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The potential use of lightweight cellular concrete in pavement application: a review

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Abstract

Protecting the pavement subgrade to increase the service life of road pavements is an aspect currently being explored. Several alternative pavement subbase materials are being considered, including Lightweight Cellular Concrete (LCC). Due to its lower weight, LCC incorporating industrial by-product, making it sustainable, and ease of use amongst other benefits, is seen as a potential candidate. This paper reports reviewing the potential application of LCC within the pavement structure with a specific application as a subbase. It examines the various properties such as modulus of elasticity, compressive and tensile strength, Water absorption, and freeze-thaw resistance necessary for pavement application. It also assesses its use in the field in Canada considering the design methods utilized. Some limitations and gaps for LCC application in pavements are also established and recommendations on how to further its use and performance. This review concludes that LCC possesses potential as a pavement subbase alternative; however, other mechanical properties like LCC's fatigue life is essential. A comparative field study is also recommended to monitor actual performance and various factors on performance.

Keywords: Lightweight cellular concrete; Pavement; Performance; Subbase

1. Introduction

Due to advancements in technology and changing climatic conditions, pavement materials are also evolving as material property is one of the factors to affect pavement deterioration [1]. Incorporating different materials into the pavement structure is being researched to see if longer-lasting and higher service pavement infrastructure can emerge. Factors considered for potential materials include sustainability benefits, workability, lower costs, time, and structural capacity.

A significant challenge with road pavements in the Canadian climate is frequent repairs associated with road pavements over frost susceptible and weak subgrades caused by frost and rapid temperature variations and the presence of organic material along road pathways [2]. These repairs are expensive, disruptive, and not sustainable, especially in virgin material and excess waste generation. Besides, the added weight on the subgrades could lead to even more settlements and more cycles of repairs.

The protection of the subgrade is a strategy being looked out to reduce these challenges. Hence the use of additives to strengthen the subgrade and alternative materials to improve the subbase directly above the subgrade could be deemed a potential solution. For the subbase layers, reducing the weight on the subgrade and other protective mechanisms are properties for any such materials chosen. Typically, the unbound granular material is utilized as a subbase in Canada; however, its added weight is a burden to a weak subgrade and its contribution to the depletion of natural resources. Its production and transportation are also sustainably detrimental to the environment. [3]. Hence lightweight alternatives are being considered to provide inexpensive designs that could reduce the weight of fills, thus reducing settlements, minimizing waste, and providing longer-lasting pavements [2,4]. Lightweight Cellular Concrete (LCC), also known as foamed concrete is one of such lightweight materials being researched.

This review studies the use of LCC within the pavement structure in Canada. It examines LCC's current properties, advantages, and potential benefits within the pavement structure as a subbase layer. This paper further proposes practices and necessary steps to improve LCC application within the pavement structure.

1.1. Definition of lightweight cellular concrete

The term "cellular concrete" or "foamed concrete" refers to a type of lightweight concrete which contains stable air bubble or gas cell distributed homogeneously in the cement mix (American Concrete Institute (ACI) and does not contain coarse aggregate in the mix like Portland cement [5-7]. According to ASTM C796 [8],

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LCC is:

"A lightweight product consisting of portland cement, cement-silica, cement-pozzolan, lime-pozzolan, or lime-silica pastes, or pastes containing blends of these ingredients and having a homogeneous void or cell structure, attained with gas-forming chemicals or foaming agents (for cellular concretes containing binder ingredients other than, or in addition to Portland cement, autoclave curing is usually employed)"

Another definition from Concrete Society that has been widely cited noted that the foamed concrete is [9]:

"A cementitious material having a minimum of 20 percent by volume of mechanically entrained foam in the plastic mortar or grout."

This definition further narrows down the type of foamed concrete since air-entrained concrete has lower entrained air (3-8%), and aerated concrete is formed chemically [10].

Both definitions classifies cellular concrete or foamed concrete as a cementitious material containing air bubble or foam in the mix. For this study, the ASTM and ACI definition is used to better suit the material being researched in Canada. Hence, the definition for cellular concrete is summarised as a cement slurry (Portland Cement or Portland Limestone cement with water), which consists of foam (a minimum of 20% per volume), and compressed air [10,11].

Lightweight Cellular Concrete (LCC) is one of the lightweight materials being considered a viable option to achieve the Canadian transportation goal of longer-lasting, better performing, and more sustainable pavements. Typically, LCC has a wet density ranging from 250 to 1,600 kg/m^3; however, below the ground, applications such as for pavements will have wet densities between 400 and 600kg/m3 [11]. Since its characteristics and lightweight are highly reliant on its constituents, Legatski classified Cellular Concrete into four [12];

1. Neat-Cement Cellular Concrete: Cellular concrete containing cement, water, and preformed foam without aggregates and its use limited by the cement content. Typical application density does not exceed 800 kg/m^3; however, an increase in density can be achieved by replacing a portion of cement with pozzolanic materials such as fly ash without producing much heat of hydration.
2. Sanded Cellular Concrete: Cellular concrete containing cement, water, and fine aggregate (sand). Its application density ranges from 800 to 2,080 kg/m^{3,} and its use depends on its cement content, water/cement ratio, and sand characteristic.
3. Lightweight Aggregate Cellular Concrete: This is similar to sanded cellular concrete, but sand is replaced with lightweight aggregate. This is to increase the strength/density ratio of the mix.
4. Cellular concrete modified with admixture: This refers to cellular concrete, which has admixtures added to the mix to customize and improve properties. For example, the compressive strength of cellular concrete is improved by adding cement dispersing agents to reduce its cement/water ratio at a given density. Chopped fibers like glass, steel, polypropylene, polyester, and nylon are added to increase tensile strength and reduce drying shrinkage. Fly ash can substitute cement to reduce cost without affecting properties, improve compressive strength, flowability, the heat of hydration, and permeability. Latex can be used to impart specific properties. Other forms of waste materials like rubber and plastic can be incorporated to control strength, density, and heat of hydration.

Furthermore, LCC can be classified according to their density [13];

1. Ultra-low-density cellular concrete has a plastic density below 600 kg/m^3
2. Low-density cellular concrete has a plastic density ranging from 600 to 1,000 kg/m^3
3. High-density cellular concrete with plastic density above 1,000 kg/m^3

LCC dates back to the early 19th century, however, in-depth studies about the material composition, physical properties, and production were only carried out in the 1950s [14]. Since then, there has been ongoing research on how to improve its characteristics and applications. It is gradually becoming a preferable option in construction than the regular concrete, especially in applications requiring lighter materials and excellent workability. LCC's positive aspects include its lower structural dead weight, free-flowing and self-compacting nature, lower thermal conductivity, ease of recyclability, and ultimately a lower lifecycle cost [15]. It also makes use of industrial by-products such as slag, silica fume, and fly-ash to customize its structural and flexural strength [11,15].

Although LCC is famously used for void fillings, ground stabilization, and more recently as a structural component in infrastructure, its use within the pavement structure is gaining recognition, especially in weaker subgrades. Numerous applications in Canada in the pavement structure have been recorded [2,11]; however, there is limited information on design and construction guidelines and performance data over time for its application in road pavements.

1.2. Material composition

1.2.1. Cement (binder)

Portland cement (PC) is the main cementitious component of LCC, with approximately 300-400kg/m^3 content. Nevertheless, the cement density can be adjusted depending on the strength requirements or the mix's design density [16]. Typically Type I Portland cement is used. Type III and IIIA cement are also used if the mixture requires high early strength [5,6]. To customize LCC properties, PC is usually combined with other materials. For instance, for compressive and flexural strength improvement, reduction in cost, heat of hydration, drying shrinkage and thermal conductivity, fly ash, blast furnace slag, or silica fume is added to PC [11,17]. Research has also shown the successful use of replacing PC with up to 75% of fly ash without adverse effects on strength [17]. For reducing setting times, Calcium Suloaluminate Cement (CSA) has been reported to work with additional benefits [18]. CSA cement also has sustainable benefits of reducing CO_2 emissions due to lower temperature requirements during production compared with PC. Construction with CSA cement has shown high freeze-thaw and chemical attack resistance, but depending on the w/c ratio, they can carbonate faster and lead to strength loss [19]. However, care must be taken when using additional materials concerning production temperatures, water content, and foam instability [20,21].

1.2.2. Fine aggregate/fillers

Fine sand, typically 2mm maximum size, is recommended for use only in LCC with dry densities equal or greater than 600kg/m3. It is found that sand with a maximum size of 2 mm yields higher strength than 5 mm sand. British Cement Association (BCA) suggests replacing fine sand with fly ash in mixes with a plastic density below 600 kg/m^3 [22]. Carbon nanotubes (CNTs) have also been incorporated into the LCC mix as fillers for support. They are found to develop a more homogenous cell structure with closed-cell bubbles [23]. However, CNTs can form clumps and ultimately cause foam instability. This will require dispersion in water, which might not prove useful [13].

1.2.3. Pozzolan materials

Pozzolan materials can be classified into materials rich in silica or alumina. Pozzolanic by-products such as fly ash and blast furnace slag could be beneficial by reducing material cost, maintaining consistency, and increasing strength in long-term performance [17]. Jones et al. stated that replacing Portland cement with fly ash up to 40% could significantly reduce the embodied carbon dioxide by 65% compared to the 100% portland cement mix while maintaining a similar 28 day strengths (0.25 MPa compared to 0.31 MPa) [24]. However, the drawbacks of using fly ash are the slow rate of strength gain, and potential foam instability as the water demand might increase [13].

1.2.4. Water

The water-cement ratio plays a vital role in LCC. The w/c ratio needs to be determined based on the constituents' materials to provide and maintain the mix's suitable workability. The typical range of w/c ratio is from 0.40 to 1.25 [25]. It should be noted that the quantity of water required is dependent on the composition and use of the material, which relies on consistency and stability [26]. Excess water may lead to the mix's segregation while lower quantity produces a too stiff mix leading to early breaking [27] .

1.2.5. Foam

Preformed foam is essential in LCC as it can control the plastic density of the mix [28]. Preformed foam consists of a foaming agent and compressed air to help produce foam [22]. A foaming agent is usually added to the base mix (Cement slurry) to produce the bubble structure in the LCC material and help decrease the water's high surface tension and created foam [13]. These foaming agents could either be blended with the base mix after they have been produced separately or mixed along with the base mix [29], with the former being the preferred method in practice. The foam should have a homogeneous bubble structure to provide concrete with reasonable strength [30]. The structure should be capable of resisting the base mix's pressure until the initial setting time is reached as the air bubbles will be surrounded by a strong skeleton of concrete [26].

1.3. Mix design

According to Brady et al., there is no standard method to calculate LCC's mix proportions [30]. It is also challenging to design for its target dry density due to the desorption (50 to 200 kg/m^3) of LCC [31]. Therefore, a target plastic density is used as the design criterion. The target plastic density is assumed to be the sum of solids and water mix as presented in equation 1 [30,32]:

$$D = C + W + F \tag{1}$$

where, D= target plastic density, kg/m^3; C= cement content, kg/m^3; W= water content, kg/m^3; F=fine aggregate content, kg/m^3.

2. Material properties of lightweight cellular concrete for pavement application

The properties of LCC are dependent on its microstructure and composition, which relies on the binder, method of pore formation, and curing [33]. Ramamurthy et al. broadly classified LCC properties into fresh and hardened state properties [26]. This study focuses on LCC properties that are essential for pavement application.

2.1. Fresh state

LCC is generally free-flowing, self-leveling, and self-compacting in its fresh state. These characteristics make LCC high workability material [10].To evaluate the fresh state of the LCC, consistency (flow behavior), and stability (volumetric stability), which depends on the water content in the mix and the amount of foam added are considered [34]. It should be noted that LCC is quite thixotropic [22], and it is difficult to restart the construction once the concrete starts to harden [10].

2.1.1. Stability

Stability refers to the consistency at which the ratio of the measured density to the design density nearly equals one with no indication of segregation and bleeding [34]. This largely depends on the base mix's consistency and ensures a fine and uniform texture of the LCC when hardening [26]. If the LCC is unstable, the separation of solids and air phases might cause segregation during the fresh state. This could lead to complete air content loss, leaving only the base mix [35]. Factors that could influence LCC stability include environmental conditions (winds, evaporation, vibration, and temperature), materials used(foaming agent, the proportion of the constituent), construction quality, and the instability of the foam itself (quality and volume) [30,35].

2.1.2. Consistency

The consistency of LCC depends on its spreadability and flowability [31]. The spreadability can be measured using the Brewer spread test and slump flow test [36,37]. The flowability is determined by measuring the time taken for paste flow through the Marsh cone with a small opening. The faster the flow time, the better its flowability. The flowability of LCC reduces with decreasing density (where foam volume is more significant compared to solids). The mix's stiffness increases as the adhesion between the bubbles and solid particles increases [27]. Mohammad stated that the flow times of 600 kg/m^3 LCC is longer than the 1,000 kg/m^3 mix [38]. Moreover, blending 30 percent(by mass) of fly ash could improve flowability. Jones and McCarthy showed that adding coarse fly ash improved spreadability 2.5 times more than the cement-sand mix [31]. An increase in the foam volume mix ultimately reduces its consistency [39]. Care needs to be taken concerning the water – solid ratio, which must satisfy consistency and stability requirements [26].

2.2. Early stage

2.2.1. Heat of hydration

LCC is considered to have good thermal insulation due to its cellular structure, which generates more heat of hydration that lasts longer compared to regular concrete. Factors influencing the hydration of LCC include; the volume of pour, cement content, concrete density, the amount, type, and characteristics of the cement/filler/aggregate used [21,30,40]. Peak temperature has been observed to reduce by 40% as cement content decreased from 600 to 300 kg/m^3 [21]. These peak temperatures could also decrease when 30% of cement is replaced with fly ash.

2.2.2. Rate of hardening

The setting time of LCC is crucial as it influences the construction time. Although there is no standard test method for determining the setting time of LCC, the ASTM C266 test method for cement may be suitable to test the setting time of LCC [30,41]. The stiffening of LCC has been noted to occurs after 5 hours after being cast at 20 °C [16,32]. However, typical LCC settings range from 12 and 24 hours [30].

2.3. Hardened state properties

The hardened state properties refer to physical, mechanical, and functional characteristics.

2.3.1. Physical properties

Because LCC may be varied in a wide range of density, an additional variable will be to select the physical properties and mix design [12]. These properties are discussed below.

Drying shrinkage Due to the absence of aggregates, LCC generates ten times more drying shrinkage than normal-weight concrete. This phenomenon is seen to decrease as density reduces [26]. On the contrary, works by BCA, Jones and McCarthy, and Concrete Society observed drying shrinkage increase as density reduced [9,22,31]. Table 1 demonstrates the amount of drying shrinkage noted at a different density.

A reduction of drying shrinkage by replacing cement content with fine fly ash up to 30% is noted by Jones et al. and Chindaprasirt and Rattanasak [36,42]. The pozzolanic property of fly ash reduces drying shrinkage by redefining the pores producing a subdivision of large pores that form nucleation sites for precipitation of hydration products.

Density LCC could either be measured as wet (Cast) or hardened (dry) state density. This is controlled by adding a calculated amount of air as preformed foam to the cement slurry [12,43]. Wet density is mostly required for mix design and casting control; however, LCC's most physical properties are dependent on the hardened density [26]. The hardened density (air-dry) is about 80kg/m^3 less than the wet density [12]. Moisture condition is essential when determining density, and factors such as aggregate size, quantity, and type of foam agent and sand/cement ratio influence the material density [44]. As density reduces, material strength, and thermal conductivity reduce; however, it is ordinarily possible to select a density that can provide needed strength and increased insulation at reduced densities [12].

2.4. Mechanical Properties

Mixes with uniform distribution of air-voids, circular air-voids, and optical spacing between voids can produce LCC with good mechanical properties [26]. These mechanical properties are discussed below.

2.4.1. Compressive Strength

Compressive strength represents the capacity of a material or structure to resist loads. The typical compressive strength of LCC with dry density from 400 kg/m^3 to 1,600 kg/m^3 is demonstrated in Table 1. The compressive strength of LCC is directly proportional to density. Some factors that influence the compressive strength of LCC are; the size and shape of specimens, water content, the direction of loading, age, type of ingredient used, curing method, and the type of foaming agents [26]. Jones and McCarthy reported that a small change in water to cement ratio does not influence LCC's strength [21]. Also, by replacing 30% cement with Fly ash, no significant difference in compressive strength is observed in the long-term (180 days) than ordinary LCC [36]. Research has also shown that up to 75% of cement can be replaced with fly ash without a significant impact on strength [17].

2.4.2. Flexural strength:

Flexural strength or modulus of rupture of concrete is the maximum value of allowable stress before the concrete fractures in pavement design [45]. This is an important characteristic to be considered for any material to be incorporated within the pavement structure [46]. Low-density LCC's flexural strength is reported to reduce with increasing w/c ratio [47]. Typically, the range for flexural strength ratio to the compressive strength of LCC ranges between 0.25 to 0.35 [14]. This ratio is almost zero for densities below 300 kg/m^3 [33].

2.4.3. Indirect tensile strength

The indirect tensile strength follows a similar pattern as the compressive strength increases and decreases as density increases or decreases [30]. The typical tensile strength ratio to compressive strength for LCC ranges between 0.2 and 0.4, whereas it ranges between 0.08 and 0.11 for normal-weight concrete [48]. The addition of fiber to LCC could increase its tensile strength [25].

2.4.4. Modulus of elasticity:

Modulus of Elasticity (E-value) in pavement design represents how much a material will compress along an axis under the opposing load applied in that axis [45]. The E-value is typically a function of its density and compressive strength [12]. LCC is reported to have E-values four times lower than normal-weight concrete, which may be attributed to the mix's lack of course aggregate [30]. LCC mixes with fly ash as fine aggregate exhibits

Table 1
Typical properties of hardened foamed concrete (adapted from [22]).

Maximum compressive strength (MPa)	Average drying shrinkage (%)	Maximum modulus of elasticity (MPa)	Minimum thermal conductivity (W/mK)	Maximum compressive strength (MPa)
1.0	0.30-0.35	1,000	0.10	1.0
1.5	0.22-0.25	1,500	0.11	1.5
2.0	0.20-0.22	2,500	0.17	2.0
3.0	0.15-0.18	3,000	0.23	3.0
5.5	0.09-0.11	4,000	0.38	5.5
8.0	0.07-0.09	6,000	0.50	8.0
10.0	0.06-0.07	12,000	0.62	10.0

lower E-values than mixes with sand [16]. Comparing the E-value of LCC with sand and fly ash to regular weight concrete and lightweight aggregate concrete, LCC with sand as fine aggregate displayed a higher E-value than that with fly ash. To improve E-value, polypropylene fibers can be added to the mix [31].

2.4.5. Poisson's ratio

Poisson's ratio is the ratio of transverse strain to axial strain and serves as a major factor in determining strain, stress, and displacement within the pavement structure [45]. A study by Tiwari et al. found Poisson's ratio for LCC with a density between 230 kg/m^3 to 800 kg/m^3 to range from 0.2 to 0.3 [49]. Poisson's ratio for LCC with densities 1,000 kg/m^3 and 1,400 kg/m^3 ranged between 0.13 to 0.16 and 0.18 to 0.19 respectively [50].

2.5. Functional properties

2.5.1. Thermal insulation/conductivity

"Thermal conductivity of a material is the time rate of transfer of heat by conduction, through a unit thickness, across a unit area for a unit difference of temperature" Measured thermal conductivity values for LCC dry densities between 600 to 1,600 kg/m^3 was found to be between 0.1 and 0.7 W/mK [31]. Also, LCC is reported to exhibit excellent thermal insulation behavior due to its microstructure [26]. Thermal insulation decreases with a decrease in density and improves with a decrease in temperature. A reduction of 26% in thermal conductivity was observed for densities between 640 and 1,440 kg/m^3 when temperatures were reduced from 22 to -196ºC [51].

2.6. Durability properties

ACI 523.3R mentioned the durability of LCC includes water absorption, permeability, and freeze-thaw resistance [6]. However, fatigue life of LCC is yet to be explored as fatigure is considered to be one of the important characteristics in pavement performance [45].

2.6.1. Water absorption

LCC's water absorption largely depends on the paste and non-interconnectedness of some artificial pores, meaning they cannot take part in water absorption [27]. Water absorption decreases with density because of lower paste volume; however, water vapor and oxygen absorption have increased with increased porosity and fly ash content [52].

2.6.2. Porosity

The porosity of LCC is an important attribute as it influences compressive strength and flexural strength. The porosity of LCC is affected by its pore diameter, distribution, continuity, tortuosity, and type of foam agent used. The most effective method for measuring the LCC's porosity is the total vacuum saturation method, which, compared with the apparent and mercury intrusion porosimetry method, produces 66% and 13% greater accuracy [53].

2.6.3. Permeability

Permeability is a measure that expresses the level of water flowing under pressure in a saturated porous medium and is related to the water absorption of the LCC. LCC permeability is almost twice that of regular concrete [53]. LCC permeability coefficient is proportional to unit weight and inversely proportional to pore ration [29].

2.7. Freeze-thaw resistance

Lower density LCC has been observed to have good freeze-thaw resistance due to the hollow voids restraining the expansion forces from frozen water [30]. The freeze-thaw characteristic of LCC is dependent on its initial depth of penetration, absorption, and absorption rate [16]. Tikalsky et al. reported the compressive strength for four low-density LCC specimens after being subjected to freeze-thaw cycles [54]. Mixtures for these low densities exhibited excellent Freeze-thaw resistance. This was attributed to the fact that they had 28 days compressive strength above one MPa, which could have enabled their durability during the freeze-thaw cycle. However, higher density specimens with lower than one MPa 28 days compressive strength were not found durable. Low-density LCC with high fly ash content has been observed to have excellent Frost-Heave resistance. Although the quality of the fly ash largely influences this property [12]. LCC also has good chemical attack resistance, enhanced corrosion resistance at lower densities, and cell like structure and porosity prevent rapid moisture penetration [31].

3. General applications of lightweight cellular concrete

LCC has been widely used in civil and structural engineering areas due to its distinctive properties such as reduced density, low thermal conductivity, excellent flowability, self-compaction ability, and relative cost-effectiveness [48]. Typical LCC applications are similar to regular concrete that require modest loads over smaller periods [12]. This is due to its lower weight and strength compared to regular concrete. Sari and Sani summarized LCC applications with different density, as shown in Table 2 [55]. The typical density of LCC currently in the application is between 1,000 kg/m^3 to 1,500 kg/m^3 and is mainly used for cast-in-place wall, prefabrication, and housing applications. Densities between

Table 2
Summary of foamed concrete applications based on density (modified from [55]).

Density (kg/m^3)	Application
300-600	For soil material replacement, stabilization, and raft foundation.
500-600	It is currently being used to stabilize a redundant, geotechnical rehabilitation and soil settlement, pavement construction.
600-800	They are widely used in void filling as an alternative to granular fill. Some applications include filling of old sewerage pipes, walls, basement, and subways.
800-900	It is primarily used in production of blocks and other non-load bearing building elements such as balcony railing, partitions, parapets, etc.
1,100-1,400	Used in prefabrication and cast-in-place wall, either load-bearing or non-load bearing and floor screeds.
1,100-1,500	Housing applications.
1,600-1,800	It is recommended for slabs and other load-bearing building elements where higher strength is required.

300 kg/m^3 to 600 kg/m^3 is related to pavement construction applications as it provides soil stabilization and road construction functions.

The application of LCC has expanded worldwide. For instance, it has been a solution for the southern US regions that suffer from housing shortage or adverse weather such as hurricanes and earthquakes. In Canada, LCC has been used as a filler for tunnel annulus grouting, flowable fills, and geotechnical applications. LCC's annual market size in the UK is estimated to be 250,000 to 300,000 m^3 annually, which includes an extensive mine stabilization project [56]. This is the same market size in Korea, where it is used as an essential component in a floor heating system. LCC has been employed as a pavement subbase material in Holland due to the low traffic loading and considered cost-effectiveness at repair and rehabilitation [56]. The LCC also provides resistance to freeze-thaw and frost heave in concrete paving [48].

3.1. Pavement design methods

According to past research listed in Table 2, LCC density ranging between 300 to 600 kg/m^3 is recommended in pavement construction and geotechnical application. However, since LCC's use within North America's pavement structure is just emerging, there are no specific standards for designing and incorporating LCC. Current applications have employed the AASHTO 93 method taking into consideration the Modulus of Elasticity of the material as the main design criteria.

In North America, the AASHTO Guide for Design of Pavement Structures (AASHTO, 1993) is the primary pavement design method for flexible pavement [57]. In the design procedure, it is essential to understand the structural number of each layers' material. However, there is a lack of comprehensive information for the structural number of LCC, limiting the use of LCC in thickness design. The structural number of LCC can be determined by using the Falling Weight Deflectometer (FWD) equipment.

The FWD is non-destructive test equipment capable of back calculating the pavement layer's moduli and shall be performed following ASTM D4694 [58]. Once the moduli of each pavement layer is obtained, the existing pavement's adequate structural number can be calculated. Based on a field test performed in Ontario, Canada, an adequate structural number of 0.2 was obtained for 475kg/m^3 density LCC [59]. However, it should be noted that depending on the mix design (i.e. proportions, foaming agent) and how the LCC is produced, the material may meet density requirements but not the specified strength.

In designing, the relationship between compressive strength and elastic modulus should be used instead as a study has indicated that compressive strength and elastic modulus have a positive relationship [51,60]. Under this circumstance, the minimum compressive strength can be used to achieve the desired modulus of elasticity.

The Mechanistic-Empirical pavement design Guide (MEPDG) was developed by AASHTO to address the limitations of AASHTO 93. Currently, the Aashtoware software based on the Mechanistic-Empirical pavement design method does not have provisions for LCC material as a pavement layer. However, since LCC is a cementitious material, it may be suitable to categorize it as a cement stabilized base or chemically treated material when using the Aashtoware. It is noted that the cement-treated and other pozzolanic stabilized materials should be treated as separate layers when used as a base layer for structural support [61]. The LCC layer could be considered an unbound material with constant layer modulus and moisture insensitive if designed to provide long-term strength and durability. Alternatively, the LCC layer could be classified as a chemically stabilized structural layer capable of providing structural support [61].

3.2. Production and placement methods

During construction, the production and placement of LCC mixes typically occur on site. The procedure may differ based on the level of target density. For instance, transit mix trucks carrying premixed cement slurry are acceptable for mixing and transporting to the site when the target density is higher than 800 kg/m^3. During arrival, the preformed foam is added just before placement is done. For target density lower than 800 kg/m^3, the batching and mixing of slurry is commonly carried out on-site using paddle-type or shear mixers. Once the mixing is completed, the preformed foam is then added to the slurry before or during placement using a positive displacement pump [12]. Dolton et al. classified production and placement methods for road construction into two categories [11];

3.2.1. Wet mix process

In this method, cement and sand slurry are batched offsite by a ready mix company and transported to the site. On-site, slurry in the LCC equipment is injected with foam, after which the material is pumped into place. However, care must be taken to ensure that the temperature, viscosity, and density of material are according to specifications.

3.2.2. Dry mix process

All material components for this process are mixed on-site. Firstly, cement and sand slurry are mixed first in the LCC equipment, and then foam is injected into this mixture before it is poured into place. This method is commonly used for high volume productions.

An experienced contractor should oversee the production and installation of LCC. If the slurry is supplied, density should be verified before use, or if mixed on-site, equipment should be cleaned before use [2]. Slurry production from bulk powder on-site should have water and bulk powder tolerance within 2% of the mix design value.

Placement can occur in freezing temperatures (below 0^{o}C) if LCC material is prevented from freezing until the required strength is gained [2]. Prior site-specific evaluations can achieve this for sub-zero temperatures and the use of hydration aids such as polyethylene sheets and insulating tarps, which can maintain LCC temperature above 4 ^{o}C. Placement can also be done under light rain. However, it becomes impossible during heavy pours. Stable surface before fall and groundwater control is also essential during LCC placement until granular base material is placed above it.

3.3. Testing procedures and Quality Control (QC)

Testing and QC procedures for LCC should be consistent with or surpass requirements according to the American Society for Testing and Materials (ASTM), Canadian Standards Association (CSA), and American Concrete Institute (ACI) [2]. ASTM testing necessary for LCC includes C495, C796, and C869 [8,62,63]. An experienced quality engineer should be employed for verification, and project specifications and requirements should be included in contract documents.

Table 3
Typical QC Program for placing LCC for roadworks (Adapted from [2]).

Material property	Frequency	Acceptance criteria	Comments/additional requirements
Density	- One per batch or every 10 m^3 - Every 50 m^3 or once per 20 minutes when doing a continuous production	10% of design density	
Compressive strength	One sample per $100m^3$	Meets or surpasses design strength	- 75 x 150 mm cylinder. - Store in an unobstructed condition within 15 m of the molding area - Curing temperature of 25 to 30^{o}C for 24 to 96 hours - Cure in 80% to 100% humidity chamber at 18 to 27^{o}C

The two main quality control parameters are the material density and compressive strength of hardened material (Table 3). Wet density and temperature of the mix should be monitored during production and placement, with necessary adjustments to density when required [2,12]. This will help monitor the consistency of the discharged mix. Accurate batching of the ingredients is very important [12]. Cement and sand are weighed into the batch, and water is measured, and preformed foam is injected into the mixture by a calibrated nozzle. Mixing should be done to suit the type of mixture, the reason for application, method of placement, and constituent material. Casting techniques also vary depending on its use.

LCC's compressive strength can be determined through sets of standard 75 mm diameter by 150 mm high test cylinders should be cast and monitored as per specifications. If unique or new materials are used as a substitute from typical components, trial batches should be produced to ensure optimum LCC mixture [2].

3.4. Pavements applications of LCC in Canada

As an alternative for the support over weak soils, LCC has been installed into several roadway sections globally. Specifically, in Canada, this has been done by provinces such as British Columbia, Alberta, and Ontario.

The roadways and sidewalk on Vancouver and View street in Victoria, British Columbia, experienced significant surface distresses and damage to underlying utilities due to excessive total differential settlement. This resulted in the use of 475 kg/m^3 density LCC as a subbase alternative to cover a total of 358m with 2,246 m^3 of LCC [11]. The pavement structure consisted of 75mm of asphalt concrete, 150mm of 20mm crushed granular base, and 500mm LCC subbase. QC test revealed LCC with 28-day compressive strength 1.0 MPa. Structural evaluation with Benkleman beam after construction revealed that compared with adjacent pavement not re-constructed with LCC, the LCC section showed more consistency with lower Maximum Pavement Spring Rebound (36% lower). Falling Weight Deflectometer (FWD) results reflected consistent static deflection for the LCC sections with that of the non-LCC section 111% times higher than that of the LCC section. The elastic moduli of the LCC were also reported to be 445 MPa (Std 146 MPa) and 341 MPa (std 99 MPa), which are higher than the typical values for gravel [64].

Similarly, in the Region of Peel in Ontario, because of the ongoing settlement of a rural road (Dixie road) due to peat deposits, an intervention using 475kg/m^3 LCC was required [59]. This was to assist in reducing the weight of fills and minimize environmental impacts on the connecting wetlands. The pavement structure consisted of 650 mm of LCC over the subgrade and overlaid with 150 mm aggregates and 140 mm of asphalt concrete. Including an LCC layer avoided the excessive removal of peat material, which was about 1.5m in depth. Four years after construction, performance evaluation was performed, including visual inspection, FWD, and GPR testing. Layer thickness results obtained from GPR testing in conjunction with construction drawings were utilized in analyzing FWD results. Results reflected that minimal distresses existed, and the Composite modulus on the LCC section was about 9 to 18% higher than the non-LCC section. LCC structural coefficient is calculated to be 0.2, which is higher than the traditional granular subbase of 0.12. Visual inspection eight years (2017) after still revealed no severe pavement distress.

In Calgary, Alberta, the Brentwood bus lane experienced significant frost-heave and became virtually impassable [65]. This roadway was re-constructed in July 2000 using LCC as a subbase material over two separate pour days. Initially, the subbase of the road was soaked with silty deposits more than 30 m in depth. 200 mm of LCC layer was installed on 50 mm of drainage rock (sub drains installed beneath curb and gutter) and geotextile fabric due to the subgrade California Bearing Ratio (CBR) of 0.8%. LCC layer was overlaid with a 150 mm granular base course and 125 mm of hot mix asphalt surface layer. A Benkelman Beam Deflection test one year after resulted in 0.30 mm of deflection, much less than the 0.89 mm allowance for such a road [65]. Since reconstruction, no maintenance of this roadway has been required. Recent visual inspection eight years after, as seen in Fig. 1, also shows the good condition for the LCC section (Fig. 1(b)) instead of the traditional subbase lane (Fig. 1(a)).

Similarly, as a result of continual settlement due to high levels of organic (peat) material depths in the pavement structure on Highway 9 in King, Ontario, the pavement was re-constructed in 2014 [2, 66]. Contrary to previous repairs that incorporated asphalt paddings that yielded even more settlement in short durations, LCC was chosen as an economical and sustainable alternative to limit settlement and reduce safety concerns and maintenance costs. The pavement structure consisted of 1,100 mm of LCC material, overlaid with 200 mm of granular 'O' (OPSS), and 200 mm of hot mix asphalt. A total of $905m^3$ of LCC was poured for this project and eliminated the need for 1.5m depth excavation of organic material. Reduced excavation depth resulted in simplified traffic staging, reduced material disposal, reduced backfill requirement, and construction time and impact to the adjacent wetland canals. Field inspection three years after construction revealed that there were no severe cracks or rutting on the road.

Fig. 1 Calgary bus lane in April 2018 (a) Traditional subbase lane and (b) LCC lane.

Worldwide, the application of LCC within the pavement structure has also yielded some success. LCC density between 400 and 500 kg/m^3 was applied as a subbase alternative in Illinois, United States, due to settlements caused by peat deposits. This has so far achieved better performance in pavement support, lower unit costs, and construction time [67]. Likewise, In the United kingdom, LCC density ranging between 410 to 590 kg/m3 applied on Route 14 as subbase material over peat material has performed well [46].

3.5. *Current pavement performance evaluation*

Incorporating a new material like LCC in the pavement structure requires evaluating its performance in the laboratory and on the field to determine its suitability. This evaluation should consider pavement distress, pavement roughness, pavement structure, and pavement transverse profile and texture [68]. Assessing these properties for LCC as subbase pavements will provide inputs for predicting pavement performance, provide pavement LCC design inputs, check pavement conditions to ensure the level of service, trigger maintenance activities, and support research development efforts, and provide inputs for funding allocation [68].

Even with some application in Canada and worldwide, these range of pavement evaluation lacks for LCC. The LCC studies have limited performance appraisal to visual and strength evaluation without control for comparison. Also, although past studies have shown how several factors could influence the performance of various types of pavements, none has shown how these factors would affect the LCC as subbase pavement compared with the traditional unbound material. Since environmental factors such as temperature, freeze-thaw cycles and freezing index, subgrade properties such as soil type and soil moisture, and traffic loadings are some factors identified as influencing flexible pavement roughness performance [69, 70], a study considering these factors for LCC as subbase pavements is essential. In terms of distress evaluation, pavement temperature, and moisture variations, traffic loads should be considered, and the quality of materials used. Environmental factors such as temperature could be investigated as is with the case for flexible pavements [71].

4. Conclusions

While introducing lightweight cellular concrete's mechanical properties relevant for pavement applications, this paper also considers field construction and limited performance in pavements. Past lightweight cellular concrete research has focused mainly on its mechanical properties. Even though the application of lightweight cellular concrete has been mentioned in a few studies, the installation and construction method in the field is limited, especially in road pavement applications. From this review, it has been established that a critical benefit of lightweight cellular concrete within the pavement structure is its lightweight, which, when combined with its other properties, indicate that it could potentially yield benefits in the pavement structure. However, its performance as a pavement material is limited and not conclusive about its potential to serve as an alternative to the traditional unbound subbase material. There is still a significant gap to fully ascertain its long term performance compared with the traditional subbase material utilized in Canada. Furthermore, a guideline for applying cellular concrete in road pavements is lacking. Hence, more specifically as future steps, this study recommends the following;

4.1. *Laboratory*

A test method for determining lightweight cellular concrete fatigue life is required. No study has evaluated the fatigue life of LCC, which is an important property in pavement applications.

4.2. *Design*

1. Since conventional pavement methods are currently used when determining layer thickness and predicting performance, this poses a problem as it might not be representative of what could occur in the field because the design parameters used are mainly laboratory-based. Although conventional design methods seem adequate for now, it is vital to incorporate LCC performance field data to develop more representative designs for better performance prediction. This will require instrumented experimental sections with LCC material as subbase and traditional unbound subbase material.
2. Data from the experimental section should be employed in calibrating existing design tools for LCC material to provide more representative designs.

4.3. *Performance*

1. There should be a comparative field study between LCC and traditional unbound material pavement. The effects of external factors, such as traffic, temperature, precipitation, and moisture, should be assessed.
2. The influence of the LCC subbase on the performance of the other layers should also be investigated. For example,

heat transfer may differ from the conventional pavement as LCC has good insulation properties. The stress-strain distribution could be changed compared to the traditional pavement as the LCC subbase is a stiffer material.

3. The service life of LCC pavement should be evaluated. Also, the performance model of the LCC subbase should be conducted.

4.4. Construction-

Quantitative information on the cost and time-saving benefits of LCC is necessary. Most studies state this as a benefit; however, no quantitative data is provided.

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