activator (typically NaOH) [42], as depicted in Fig. 3. Foamed concrete (FC) has different pore shapes, sizes, and distributions, according to previous research (FC). The primary drawback of FC is its significant volumetric shrinkage of 0.10–0.36% (5–10 times more than that of ordinary concrete) [69]. Zeolites have also been used as a binder ingredient in the manufacturing of cellular concrete [70].

3.2. Fillers

In cellular concretes with non-structural uses, which are typically associated with very low density, an aggregate is not utilized; instead, fillers are employed to minimize cement usage without adding substantial weight. In the manufacture of structural aerated concrete (densities exceeding 1200 kg/m^3), aggregates of any provenance are utilized. Industrial waste with pozzolanic activity is the most often used filler material. Fly ash is one of the most frequently utilized leftovers to substitute for natural aggregates. Its usage has increased mechanical performance relative to density [71,72] and a 24% reduction in hydration heat at the peak temperature [60]. Though, the inclusion of this material in the mixture produces a low water/cement ratio and improved workability, leading to a product with a higher water absorption capacity, lowered thermal conductivity, and reduced Poisson's modulus [72,73]. Additionally, recycled concrete is a common filler used in the manufacturing of cellular concrete. It has no substantial influence on the compressive strength of recovered concrete [12]. It has also been shown that different percentages of burned ceramic wastes may be used in lieu of aggregates to produce cellular concrete with compressive strengths of 25 MPa and a weight of 1674 kg/m^3 (the optimum replacement value from 25%, 50%, 75%, and 100%) [74] and a 50% improvement in indirect tensile strength [75]. Other materials that have been

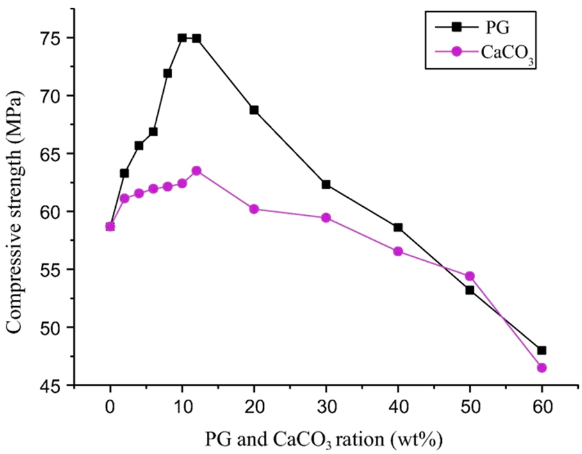

Fig. 3. Influence of calcium carbonate content and Original phosphogypsum (PG)
Adapted from [66].

described as fillers in the manufacture of cellular concrete include polyethylene, polyvinyl chloride, and polystyrene waste [76,77]. This type of waste reduces compressive strength but improves other characteristics, such as acoustic isolation [78], thus allowing cellular concrete to be lighter than 500 kg/m^3 in density [41]. Expanded polystyrene (EPS) stands out among polymer fillers, due to its potential to increase thermo-acoustic insulation characteristics. However, the presence of this filler has a detrimental effect on mechanical performance because it weakens the interfacial paste-filling bond due to the hydrophobic characteristic of EPS. The density and fire resistance of EPS varies according to its composition [79]. Additionally, the utilization of lateritic soils with an optimal replacement value of 5% has been described [9]. Alternatives include combinations of soils and pozzolanas [80] and silica powder with red sand and kaolin [81], as illustrated in Fig. 4. The most significant effects are enhancement in pore distribution homogeneity and thermal isolation. The essential point to note is that even when the porosity is above 90%, the foam is virtually totally closed cell. This foaming process for ceramic materials frequently results in the formation of reticulated structures exceeding roughly 80% porosity [82].

3.3. Pre-formed foam

Pre-foamed is beneficial in regulating the density and porosity of cellular concrete by including air bubbles [21]. In the hardened condition, foaming agents control the characteristics, such as density, pore distribution, and strength performance. In the fresh state, controlling the characteristics of cellular structures is difficult due to the tendency of foams to collapse during the preparation process. Hence, improving the stability of new foams is important to generate high-quality cellular structures in a predictable and repeatable manner [83]. Pore distribution and size, which determine the ultimate strength, are primarily affected by the agent concentration employed in cellular concrete [84]. As a significant part of foam cementitious composites, foam is prepared by pre-forming foam or mixed foaming. The pre-foaming process demands the use of a compressed air tool to produce pre-foamed air bubbles, which can be incorporated into a fresh mix of cementitious composites, leading to a cellular structure [6]. This method can use either dry or wet foam. Dry foam is prepared by subjecting the foaming agent to several restrictions and compressed air in a mixing unit. Dry foam is comparatively more stable than wet foam that eases the blending process [51]. In wet foaming, an aqueous foaming agent is sprayed over a fine mesh with a size varying between 2 and 5 mm [5]. The pre-foaming method, wherein a stable aqueous foam and a base mix are made separately and later appropriately mixed [85,86].

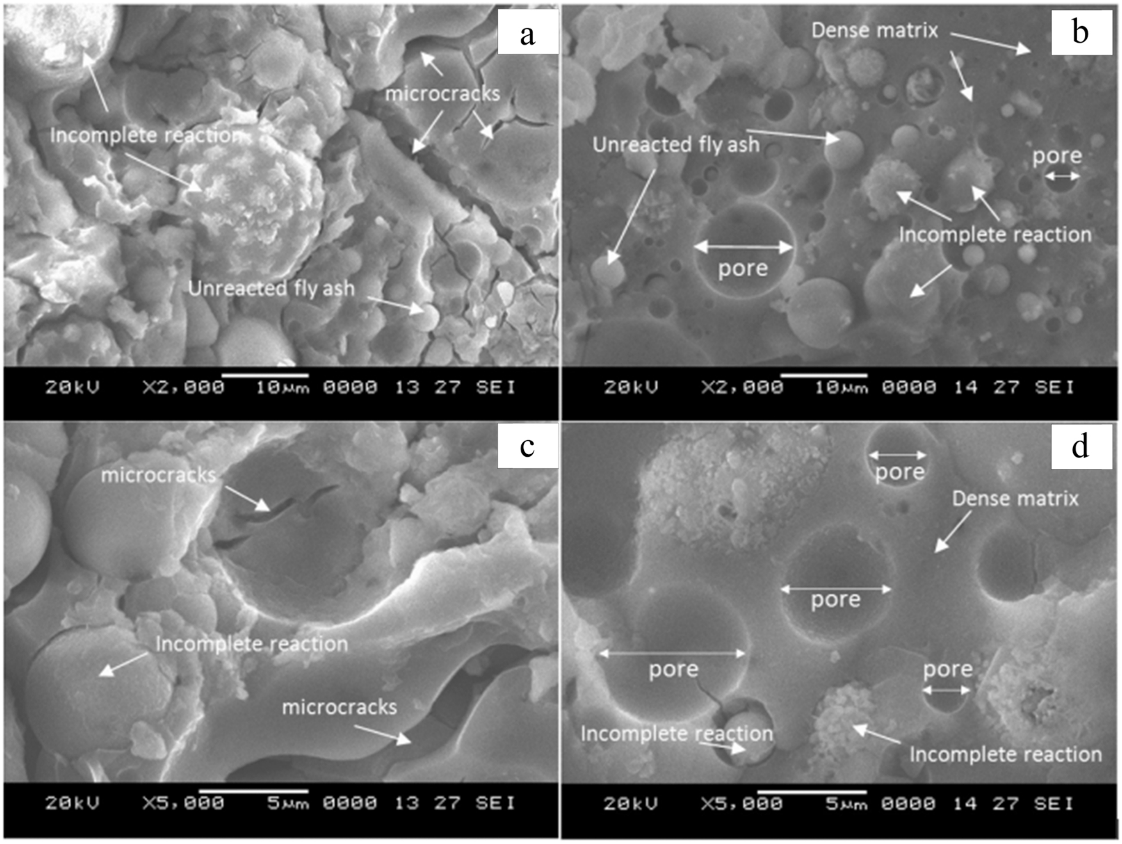

Fig. 4. (a) LW1 at a 2000 × exaggeration; (b) LW2 at a 2000 ×exaggeration; (c) LW1 at a 5000 × exaggeration; (d) LW2 at a 5000 × exaggeration Adapted from [42].

The foam generated during the mixing process leads to a porous structure in the resulting cementitious composite. Synthetic and protein-based foaming agents are highly popular, but detergents, glue resins, and saponins can also be used [86]. Protein-based foaming agents are generally prepared from naturally available hydrolyzed proteins. A protein agent's mechanism of action is its breakdown, which produces bubbles. Small hydrophobic molecules are produced when large molecules' bonds are disrupted. This procedure decreases surface tension and generates air bubble interfaces. Temperature and pH affect the efficacy of these agents [6]. The effect of two different foam (protein and synthetic) on slump and plastic density is shown in Fig. 5. Fig. 5(a) shows that the slump of the foam rises with increasing plastic air concentration, regardless of the type of foam used (protein and synthetic). This trend is good-aligned with the earlier research, which indicates that increasing air content is associated with a drop in plastic viscosity; this indicates a positive correlation with an increase in slump. Once the air content reaches percent, there is a less noticeable change in the slump. There are distinct differences in the air entrainment mechanisms of protein-forming and synthetic agents. Degradation of proteins in the former causes air bubbles to develop. Hydrophobic tiny molecules are produced when the peptide linkage of big protein molecules breaks. Hydrogen bonds between chemical groups aid in forming stable air bubbles by reducing the surface tension of the solution results in creating an interface for air bubbles. When using protein foaming agents, temperature and pH impact their efficacy. A significant linear connection exists between the plastic density of concrete and its air content, as seen by Fig. 5(b). The density does not seem to be affected by the kind of foam that is utilized.

Many studies have revealed that protein-based agents allow for a strong and closed pore structure, resulting in a stable web of empty spaces [12,87–89]. Notably, synthetic foaming agents, such as highly hydrophilic and amphiprotic chemicals, lower the surface tension of the dilution, thus allowing for increased expansion and therefore reduced densities. However, because these agents generate a complicated chemical environment, surfactant and cement compatibility are critical for allowing the required entrance of air and the formation of the cell microstructure [6]. When it comes to compressive strength, both protein and synthetic agents are comparable. But the advantages of synthetic agents outweigh the disadvantages of protein-based agents [21]. Protein-based foaming agents can also produce smaller isolated spherical air bubbles and higher compressive strength [6,90,91]. Another crucial task is to use the right foaming agent in conjunction with the right water/cement ratio. Synthetic foaming agents create FC specimens that are more stable than protein foaming agents at a fixed water/cement ratio [90]. To emphasize the strength gain obtained with the superplasticizer, When using a superplasticizer to achieve a certain target dry density, a compressive strength histogram is shown in Fig. 6.

According to the superplasticizer, a rise in compressive strength of about 11%, 26%, and 9% is achieved under air curing, cellophane curing conditions, and water curing conditions, respectively. The synthesis of agents based on highly efficient artificial enzymes with biotechnological origins has improved foam stability and accelerated concrete pumping. The introduction of new agents improved the final properties by providing enhanced freezing resistance and reduced mixing water needs without sacrificing slump. Aluminum powder and hydrogen peroxide can be combined to make a foaming agent. Although this combination expands rather than foams, even at low densities, it has the ability to build linked holes that are smaller than those formed by foaming agents [69]. Coadjutants, such as oxides and silica nanoparticles, have also been utilized to improve the robustness of bubble boundaries in triphasic foams. Nanoparticles are delivered to the air-water interface in these foams by partial hydrophobing caused by surfactant adsorption, resulting in stable Van der Waals interactions. Materials with a stable and uniform pore structure and increased strength can be feasible to create densities below 100 kg/m^3 [92]. The gas-liquid interface has also been altered by combining the actions of an organic surfactant and nanoparticles. To prevent bubbles from coalescing, researchers add nanosilica and hydroxypropyl methylcellulose. Adding this organic surfactant and nanoparticles, a more uniform and finer pore structure than the one before is created [93]. The foam stabilizer xanthan gum (which has a thickening capability) has also been used to aggregate the bubbles' liquid layer. This stabilization technique has been demonstrated to improve the pore size distribution and decrease bubble coalescence [83]. The general mixing method adopted for of ULCC containing prefoamed can be broadly divided into three steps. First of all, the cement

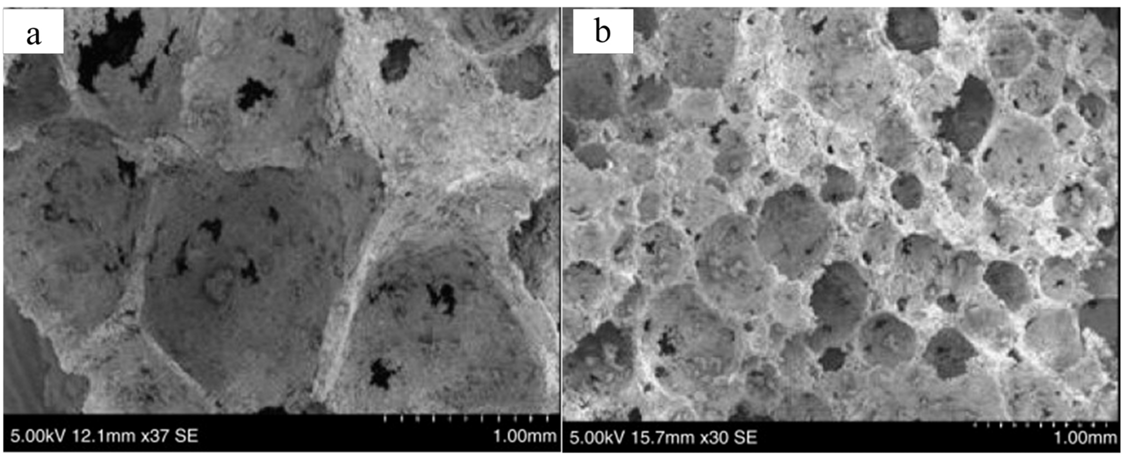

Fig. 5. SEM images (a) higher exaggeration depiction displaying that the foam is closed cell and (b) 91% porous foam produced with 13.5% OPC Adapted from [81].

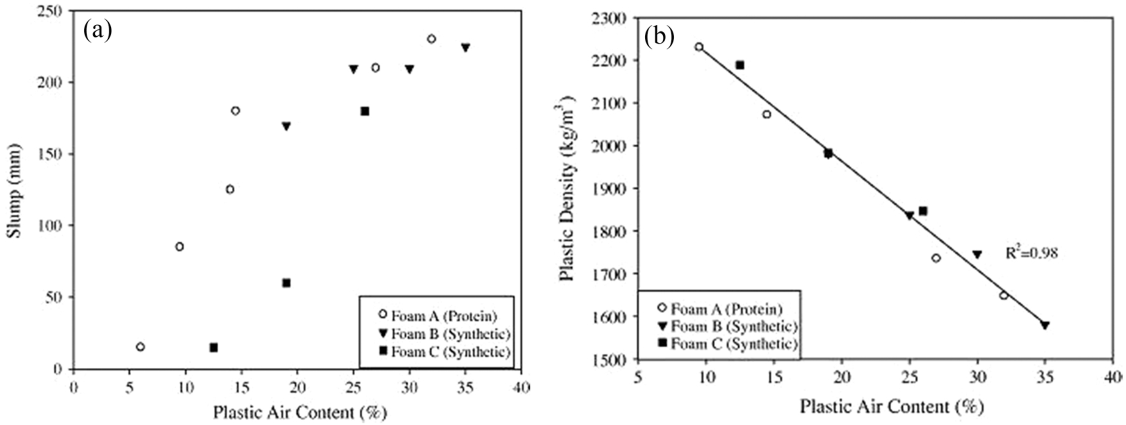

Fig. 6. Effect of foam type (a) slump–plastic air content, (b) static elastic modulus-air content
Adapted from [6].

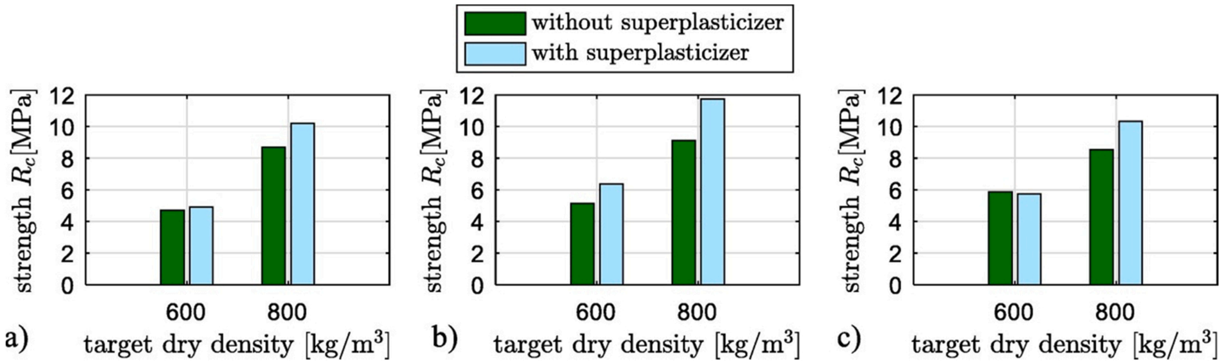

Fig. 7. Compressive strength of FC (a) air; (b) cellophane; (c) water
Adapted from [90].

slurry is prepared as per the design requirement. Secondly, the foam is produced. It is should be noted that the preparation of both cement slurry and foam should be done simultaneously, and the foaming agent is diluted at a dilution ratio of 1:30–50, before foaming. Finally, cement slurry and preformed foam are added to produce ULCC. However, mixing of cement slurry and preformed should be done with the provision of continuous mixing to achieve a homogenous mix [5]. To ensure the quality of pre-formed foam based ULCC prepared, electronic control system is used to monitor the construction parameters in the real-time. These construction parameters generally include the flow rate of foaming agent, compressed air, cement slurry, and ULCC. Though the production of ULCC using prefoamed foam is expensive as compred to the normal mixing method, but it produce a more efficient better quality foam. Moreover, the preformed method is more extensive owing to some comparative benefits with in-mixing method such as consumption of less foaming agent, cost reduction, direct relation between the porosity in the mix and quantity of foaming agent used.

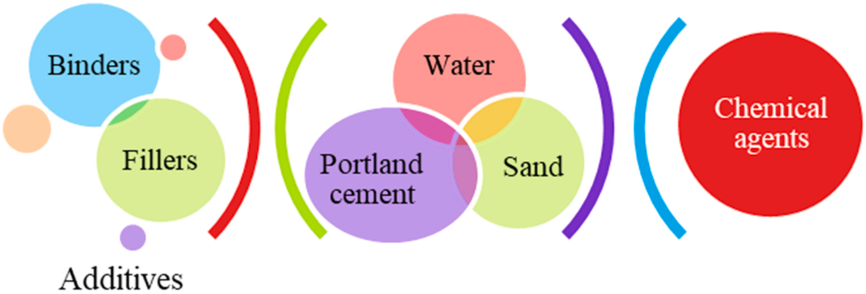

Fig. 8. Raw materials of ULCC.

Table 2 (a)
Raw materials and properties of different ULCC modified composites.

Function	Type of additive	Ratio of additive	Physical properties			Mechanical properties 28 days		Notes	Refs.
		Binder	Dry density [kg/m^3]	Thermal conductivity [W/mk]	Porosity or sorptivity, % or mm (Shrinkage, %)	Flexural strength [MPa]	Compressive strength [MPa]		
Cement replacement	Fly ash, class F	1:1	650–1150	–	31%– 34%	–	4–19	–	[97]
		1:3	–	–	2.5 mm (0.37)	–	5.5	–	[71]
	Fly ash	1:0.25	1000	–		–	1.4	–	[60]
		0.3	800	–	56%	–	3.92	–	[61]
		1:1.5	1000–12001300–1500	–	< 10% (0.06–0.10)	–	3.7–6.710–18.8	Structural blocks	[98]
	Fly ash, class F	1:0.3	1590	–	(150–550)	–	12.1–32.1	Different curing conditions	[99]
	Fly ash + silica fume + blast furnace slag	1:20	1020–1550	0.24–0.75	–	–	4.2–44.1	Massive casting in situ and of filling casting	[67]
	Fly ash class F + blast furnace slag	0:51:9	1889–2106	–	12–25.4%	5.01–6.87	38.3–47.8	SCC slump 260–280 mm	[100]
	Fly ash + peroxide	1:0.4	100–300	0.043–0.078	80.3–70.9%	–	0.12–1.0	–	[101]
	Fly ash + silica fume	1:1.51:2.5	1280–1870	0.498–0.962	–	1.4–5.3	19–47	–	[68]
	Sugarcane filter cake	0, 0.05, 0.1, 0.15, 0.20	11001000900	0.878–0.718	14–30% (−800 micro -strain)	0.7–1.40.6–1.20.5–1.1	1.7–3.51.5–2.71.2–2.2	Spread: 45% ± 5%	[63]
	Blast furnace slag	1:6	153–303	0.05–0.071	6.6–8.3%		0.57–1.1	Reinforced with PP fiber	[65]
		0.3–0.7	1300		–	6.1–2.2	2.2–0.5	–	[64]

Table 2 (b)
Raw materials and properties of different ULCC modified composites.

Function	Type of additive	Ratio of additive Binder	Physical properties			Mechanical properties 28 days		Notes	Refs.
			Dry density [kg/m^3]	Thermal conductivity [W/mk]	Porosity or sorptivity, % or mm (Shrinkage, %)	Flexural strength [MPa]	Compressive strength [MPa]		
Aggregate replacement and filler	Palm oil fuel ash	0.1–0.2	1000	0.65–0.74	–	1.36–1.8	3.28–5.22	Elasticity modulus: 0.37–0.093 GPa	[72]
	Laterite	0, 10, 20, 30, 40, 50%	Function of curing method		–	–	4–12	Spread:580–0 mm	[41]
	Laterite	0, 5, 10, 15%	800–1800	0.17–0.55	–	–	40–5	–	[41]
	Waste clay brick	0, 25, 50, 75, 100%	1631–1734		15.98–19.29	–	25.91–6.25	–	[73]
	Plastic wastePE + PVC PVC and PE	0, 2.5, 5, 0, 20%	1950–14502050–17501950–1500	1.467–0.6631.467–0.7691.467–0.774	8.2–20.67.7–17.17.8–16.1	4.5–1.04.5–1.44.1–1.3	29.9–3.431.9–6.630.8–4.0	Flexural and compressive strength increases with age	[75]
	Soil	100%	780–1825	0.2–0.55	–	–	4–42	–	[9]
	Clay brick	0, 25, 50, 75, 100%	750–550	↓ 40%	65–72%	–	3.0–1.9	Aluminum addition	[74]
	Recycled waste glass and PP	1:11:0.33	1253–1599773–1248	–	13.3–31.319.5–44.7	–	5.28–10.261.53–6.06	Superplasticizer increased strength	[102]

Table 2 (c)
Raw materials and properties of different ULCC modified composites.

Function	Type of additive	Ratio of additive	Physical properties			Mechanical properties 28 days		Notes	Refs.
		Binder	Dry density [kg/m^3]	Thermal conductivity [W/mk]	Porosity or sorptivity, % or mm (Shrinkage, %)	Flexural strength [MPa]	Compressive strength [MPa]		
Mix cement and filler replacement	Silica fume + soil	0.05–0.2	758–790	0.155–0.195	18–40%	–	4–8	Finer pores	[103]
	zeolite + salt waste + PP fibers + fly ash	0.1, 1 kg/m^3	650	–	76.4%	–	2.7	Pore size: 0.16–0.21 mm	[70]
	Portland cement + alumina cement + silica fume PP + latex fibers	1:0.16(10%SF + 6% HAC), 75.5–86% 0.1%PP + 0.2%	332–489	–	75–90%	–	0.7–2.5	Elasticity modulus: 0.7–2.5 GPa	[78]
	Soil + quick lime	0.05–0.15	1047–1650	0.2–0.73		–	4–28	Broken foam	[103]
	Silica fumeSoil	0.05–0.15, 100%	821–855	0.166–0.19	–	–	3.8–7.5	–	[9]
	Red sand Silica powderKaolin	3:1, 2:13:1, 2.5:1, 3:1	903, 8001,065,650, 800		–	–	5.9, 2.05.60.5, 1.2	–	[80]
	Poly-olefin Fly ashMacrofibers Microfibers fibrillated	1:3, 0 0.55 volume fraction (0–5 kg/m^3)	800–900	–	–	–	3.91–8.445.94–6.58	Masonry block	[104]
Foam replacement	Bentonite	0%, 10%– 50%	300,600	0.085–0.0590.153–0.127	36.8%, 39.3%24.4% 30.3%	–	0.9–0.44.8–3.0	–	[105]
	Food additives: iota carrageenan gum and methyl cellulose	0.15	140–630	0.11	92%	–	Very low	Glass fiber: 18 μm diameter	[81]
LCC admixtures	Silica fumePVA fibers chemical admixturesCenospheres	12:13%0.5, 0.9, 0.2% 335 kg/m^3	1450	–	–	2.6–5.0	52–63.3	Elastic modulus: 16.5 GPa	[106]

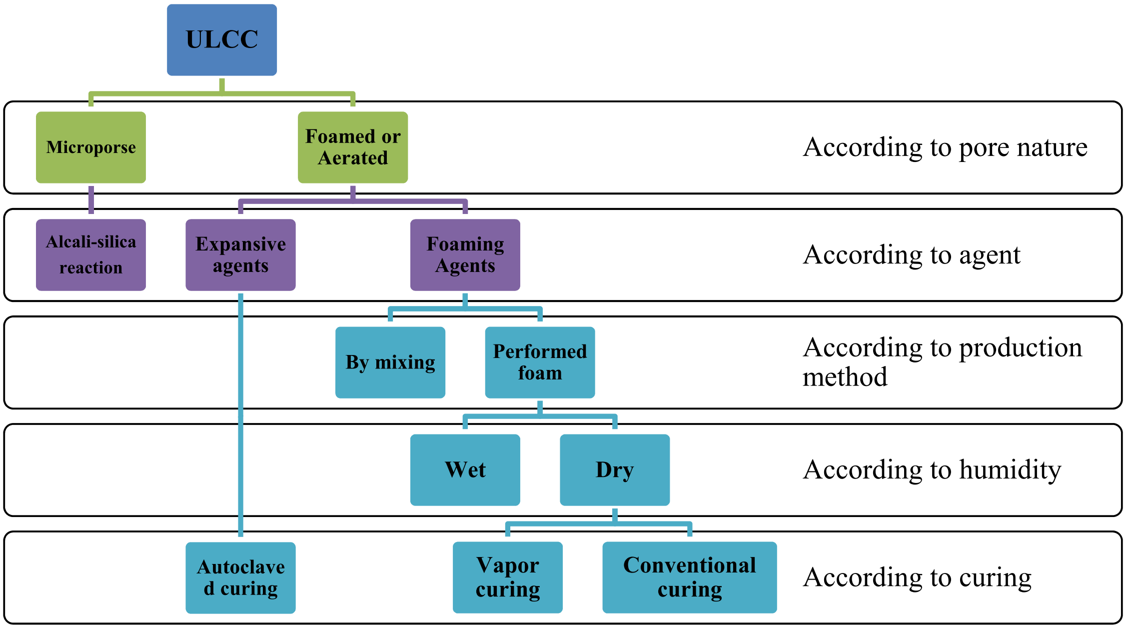

Fig. 9. ULCC classification
Adapted from [3].

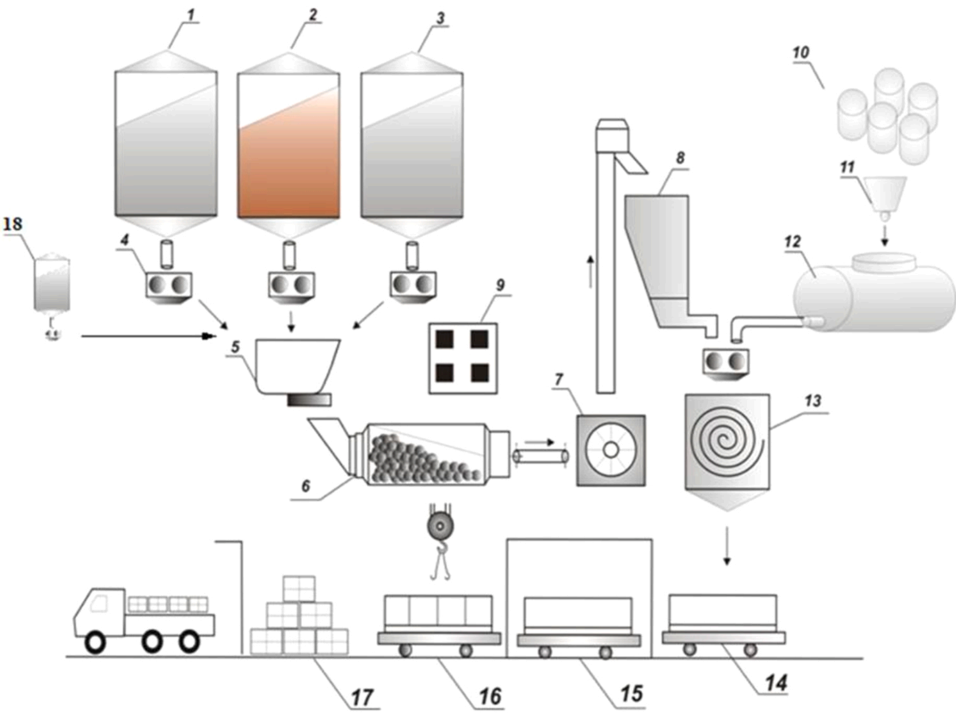

Fig. 10. Production of concrete via batch mixing: 1—PC bin; 2—marl bin; 3—binder bin; 4—weighers; 5—mill bin; 6—mill; 7—air pump; 8—blended binder bin; 9—control room; 10—foamer; 11—volumetric distributor; 12—foam producer; 13—FC blender; 14—moulding zone; 15—strength gain zone; 16—stripping zone; 17—packing and storing; 18—superplasticizer bin
Adapted from [107,108].

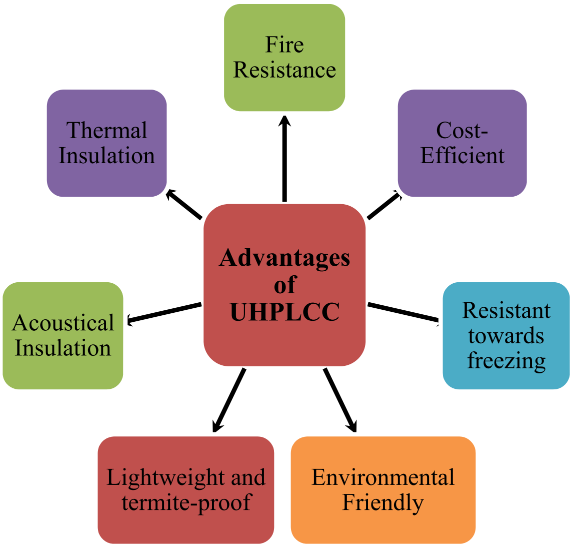

Fig. 11. Advantages of ULCC.

3.4. Water

The quantity of water required to produces cellular concretes is determined by several parameters, including the composition of the binder ingredients, as shown in Fig. 7, the kind of filler used, and the desired workability. Low water content produces stiff mixes that

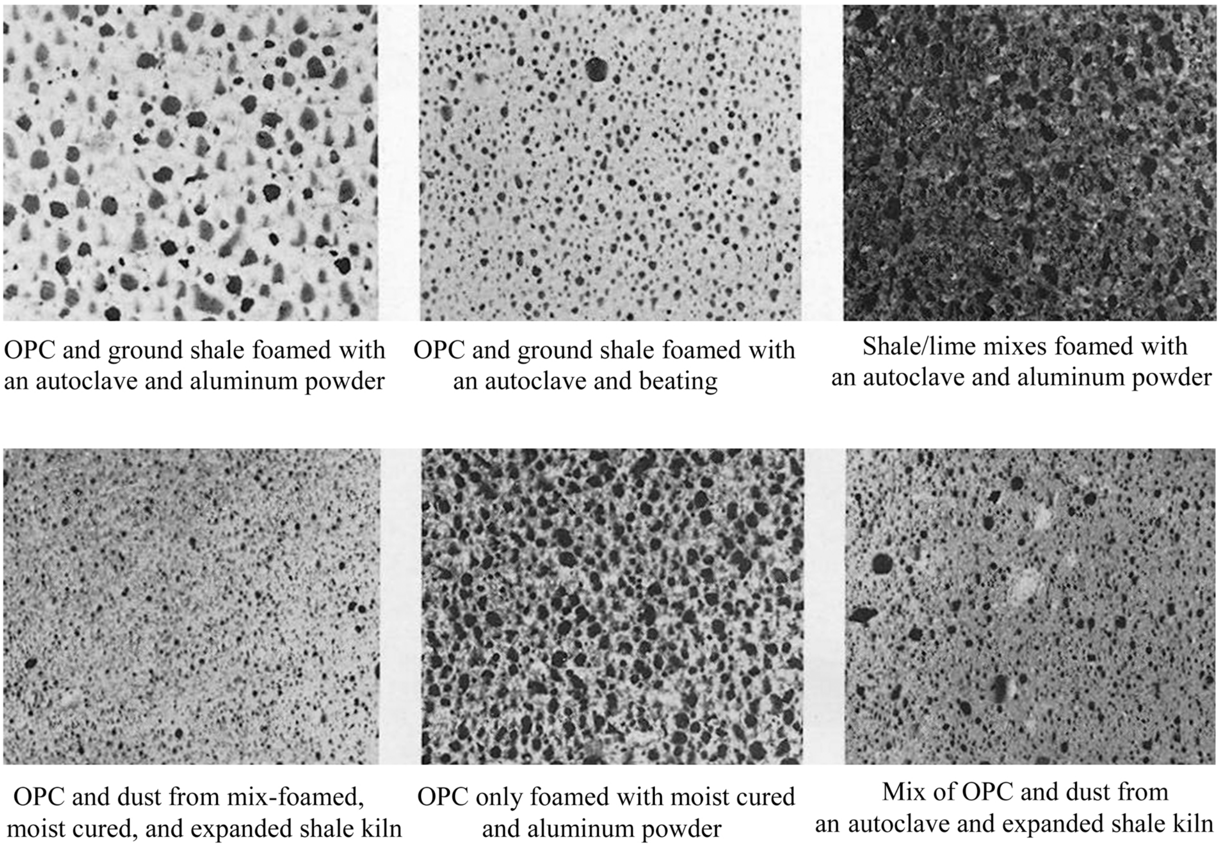

Fig. 12. Textures of various ULCCs
Adapted from [119].

enable bubbles to rupture; Thin mixes with a high water content lead to material segregation. The water/cement (w/c) ratio ranges from 0.4 to 1.25; the latter value is obtained when no superplasticizer is used. Water content is a critical factor in determining concrete strength because it is primarily related to the created voids and The cement contains evaporable water, therefore lowering the w/c ratio would be beneficial which facilitates the achievement of high strengths. Water consumption may be reduced by using the right combination of superplasticizers and mineral mixtures [5]. According to ACI 523.3 R.93, the pure water should be used to produce FC, presence of impurities or organic components cause the performance of foaming agents, particularly protein-based foaming agents.

4. The production technique of ULCC

Batch mixing and auger mixing are the two production systems generally used to mix the cement and water in LCC [94]. Fig. 8 depicts a variety of methods for producing cellular concrete [3]. Foaming agents are the perfect way to make cellular concrete since the compressive strengths are greater [4]. In Fig. 8, a stable cellular concrete mixture is dependent on several parameters, including the foaming agent, the foam generation process, and the design of a cellular concrete mixture [5]. The high rotational speed of the mixer used in the mixing technique generates bubbles due to the addition of a foaming agent [21]. This procedure is simple to carry out, well-documented, and often used [89]. This method, however, might result in a large volume of bubbles that have been destroyed, reducing the quantity of air involved [88].

A compressor is used in the premade foam process to produce air bubbles that will subsequently be used to construct cells in a mortar mixture [95]. Wet or dry, the pre-formed foam may be used [89]. Dry foam is simpler to mix and pump because it is more stable and forms bubbles with a diameter of less than 1 mm [88]. The wet foam creates bubbles between two and five mm in size but is less stable than dry foam [12]. Compared to the mixing process, prefabricated foam is a more costly procedure, but it produces a higher-quality foam [96]. Premade foams are preferable to in-mixing foams because they use less foaming agent and there is a direct correlation between the amount of agent used and the amount of air contained in the mixture [5]. The raw materials used to produce ULCC and mechanical properties are demonstrated in Table 2.

4.1. Batch mixing

Batch mixing has long been the standard method for producing concrete mixes in the industry [107]. In this method, all raw materials, aggregates (fine and coarse), admixtures, cement, and water are weighted and batched, at the cement and aggregate weight hoppers and at the admixtures reactors. Most batch mixing plants have different compartments for aggregates, cement, and admixtures based on the size and type [108]. There is only one weigh meter for weigh hoppers; therefore, each type of mentioned raw materials are added consequently rather then adding the altogether. The water can be controlled via meter required to ensure consistency of concrete. For the effective mixing of constituents, twin shaft mixer is commonly used to certify thorough mixing of concrete until its appearance gets uniform and all constituents are uniformly distributed [107]. Finely, the freshly mixed concrete is loaded in agitated or non-agitated trusks for delievery to construction site. The process of batch mixing is shown in Fig. 9 [108]. This method can be used with any type of concrete, including ULCC and any batch mixer.

4.2. Auger mixing

Auger mixing is generally conducted in mobile volumetric concrete trucks and entails blending the materials with a spinning shaft and flange (auger). The raw materials are received at one end of the auger, which rotates and mixes the components as they are pushed down. A progressive cavity pump is used in most ULCC placement devices. This pump is highly stable with no pulsation, and it maintains itself clean on the inside while in use. ULCC can also be transported using peristaltic pumps. The cementitious ingredients are separated from the pumping motor with this type of pump. Additionally, piston pumps are utilized to move various fluids and slurries, including ULCC, because of their exceptional dependability and robustness. A check valve and a piston retraction system are employed in piston pumps to draw in the material and subsequently push it out.

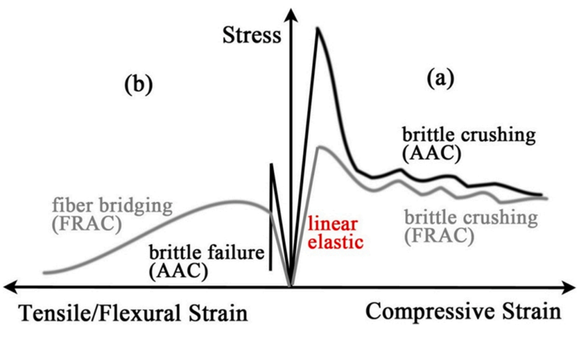

Fig. 13. Stress–strain curves for (a) AAC and (b) FRAC
Adopted from [137].

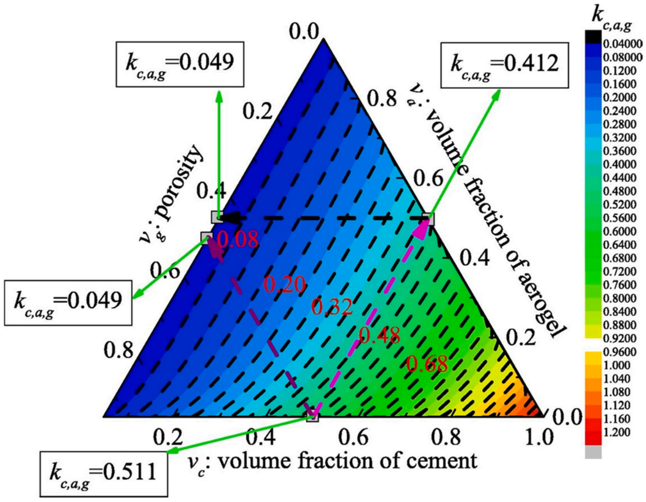

Fig. 14. Ternary graph for aerogel FC representing the relationship among thermal conductivity, porosity, and volume fraction of the binder and aerogel
Adopted from [26].

5. Cellular concrete properties

Cellular concrete is similar to self-consolidating concrete in that it is meant to provide ideal flowability and compactibility, which are regulated in part by the quantity of water and foam used in the mix. The growth or burst of air bubbles may be impeded by a stiff concrete mix, and abundant fluid slurry or fluid concrete mixture may not be able to retain bubbles and the homogeneous distribution of the components, leading to the separation of the mixture components. To ensure stability, the density ratio (i.e., the density ratio in fresh and hardened states) should be close to 1:1 [5].

The compressive strength and density of cellular concrete have been studied by several researchers [109,110]. Compressive strength is a function of dry density, and it decreases quickly as density decreases [44]. As a result of research into the relationship between density, compressive strength and air content, it has been discovered that increasing air content does not cause an increase in void size, but rather increases the number of voids per unit volume; as a result, density decreases without a significant reduction in compressive strength [111]. These results indicate that when the optimal air content is surpassed, air spaces coalesce, the size of the void increases, and strength is reduced. At a water-to-binder ratio of 0.3, the ideal air content for an FC comprising 50% regular Portland cement and 50% ground granulated blast furnace slag is 42%. Furthermore, in FC, the compressive strength is more strongly influenced by air gaps than the elastic modulus. Determining the effect of the hydration heat of cellular concrete poses a more serious challenge in understanding the hardened properties of concrete than the strength–density relationship because more factors influence heat development in cellular concrete than in normal-weight concrete [60].

Density and the type and weight percentage of aggregate significantly affecting heat capacity per unit volume in cellular concrete, with the latter having more variance than in conventional concrete [112]. Hydration heat cannot readily disperse in cellular concrete due to the comparatively high amount of air, resulting in a high temperature inside the concrete; meanwhile, density has an inverse relationship with such impact. Further study is needed to determine the current hydration models for normal concrete apply to cellular

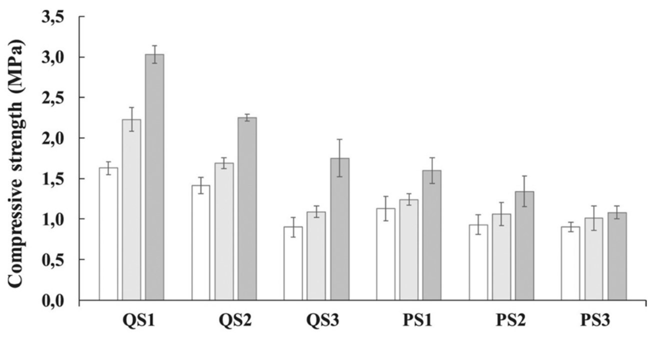

Fig. 15. Compressive strength of cellular concrete with sand and EPS (Adopted from [159]), Annotations: QS: Quartz sand incorporated with cellular concrete and PS: EPS incorporated with cellular concrete.

concrete [96,112–114]. Further, Fig. 9 shows some of the advantages of ULCC. Despite many advantages in ULCC, there are a few disadvantages, including complications in finishing, mixing time is longer and compressive and flexural strengths are affected by decreasing density.

6. Types of ULCC

Cement-based lightweight fill (which comprises cellular and lightweight aggregate concrete) and plastic-based lightweight fill are the two main varieties (which includes expanded polystyrenes and high-density polyurethanes). Cellular concrete (also known as FC) and high-density polyurethane (HDP) are two common types of lightweight fill.

Lightweight concrete is classified based on its unit weight or density, typically varying between 320 and 1920 kg/m^3 [21,77,115]. In terms of strength range, LCC's are classified into three types: low-density (0.7–2.0 MPa), moderate-strength (7–14 MPa), and structural (17–63 MPa) concretes [116], and the densities of these concrete classes range within 300–800 kg/m^3, 800–1350 kg/m^3, and 1350–1920 kg/m^3, respectively. The United States has been using lightweight concrete since the early 1900 s in massive construction such as offshore platforms, long-span bridges and multistory buildings [117]. There are several benefits to using low-density lightweight concrete in the building industry, including decreased dead load, reduced transportation cost, and high building rate, because of its excellent heat resistance, low shrinkage, low thermal conductivity and low density [118]. Lightweight concrete can be created through various methods, a lightweight aggregate or matrix is the most prevalent. Fig. 11 depicts the textures of various ULCCs.

6.1. Autoclaved aerated concrete

Natural pumice aggregate and man-made sintered aggregate, such as sintered fly ash, are two the options for lightweight aggregate [117]. Similarly, different aerated concrete, or FC types can be classified as either autoclaved aerated concrete (AAC) or air-cured FC [120]. Aerated concrete can be divided into two types: FC and AAC. Various detergents, resin soap, adhesive resins, or proteins (e.g., keratin) can be used as foaming agents [51]. Mechanical or physical methods can be adopted to add foam [120]. The creation of foam through the mechanical method involves pounding foaming agents together. The creation of foam through the physical method involves adding a foaming solution to the mixing process [121,122]. When it comes to creating even pores, the latter method has been demonstrated to be more reliable than the former [116]. Typically, this FC is air-cured. AAC is a type of lightweight concrete produced by infusing gas bubbles into fresh concrete then curing the concrete in a high-pressure steam curing chamber, which is referred to as an autoclave [89,114]. This process is often used to make AAC blocks because of the evenly developed cellular structure generated in the cement paste or mortars of air gaps in the range of 0.01–1.01 mm in the autoclaved aerated concrete [12,88,117].

AAC has been manufactured as a construction material since the early 20th century [123], with the first commercial production being in Sweden in 1923. Since then, AAC building systems, such as masonry bricks, reinforced slab panels, and lintels, have been employed in every continent and climate. AAC can also be hand-sawn, made, and pierced with nails, screws, and other fasteners. Quartz powder (or fly ash), gypsum, lime, cement, water, and minor quantities of aluminum powder are all common ingredients in AAC, which is subsequently reinforced and hardened by steam pressure [124,125]. Compared to conventional concrete, AAC offers

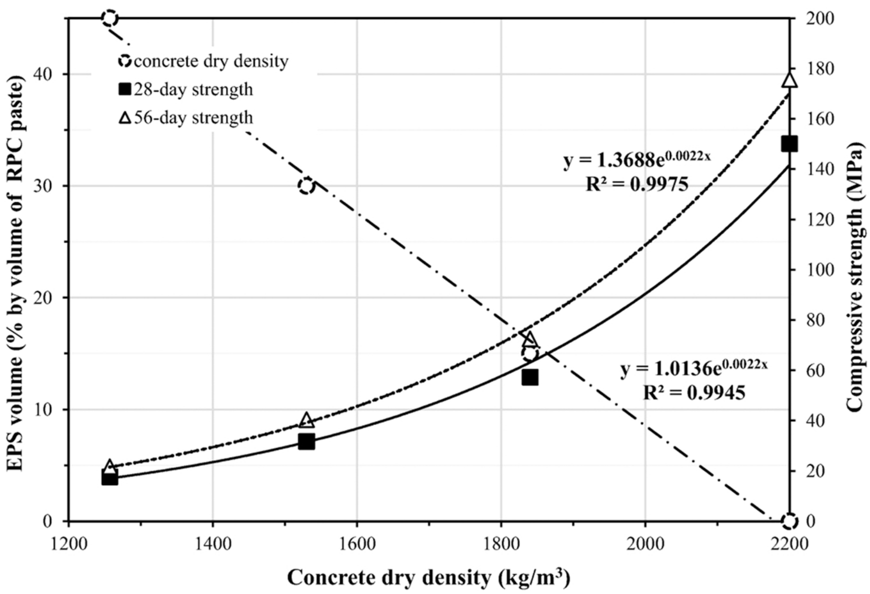

Fig. 16. Green lightweight reactive powder concrete density versus EPS volume
Adapted from [164].

superior thermal insulation characteristics and lower density [126–128]. However, AAC materials have certain disadvantages, its commercial usage is limited by their extreme brittleness and poor mechanical strength. [129–131]. The incorporation of fibers can counter the brittle nature of AAC (e.g., polypropene fibers [132,133], carbon fibers [132,134], glass fibers [134], etc.) that can provide sufficient ductility to ACC in a similar manner as fiber-reinforced aerated concrete (FRAC). Incorporated fibers can bridge the macro- and micro-cracks of AAC. For instance, the ratio between residual strength and peak strength in FRAC is higher than that in ACC, leading to the failure of AAC [135], as displayed in Fig. 12, under tensile/flexural loadings as soon as ultimate loading is reached, whereas FRAC experiences ductile failure [136].

Notably, FRAC may also reduce compressive strength using certain fibers (e.g., polypropylene fibers). Adopting a high volume of fly ash slows down the pozzolanic reaction, particularly at room temperature. Use of industrial wastes in the building sector to produce high-performance AAC with excellent thermal insulation properties and high volume stability has become more popular [138].

6.2. Foamed concrete

Foamed concrete (FC) is a low-density, efficient substance that may include up to 75% air voids [139], and it is classified as self-leveling, self-compacting, and pumpable in most cases [94]. FC is ideal for filling superfluous voids, such as abandoned fuel tanks, sewer systems, pipelines, and culverts, especially in areas with limited access [2,140]. Moreover, FC is a well-known medium for resurfacing temporary road trenches, and its excellent thermal insulation qualities make it ideal for sub-screeds, filling under-floor voids, and insulating flat concrete roofs [141]. In recent decades, many studies have been conducted to further improve high-performance FC's thermal insulation and mechanical strength. They pointed out that FC's thermal insulation can be enhanced by adding lightweight aggregates, such as expandable polystyrene (EPS) [142], polyurethane (PU) [143], industrial waste (e.g., high-temperature slag [144]), glycol compounds and fly ash waste [145], and quartz stone waste [146]. Meanwhile, FC's mechanical strength may be increased by the addition of different fibers and foam modifiers, namely, polypropylene fiber [147], glass fiber [148], and nanometer-scaled silica [93]. A three-value model can be used to forecast and control the thermal conductivity of FC [149]. These studies have reported that current FCs have densities ranging within 400–600 kg/m^3 and thermal conductivities ranging within 0.10–0.20 W/(m.K). Other studies have shown that if the technique utilized to create additional high-performance FC had a density of less than 400 kg/m^3 and a thermal conductivity of less than 0.10 W/(mK), FC's strength would be insufficient, resulting in brittle concrete [150]. Hence, further research is required to produce high-performance FC with low density ($\leq$400 kg/m^3) and low thermal conductivity (0.10 W/(mK)).

Silica aerogels have gained widespread recognition in the last decade as one of the most efficient super-insulating materials for use in construction applications. In various applications, silica aerogels display a very low thermal conductivity ($\sim$0.015 W/(mK)) and a very low density ($\sim$100 kg/m^3) [151]. Multiple studies have described the use of aerogels as insulators in the construction sector [152]. It is developed aerogel concrete with a density of 1000 kg/m^3 and thermal conductivity of 0.26 W/(m.K) by using 15% aerogel [153]. Another study examined the thermal conductivity of aerogel concrete in relation to its aerogel concentration [154]. The results showed that aerogel concrete with thermal conductivity of 0.55 W/(mK) and aerogel content of 50% could be created and demonstrated that the addition of aerogel benefits concrete density and thermal conductivity compared with a density of around 1500 kg/m^3 and thermal conductivity of around 0.7 W/(mK). Li et al. [26] prepared a ternary graph to observe the relationship among thermal conductivity, porosity, and volume fraction of the binder and aerogel in the prepared aerogel FC, as shown in Fig. 5. Fig. 5 indicates that the volume of porosity, cement, and aerogel vary within 0–0.95, 0.05–1, and 0–0.95, respectively, leading to thermal conductivity of 0.0487–1.232 W/(m.K) for aerogel FC.

Additionally, at a constant porosity, thermal conductivity considerably decreases with a decrease in the cement ratio and an increase in the aerogel ratio. For example, keeping the porosity and aerogel volume ratio at 0.5 and 0.45 leads to a 90.4% decrease in the thermal conductivity of aerogel FC compared with concrete without aerogel, as clarified in Fig. 13.

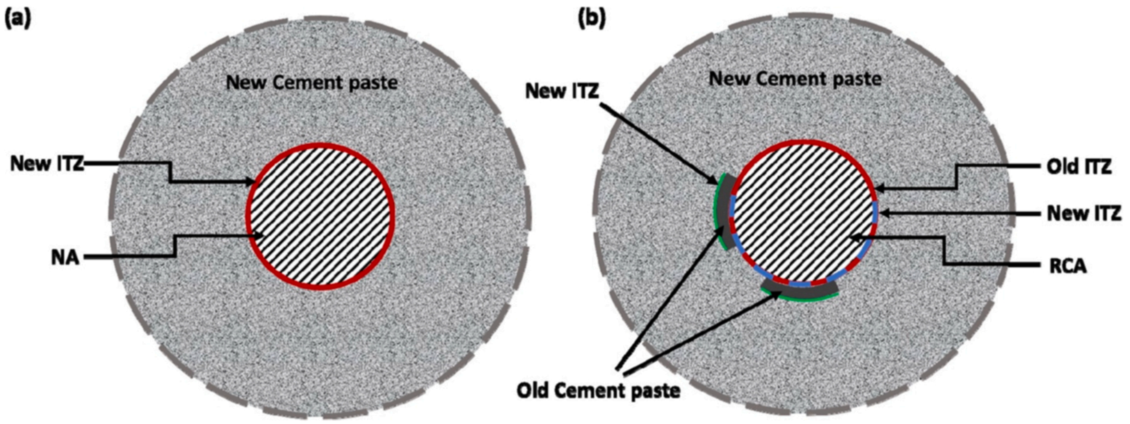

Fig. 17. Phases of concrete prepared with (a) NCA and (b) RCA
Adopted from [185].

Moreover, keeping the aerogel volume ratio at 0.5 and decreasing the cement volume ratio from 0.5 to 0.05 results in decreased thermal conductivity by 88.2%. However, aerogel concrete still has high density and heat conductivity, which are considered less than satisfactory. The density and heat conductivity of concrete can be reduced using super-insulative aerogels, however the decrease is smaller than that obtained by adding foam. However, the higher aerogel content raises the price of aerogel concrete and hinders its technological applications.

6.3. Polystyrene cellular concrete

Early studies focused on EPS concrete to determine if it could be used to leverage properties, such as low water absorption, low thermal conductivity and lightness, compared with other lightweight concretes. According to the extant literature, after 12 years of research, structural EPS concrete blocks, thermally insulating and lightweight have been achieved [155]. The ease of setup, availability of raw materials cost, equipment and labor estimates for bulk manufacturing have also been mentioned. EPS concrete has been utilized as a sub-base material for pavement [156]. It is proposed using EPS concrete to cover underground military facilities and serve as fenders for offshore platforms, floating structures and sea beds [157]. However, early studies have identified EPS concrete's poor workability, which leads to an unattractive surface finish. Ravindrarajah et al. [156] utilized coated EPS beads with a hydrophilic chemical coating to increase the workability of EPS concrete. Foaming agents were used by Laukaitis et al. [158] to enhance the beads' adherence to the aerated cement matrix. It is revealed that preparation of cellular concrete with polystyrene as sand replacement decreases the compressive strength, as shown in Fig. 14 [159]. As presented in the figure, the compressive strength of EPS concrete specimens decreases by 47.2%, 40.4%, and 38.3% compared with the value for cellular concrete incorporated with sand. This is because EPS appreciably affects the density and strength of cellular concrete due to the low resistance of EPS against applied loadings, leading to the formation of cracks between cement paste and aggregates. Moreover, EPS is highly compressible and has a smooth surface, which leads to inferior bond properties.

Enhancing the EPS concrete matrix's characteristics is the subject of recent research. Babu et al. [160] studied the effects of silica fume on the mechanical performance and durability of EPS concrete. In another research, it was shown that the mechanical and moisture migration of EPS concrete were affected by the addition of fly ash [161].

Further efforts were exerted to develop EPS concrete for better understanding and simulating its mechanical characteristics. It is investigated whether changing the size of EPS beads contributes to improving the compressive strength of EPS concrete [162]. The authors proposed a model for predicting the influence of EPS particle size on normalized compressive strength. It is studied the relationships between EPS concrete composition and characteristics and utilized the best mixture to manufacture lightweight hollow bricks [163]. In the study, EPS beads were used. A correlation equation was provided to calculate the density of the mixture in terms of cement content, water/cement ratio, EPS volume, and sand ratio. The researchers concluded that the percentage of EPS beads used is the most critical factor influencing the mixture's density. Furthermore, the researchers suggested the following correlation between mixture density (γ) and compressive strength (fc): $fc = 2.43 \times \gamma 2.997\ 10^{-9}$. Allahverdi et al. [164] developed a new lightweight mortar using EPS beads, silica fume, and blast furnace slag in place of quartz powder and quartz sand. The density of the developed mortar ranges between 1257 and 1840 kg/m^3, and the compressive strength ranges between 20.8 and 85.6 MPa, as revealed in Fig. 15. It is experimentally investigated lightweight concrete's physical and mechanical performance using EPS beads and soft marine clay [165]. They noted that the EPS-to-clay ratio is the most crucial element in determining the density of the composite. The researchers also presented an equation to link a mixture's compressive strength to its failure strain. Nevertheless, the research on evaluating the heat conductivity of EPS concrete is limited. An example is the study of Bouvard et al. [166] evaluated the heat conductivity of low-density EPS concrete. Furthermore, studies focusing on the utilization of recycled EPS shreds and crumbles are practically non-existent. It is predicted a cost gain from utilizing shredded wastes [157] and it is utilized EPS waste crumbles to investigate the influence of large beads [158], tiny beads, and crumbles on the mechanical and thermal properties of a low-density FC matrix.

6.4. Recycled lightweight aggregate concrete

Concrete waste reuse and recycling can be a successful strategies for achieving long-term sustainability [167]. In the construction sector, recycled concrete is used to replace natural coarse aggregate (NCA), which is collected, crushed, and reused efficiently to achieve sustainability [168]. Many organizations worldwide have implemented various efforts to control and limit the use of virgin aggregate and enhance the recycling of concrete waste for reuse as materials when ecologically, technically, and economically feasible [169]. Rising landfill costs and land scarcity are well-known contributors to environmental concerns. Reusing concrete waste may help solve sustainability issues in this regard [170]. However, most concrete producers are hesitant to synthesize and fully utilize recycled concrete aggregates (RCAs) [171]. Production facilities have not yet mastered the use of RCA because of its ambiguous properties and its unknown manufacturing procedures that have yet to be identified [172]. Most concrete batching plants are reticent to make and use RCA to its full potential [173]. However, this matter warrants serious interest.

Many towns, cities, and residences are destroyed as a result of artificial or natural disasters. The challenge is eliminating the debris, sustain natural resources to rebuild cities, and use parts of destroyed buildings and structures [174]. One method is to transport debris to relatively low levels of the Earth's surface, store it, cover it with dirt, plant a forest on top of it, find new construction materials, and recreate cities and villages from these new materials [175]. However, this endeavor is costly [167]. The second option is to use parts of destroyed buildings and structures to recreate construction materials, which may then be used to restore and build new buildings and structures in place of the destroyed ones [176]. The demolition of old structures and the construction of new ones are regular occurrences resulting from natural catastrophes, increments in traffic routes and highways, acceleration of urban development, structure

Table 3
ULCC applications.

Type of components	Reinforced walls	Components for mitigation of explosions	Refs.
Arctic offshore structures and offshore deck and structures	Flat slabs in residential and commercial buildings	Energy-efficient buildings	[106,122,211, 212]
Sandwich panels	Spandrel-type units	Decorative concrete	[12,76,77,96, 115,197].
Precast rake/riser beams	Specialized single-skin composites High-performance composites Double-skin composite slabs Steel–concrete composite slabs	Fire-resistant materials Lightweight aggregatesfor projectionCell grout	[3]
Loading wall units and coating Shear walls	Corrugated panels Beams, composite panels Hollow core panels	Elements for sound attenuation	[203]
Columns and beams cast on site	Fireproof walls Division walls	Seismic energy absorption systems	[12,107,197]
Facade walls	Segmented modular systems	Foundation renovation	[203]
Beams and pre-stressed columns	Ballast for high-speed trains Noise reduction Bridge coatings Transport structures Bridge deck	Pressure pipes	[213]
TT or T beams	Concrete walls for the system Tilt-up	Masonry blocks	[214,215]

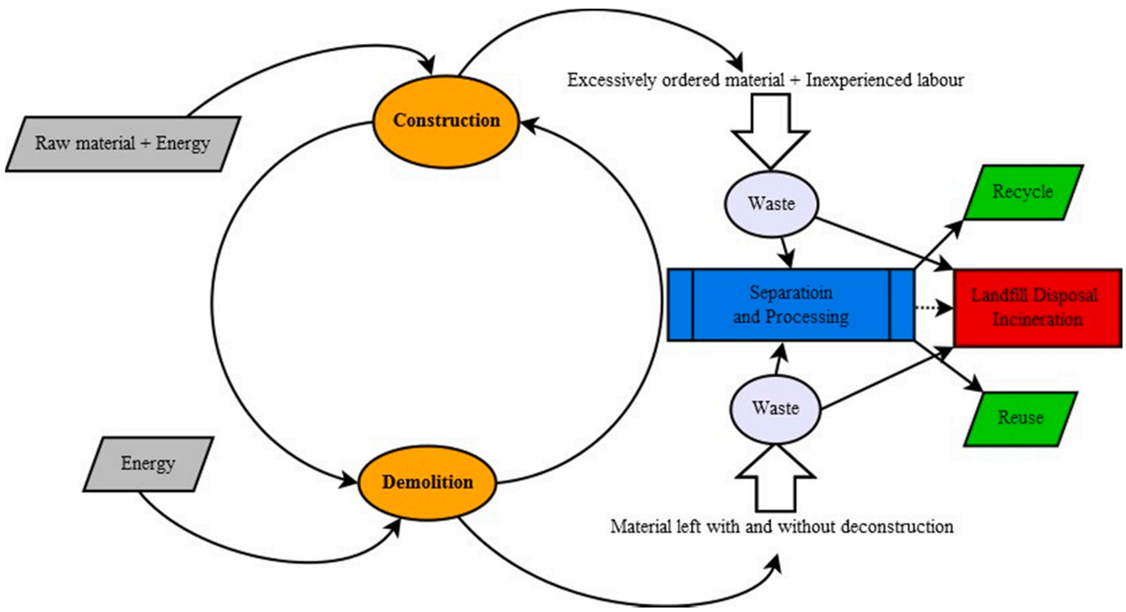

Fig. 18. Diagram flow of the materials during the C&D activities
Adapted from [189].

collapse, and changes in the functions of buildings [177]. Around 850 tons of construction trash are generated yearly in the European Union and account for approximately 30% of the total garbage [178]. In the United States, demolition debris alone amounts to around 123 tons per year [179].

Massive amounts of concrete waste are generated during the demolition of old structures; these are frequently disposed to landfills, posing severe health concerns and wreaking havoc on the environment [180]. The study of the features of RCA began more than four decades ago [181].

Given the negative physical characteristics of RCA, such as high water absorption that increases the demand for water for particular workability, most previous studies were confined to the fabrication of unstructured concrete [182–184]. The major reasons for the inferior quality of RCA compared with NCA having adhered mortar, an ambiguous preparation method, and an inferior interfacial transition zone (ITZ) [185], as shown in Fig. 16. RCA modified concrete has five phases: NCA, old ITZ, old cement paste, new ITZ, and new cement paste; conventional concrete only has the last three phases [186]. The more significant number of phases in RCA modified concrete than in NCA leads to increased porosity and consequential water absorption, leading to reduced rheological and mechanical properties and durability of concrete.

Fig. 19. Common applications of ULCC.

Table 4 (a)
Several geotechnical applications.

Geotechnical applications	Background	Function	Footnotes	Refs.
Lightweight road bases, dams, and fills	Structural pavement portion with concrete or asphalt riding/wearing course on top of the base and/or subbase layers (usually crushed stone or stabilized materials). ULCC can be used to strengthen and overcome many of the problems that poor subgrade materials might cause.	In addressing construction and long-term loading arrangements, the estimate must also account for potential alterations and potential roadway elevation and groundwater due to seasonal cycles or construction dewatering.	Geotechnical engineers use representative material parameters and unit weights for different materials and soils to calculate pavement thickness, weight reduction, and embankment stability, mostly based on laboratory testing.	[216] [11] [220] [217] [221]
Void, cavity, and annular space grout filling	Impervious cellular concrete is one of the best materials for annular gap grouting. It also flows smoothly through narrow holes and tight annuluses. Within a void or cavity, the air bubbles introduced to the cement paste act like small ball bearings, allowing the material to flow quickly into all available places.	The extremely flowable nature of ULCC allows for easy pumping and long-distance transportation in hoses, resulting in straightforward installation in difficult places once all water can be removed from the voids prior to commencing. An annular space tunnel grout is used to fill the free area around a new pipe inserted in any new channel.	There is no aggregate to segregate out because the mix consists primarily of cement paste (water/cement ratio of 0.5) and air bubbles. The low pumping pressures lower the external pressure on the lining pipe joints. There is a space between the pipe and the tunnel casing to be filled after this installation.	
Pipe, culvert, and tunnel abandonment filling	ULCC pipe and tunnel abandonments are cost-effective and efficient. This permits long constructions to be abandoned with few pumping sites while still ensuring total fill.	Flowable fill often strengthens over time, resulting in a material that is extremely difficult to remove if further excavation is required.		

Given the impact of RCA on the changing aspects of the construction sector, insufficient knowledge of the lifespan and sustainability of RCA manufacturing is a major issue that requires continued attention and further research [187]. Whether the manufacturing, quality control, and production costs of standard RCA manufacturing exceed the benefits of using RCAs as concrete components at a cheaper cost than NCAs remains unclear [188]. The existing factories for the manufacturing of bulk ready-mixed concrete might be a reason for the sluggish acceptance of RCA production [189], as clarified in Fig. 17. Recycling is another potential alternative to consider when dealing with this waste stream, in which all garbage created is processed and separated into several categories such as steel, wood, concrete, and glass. This trash can be recycled and reused, or it can be combined with other building materials.

However, for particular reasons, modern models in which RCA progressively replaces NCA in various structural designs have steadily increased [190]. For instance, RCA production ensures the long-term sustainability of concrete by encouraging recycling

Table 4 (b)
Several geotechnical applications

Geotechnical applications	Background	Function	Footnotes	Refs.
Retaining wall backfills and energy arresting systems	ULCC is appropriate for retaining wall applications where lightweight vertical embankments are required when utilized as a lightweight backfill in place of granular soil.	Despite the widespread use of ULCC materials in retaining walls and engineered fills, there is little the literature about the engineering characteristics and design procedures.	A few articles show how ULCC materials can be used in retaining walls. Backfilling behind retaining walls using ULCC made from foam liquid is a good option.	[218] [219]
Levee structural fills and bridge approach embankments	Dams and levees made of ULCC are frequently used in areas with deep soft sediments, where settling can be a severe issue. While repairing a levee and filling it back to design grade, ULCC can handle this difficulty by being installed in the levee segment below the surface.	The challenge is that the approach embankment's usual height rises as it approaches the bridge, thus increasing the risk of settlement and necessitating a higher factor of safety and greater intended ULCC thickness to resolve the settlement potential.	Structural fillings for dams and levees are light in weight, avoiding increasing the weight on the deep soft soils. The ULCC section can be installed at any level, and its buoyancy effect must be evaluated to choose the best location within the levee or dam.	
Landslide repair, foundation fills, and slope stabilization	Landslides can be sudden, dangerous failures that cause major problems. The ideas of void filling and the net load design approach are also used for foundation fills depending on the desired usage. Fill is occasionally required in a basement that is difficult to access when performing foundation repair work.	Fills for sea-level rise and elevation rise are similar to foundation backfills. Coastal armoring as elevated ULCC seawalls and bulkheads can defend shorelines from heavy wave action. Existing progress can be protected from rising water owing to storm surge and baseline sea level rise with these types of fills.	ULCC can be applied at the slide's crown/head scarp to lessen the pushing pressure caused by the current soil's weight. The mass is lowered, and the pulling power acting on the slide mass is greatly reduced by removing the top of the slide area and replacing it with ULCC.	
Load reduction and controlled density fills	ULCC is an excellent lightweight fill material for use in heavy-duty highways and other constructions.	Lightweight fills allow for much deeper fills with the same burden weight while building up heights. ULCC is a cost-effective material for many applications.	Bearing capacities start at roughly 350 kN/m^2 despite the modest unit weights. Controlled density fill has compressive strengths of 0.34–1.03 MPa.	

rather than landfill disposal [191]. Additionally, it emphasizes the scarcity of natural aggregates, reduces their demand, and eventually allows for the preservation of NCAs extracted in open pits [192]. Despite the expense, these and other advantages have made the manufacturing and utilization of RCA popular [193,194]. Furthermore, various lightweight aggregates can promote the production of lightweight aggregate concrete [195]. Lightweight concrete's required characteristics dictate the type of lightweight aggregate to utilize. A light, the weak aggregate may be employed when minimal structural requirements exist, but excellent thermal insulation characteristics are required. This could result in concrete with a relatively low strength [196].

6.5. *Structural lightweight concrete*

Various structural applications have demonstrated that lightweight aggregate concrete can be used while ensuring a compressive strength equivalent to conventional concrete [2]. The following are some of the advantages of utilizing lightweight concrete:

1. Reduction in formwork and propping [115,197].
2. Savings in transporting and handling precast units on-site [120];
3. Improved fire resistance [5];
4. Improved thermal properties [94];
5. Reduction in dead loads, resulting in savings in foundations and reinforcement [2];

Lightweight concrete has a lower elasticity than conventional concrete with the same strength. However, the lower self-weight is offset when considering slab or beam deflection [76,77]. Eurocode 2 Part 1–1 covers the fundamentals of lightweight concrete design, with Section 11 containing specific requirements for lightweight aggregate concrete [198]. On this basis, lightweight concrete can be classified as lightweight concrete if it has a density of less than 2200 kg/m^3 (the density of standard weight concrete is supposed to be between 2300 and 2400 kg/m^3), and the used aggregate should have a density of less than 2000 kg/m^3 [199]. The strength class notation LC denotes lightweight concrete; for example, The LC30/33 symbolizes a lightweight concrete that has cube strength of 33 MPa and cylinder strength of 30 MPa [89].

The lower the density of concrete is, the greater the differences that must be considered regarding the properties of concrete [5]. The tensile strength, ultimate stress, and shear strength of lightweight concrete are lower than traditional weight concrete with the same cylinder strength [88,200]. Additionally, lightweight concrete is less stiff than similar standard-strength concrete, but this is offset by the reduction in self-weight, resulting in a modest reduction in the depth of a beam or slab [77,115,197].

The creep and shrinkage of lightweight concrete higher than conventional-weight concrete, and this condition should be considered in structure design [2]. Typically, lightweight concrete is batch-mixed in ready-mixed concrete manufacturers. When the workability of concrete is poor, it can be simply placed using a skip or chute [94]. Pumping lightweight concrete is achievable, but caution must be exercised to prevent the concrete mix from segregating [5]. Natural sand is often used in pumpable mixes (i.e., not a lightweight aggregate for the fine component of the mix and has good workability to avoid increased pump friction and obstruction) [9]. The use of admixtures accomplishes this, and because excessive vibration of lightweight concrete might result in segregation, flowing concrete should be used while pumping because it requires less vibration [3,5].

7. ULCC applications

7.1. General applications

Cellular concretes can be used in various ways depending on their density [5,89]. Given that ULCC (300–600 kg/m^3) has poor mechanical properties, it is utilized for fire protection and thermal and acoustic isolation [3]. Brick manufacturing, blocks, and nonstructural components (e.g., railings, divisions, and fences) are the most common use of materials with densities between 700 and 1100 kg/m^3. There have been various occasions when ULCC has been utilized as a leveling mortar or flooring filler. [74]. Precast forms, weight-reduction mortars, load supports, on-site casting, and slabs made of high-density cellular concretes (1200–1800 kg/m3) are used when high strengths are needed [201]. Currently, the most sophisticated type of cellular concrete is high-performance cellular concrete (HPCC) [202]. It is referred as as HPCC because it has unique performance and uniformity standards that ordinary materials and regular mixing, placing, and traditional curing techniques cannot always meet [203]. HPCC has a compressive strength of 55.37 MPa, and higher strengths can be achieved by using extra cementitious materials and reducing the w/c ratio. Additionally, HPCC bubbles contribute to increased resistance to freezing and thawing, sound absorption, excellent fire resistance and minimal water absorption [203]. Compressive strength of up to 65 MPa and density of less than 1500 kg/m^3 are considered the most sophisticated types of HPCC [106]. Furthermore, ULCC has a higher specific strength than conventional-weight concrete of the same strength; ULCC's strength-to-density ratio, for example, is 47 kPa/(kg/m^3), whereas normal-weight concrete's is 27 kPa/(kg/m^3). [106]. Table 3 provides an overview of the principal uses for cellular concretes that have been documented so far.

With respect to the application field, a thorough description of cellular concrete's usefulness may be provided with abundant details. For example, geotechnical applications for coating and tunnel stabilization have resulted in a 61% reduction for vault settling [11,204,205]. With a width of 0.5 m and density of 650 kg/m^3, it is used as ballast for high-speed trains on rail roads., has achieved long-term dynamic stability and cyclic loads and relative layer settling [206]. Furthermore, cellular concrete has been utilized in several structural applications, such as making thin walls with reinforcement [207].

Precast elements are the most commonly used in applications, such as nonstructural cracks with compressive strengths of up to 5.4 MPa [208]. Panels with up to 95.4% porosity, 0.063 Wm-1 K-1 thermal conductivity, and 0.25 MPa compressive strength [209]. Thermal isolation panels with thermal conductivity of 0.016 m^{-1} K^{-1}, compressive strengths between 5 and 25 MPa and densities ranging from 800 to 1500 kg/m^3[210]; and the mechanical behavior of sandwich-type constructions used in precast slabs has been modeled on a greater scale as well. [12,76,77,96,115,197].

These concretes have been used in the construction of buildings, offshore structures, and challenging weather conditions including snow. Flat slabs in commercial and residential buildings, steel-concrete composite slabs, offshore decks, double-skin composite slabs, bridge decks and Arctic offshore constructions are several other diverse applications for advanced cellular concretes as ULCC [3]. Low thermal conductivity in ULCC is required for the development of energy-efficient structures [106,122,211,212]. In addition, new methods of re-mixing conventional concrete and converting it into high-performance sub-grade concrete are being investigated. This new mixture comprising foam and silica fumes is pumped under appropriate pressure and dropped at high speed at the place specified for it, resulting in the formation of aerated sprayed concrete [213]. On-site, sprayed concrete can be used to coat tunnels, walls, and floors. It is a simple, cost-effective technique of extending the usage of cellular concrete.

7.2. Geotechnical applications

The advantages of the geotechnical structural solution for a rapidly settling roadway begin with its long-term efficiency with minimal or no settlement, as presented in Fig. 18. According to the ULCC guideline [216], it creates a relatively strong, self-consolidating roadway subbase material that extends pavement life and reduces the risk of major settling. One of the advantages of ULCC over other options is that it often requires less time and equipment to install, resulting in substantial cost and time savings, especially when compared with a solution that requires enormous surcharge loadings of embankment foundations, which can take months. ULCC eliminates the need to compact and level the subgrade before it is laid because it is a highly flowable, self-consolidating, self-leveling material [3]. These characteristics lessen the requirement for additional equipment and labor on a construction site. The reduced trucking greatly reduces CO_2 emissions, traffic congestion, pavement wear, and noise. It also decreases the consumption of finite natural resources.

Several geotechnical applications are shown in Table 4. For example, in retaining wall backfills and energy arresting systems, mechanically stabilized earth (MSE) walls made of ULCC materials should, in general, be freestanding after curing. It is proposed using friction angles of 35° for short-term and 40° for long-term situations because the present MSE wall design guidelines and procedures in the United States demand using the friction angle backfill material [11,217]. Its also stated that the ULCC materials to be fully saturated during their lifetime. It is also reported that the free-standing quality of ULCC is permanent, not transient, given that thousands of applications across the United States and Canada have had no concerns [218]. Cracks on ULCC retaining walls are caused by shrinkage and creep rather than loading stress and have no negative impact on the walls' performance.

It is also performed a numerical analysis of a 23-foot-tall MSE wall composed of a ULCC material built on soft ground and subjected to seismic pressure [217,219]. Their numerical study used the dynamic and static strength properties reported by Tiwari et al. [11, 217]. According to their numerical simulations, the retaining wall (referred to as the MSE wall in their paper) moved monolithically under seismic loading. According to the investigation, the seismic stresses sustained by the geo-grid reinforcement were instantly transmitted to the LCC material. As a result, the geo-grid was restricted to limiting fracture growth. They performed over 20 shaking table experiments on ULCC blocks with the geo-grid at the center to evaluate the performance of the geo-grid and ULCC material during seismic loading by using the dynamic and static strength values reported in [11,217]. Furthermore, current geotechnical applications entail cementing sands to improve bearing capacity, destabilization resistance, and carbon capture.

8. Hotspot research topics for future investigations

This review study revealed ineffective ways for ULCC design and placement and the production of quality control standards. As a result, implementing the proposed research developments in the real world remains a challenge. To improve the potential of using cellular concretes as structural materials, the obstacles experienced in various procedures of FC industrial production, such as mixing, transporting, and pumping, must be resolved.

1. Comparative field research is recommended to track various parameters' actual performance and effects on ULCC performance [222].
2. Experiments with different binders are recommended for understanding foam stability [21].
3. For the large-scale commercial application of this form of ULCC, considerable efforts in process scaling and control of production conditions are necessary [3].
4. Despite the few studies conducted on the practical uses of LCC in civil engineering, LCC may be regarded as a major milestone in the evolution of ULCC applications [12].
5. Using a superplasticizer in combination with other additives in FC can help increase the pore structure [223].
6. Several areas of drying shrinkage reduction, including water content control, binder and foaming agent selection, and mixture modification with fine aggregates, deserve further research [224]. The use of fibers can greatly improve drying shrinkage resistance due to the improved tensile strength of the cement base mixture, prevention of additional crack development in the cement base mixture, and increased capacity to resist deformation.
7. Highly durable concrete with superior requirements and performance could be created with novel combinations of elements in various proportions [225].
8. Combining three-phase foams with other nanomaterials or using the discovered methods can further increase the characteristics and performance of FC [226].
9. The effects of freeze-thaw cycles on ULCC performance can help increase and optimize the durability of ULCC used as insulation materials [227].
10. ULCC has many applications in the geotechnical sector of the construction industry as repairing and filling material. However, the absence of any study that deals with the long-term properties of ULCC in geotechnical applications makes the commercialization of ULCC challenging. More work is needed for large-scale commercial use of this form of concrete in-process scaling and manufacturing conditions control.

9. Conclusion

Cellular concretes are undergone rapid development with a major focus on improving the specifications and performance of novel combinations of elements in various proportions to produce more serviceable concrete. Therefore, this study investigated the utilization of ULCC in the construction industry with major emphasis on ULCC's raw materials, production techniques, properties and performance. The following conclusions were derived from the discussions:

1. ULCC reported to improve the strength-to-weight ratio and has been used in lightweight road bases and fills, bridge approach embankments, void and cavity filling, culverts, pipe and tunnel abandonment filling, foundation fills, annular space tunnel grout filling, energy, retaining wall backfills, arresting systems, lightweight dam and landslide repair fills, levee structural and slope stabilization, and load reducing fills.
2. ULCC reduce the thickness of structural parts, promote usable interior architectural spaces, reduce the amount of reinforcement, increase flexibility, and reduce the influence of temperature variations, which are important for energy conservation in buildings.
3. Reduced thermal conductivity is the most important phenomenon of ULCC that favors its utilization. However, due to the increase in the porosity of ULCC, mechanical properties decrease significantly (i.e., more than 40%).
4. Several areas, such as rheology and the interior structure of the pores, require further research, but this process has recently begun. The application of nanotechnology, the discovery of new and improved foaming agents and stabilizers, and the fabrication of geopolymeric cellular concretes novel developments in ULCC use.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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