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Title

The current state of practice and research on lightweight cellular concrete

Abstract

Lightweight concrete has been used in construction as early as the Roman Empire and has evolved in its constituents over time. Modern lightweight concrete utilizes foam to produce lightweight cellular concrete and ranges in unit weights from 20 pcf to 120 pcf. Typical construction projects with geotechnical applications make use of lightweight cellular concrete for vertical stress reduction. As the use of lightweight cellular concrete for geotechnical applications is relatively new, a complete synthesis of the current state of practice and research is not readily available. This paper presents a review of the literature including project showcases, guides, and research on geotechnical applications of lightweight cellular concrete. Additionally, research gaps germane to the topic are exposed and subjects to advance the state of practice and research are suggested.

Introduction

According to ACI Committee 523 (2006) Lightweight Cellular Concrete (LCC) is a concrete product with an oven-dried unit weight of 50 pcf (800 kg/m^3) or less and is made from hydraulic cement, water, and preformed foam. Although not technically within the bounds set forth by the ACI, it is commonly accepted that LCC is in the unit weight range from 20 pcf to 120 pcf. LCC is also known as low-density cellular concrete (ACI Committee 523 2006), foamed concrete (Amran et al. 2015), lightweight foamed concrete (Kozłowski and Kadela 2018), low-density foam concrete (Song and Lange 2021), aerated concrete (Narayanan and Ramamurthy 2000), or simply cellular concrete (Hardy et al. 2004).

Background

Lightweight concrete has been employed in construction as early as the Roman Empire where vesicular volcanic aggregates were included in concrete construction. The technology of LCC was first developed in the early 1900s in Sweden (Sutmoller 2020) and used in Europe and the United States as part of a flooring system. Cellular concrete was initially patented in 1923 by Axel Eriksson and was known as Ytong (Chica and Alzate 2019). A Swiss patent in 1932 by Siporex included a vapor curing process developed by Eklund (Chica and Alzate 2019; Taylor and Halsted 2021). Foamed concrete was used in the Soviet Union by Kudriashoff starting in 1938, where it was employed for non-structural construction elements (Chica and Alzate 2019). The use of LCC expanded through Europe and the rest of the world from the mid-1940s and began incorporating hydrolyzed protein-based foams, which in turn increased the quality control of LCC production (Sutmoller 2020). The United Kingdom was introduced to LCC for load-bearing application, including coal slag from thermoelectric plants, in 1950 (Chica and Alzate 2019). LCC was applied in oil wells and as fill for excavations around 1970 (Chica and Alzate 2019). In 1980, the Falkirk railway tunnel in Scotland utilized approximately 4500 m^3 of LCC for the first large-scale project using LCC as fill (Chica and Alzate 2019). These introductions made advances in the production and quality of LCC of synthetic-based foam liquid concentrates in the early 1990s, which brought more stability to the foam air cells and the longevity of the LCC (Sutmoller 2020). Typical lightweight cellular concrete is considered a relatively impervious (i.e., impermeable) material but may also be classified as permeable using modern hybrid foam. Hybrid foams, consisting of protein-based and synthetic-based concentrates, were developed in the early 2000s, introducing permeable lightweight cellular concrete (PLCC) (Sutmoller 2020).

The primary advantages of LCC are (1) a significant reduction in weight, (2) thermal and acoustic insulation, (3) fire resistance, (4) relatively lower cost of production when compared with typical concrete, (5) ease of pumping, (6) omission of vibration during the placement as needed in typical concrete placement and (7) does it require compaction like typical fill soils (Chica and Alzate 2019).

Much of the recent advancements of LCC technology involve using additives. These include fly ash, peroxide, slag, silica fume, sugarcane filter cake, laterite, palm oil fuel ash, waste clay brick, clay brick, soil, plastic waste (PE, PVC), recycled waste (glass, plastic), EPS, latex, salt waste, polypropylene fibers, quick lime, poly-olefin, silica powders, sand, kaolin, bentonite food additives (methylcellulose, iota carrageenan gum), PVA fibers, cenospheres (Chica and Alzate 2019), vermiculite, perlite, water-reducing admixtures, set accelerators, high-reactivity metakaolin (ACI Committee 523 2006). Much of the advances in additive constituents appear to be driven by structural applications in Civil Engineering.

<u>Previous Research and Characterization</u>

LCC may be generally classified by its unit weight and compressive strength, as shown in Table 1. Much of the laboratory characterization of LCC follows the typical concrete strength protocol where it is defined by the compressive strength (unconfined, uniaxial) as a function of curing time. Also, as customary, the 28-day compressive strength is the defining strength characterization for LCC. The compressive strength of LCC should be performed per ASTM C796 and C495 (ACI Committee 523 2006; ASTM C09 Committee 2012, 2019a).

The determination of the as-cast density of LCC is described in ASTM C796, while the sampling and testing of insulating LCC are to be performed per ASTM C513 (ASTM C09 Committee 2011, 2019a). The coefficient of thermal expansion is typically 5.0 x 10^{-6} to 7.0 x 10^{-6}/°F but varies with density (ACI Committee 523 2006). Determination of the thermal conductivity is performed per ASTM C177, C518, and C1363 (ASTM C16 Committee 2019a; b, 2021) while the fire resistance of LCC is performed per ASTM E119 (ASTM E05 Committee 2020). The permeability or, more appropriately, hydraulic conductivity of LCC is typically in the range of 1x10^{-5} to 1x10^{-6} cm/sec. This property is generally performed per ASTM 2434 (ASTM D18 Committee 2019), with freezing-and-thawing evaluated per ASTM C666 (ASTM C09 Committee 2015). Constituent compatibility of LCC mixtures is evaluated per ASTM C796 and C869 (ASTM C09 Committee 2011b, 2019a). Also, Kearsley and Wainwright (2001) have developed a methodology to optimize the fly ash content for strength.

Table 1 – Classification of LCC, after (Aerix Industries n.d.).

Class	LCC Unit Weight (pcf)	Minimum Compressive Strength at 28 days (psi)
I	24-29	10
II	30-35	40
III	36-41	80
IV	42-49	120
V	50-79	160
VI	80-90	300

René Féret first developed a relationship for the strength of concrete in 1896, which includes the volume of air,

$$f_c = K\left(\frac{c}{c+w+a}\right)^2 \qquad \text{Equation 1}$$

where f_c (MPa) is the compressive strength of concrete, K is a constant, c is the volumetric proportion of cement, w is the volumetric proportion of water, and a is the volumetric proportion of air (Kearsley and Wainwright 2002). Additionally, Kearsley and Wainwright (2002) have determined experimentally that the compressive strength of LCC may be determined by,

$$f_c = 39.6\big(ln(t)\big)^{1.174}(1-p)^{3.6} \qquad \text{Equation 2}$$

where t is the time in days since casting, and p is the mature porosity measured after one year. A plot of the compressive strength as a function of the porosity from Equation 2 is shown in Figure 1.

The vacuum saturation porosity (%), P, of LCC may be determined by,

$$P = \frac{W_{sat}-W_{dry}}{W_{sat}-W_{wat}} \times 100 \qquad \text{Equation 3}$$

where W_{sat} is the weight in air of the saturated specimen, W_{wat} is the weight in water of the saturated specimen, and W_{dry} is the weight of the oven-dried specimen. The specimens are oven-dried to a constant weight and placed in a desiccator under vacuum for a minimum of 3 hours, then filled with de-aired distilled water (Cabrera and Lynsdale 1988). Various alternative methods have been evaluated to determine LCC's porosity, including (1) freeze-drying, vacuum-drying, (2) oven-drying at 60°C, and (3) oven-drying at 105°C. The last method shows the largest porosity determination and perhaps overestimates the porosity due to damage to the microstructure (Galle 2001). Galle (2001) suggests the most appropriate method of porosity determination is the freeze-drying method.

Tikalsky et al. (2004) have developed a modified freeze-thaw procedure that involves saturation of the LCC specimens before the freeze-thaw cycling. The study has shown that strength, depth of initial water penetration, absorption, and absorption rate all affect the freeze-thaw durability of LCC. The authors demonstrated that the density and permeability of the LCC are not significant variables in freeze-thaw durability. However, further research should be undertaken to generate a more extensive data set to further and more completely characterize the freeze-thaw durability of LCC.

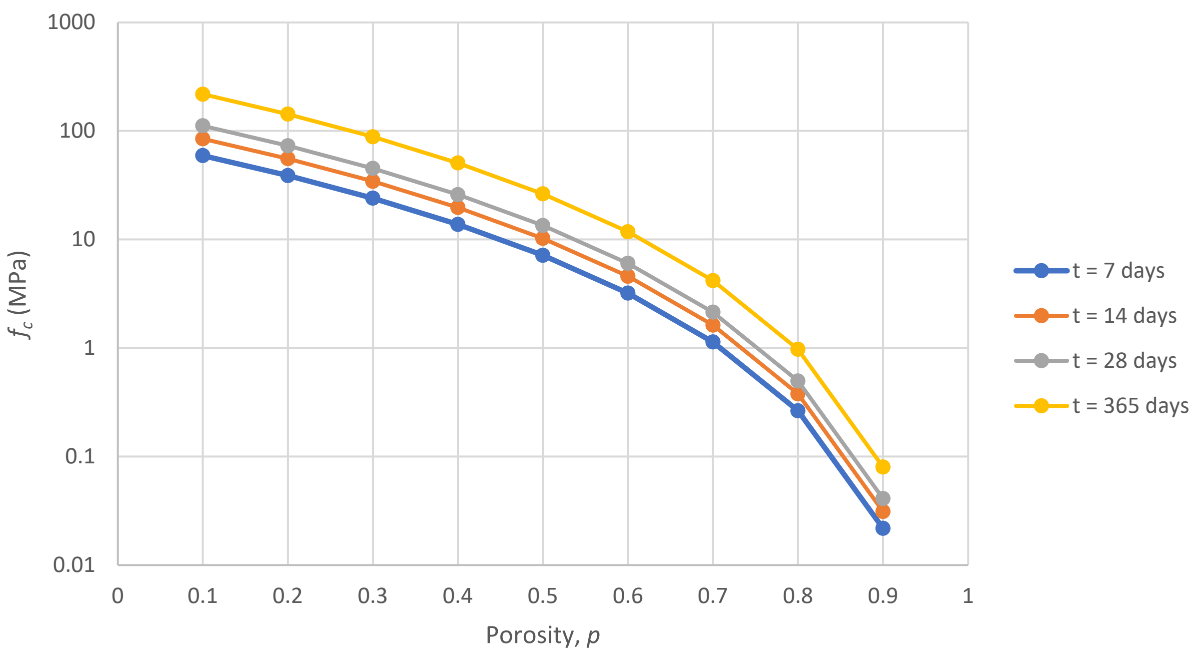

Figure 1. Plot of the compressive strength of LCC from the predictive model shown in Equation 2 as a function of porosity at various cure times, *t*.

A comprehensive experimental study was undertaken at the Sandia National Laboratories to determine the mechanical material properties of cellular concrete with unit weights of 62.4 pcf and 87.4 pcf. This testing included unconfined compression, triaxial compression, uniaxial strain, triaxial extension, and uniaxial tension tests (Hardy et al. 2004). The Sandia study generated constitutive models based on the cap plasticity models (Sandler and Rubin 1979) for both unit weight classes.

Kearsley and Wainwright (2002) showed that the strength of LCC is dependent mainly on dry density as well as age but not necessarily affected by the ash type or ash content. In contrast, Jones and McCarthy (2005) have shown that the use of fly ash in foamed concrete significantly improves its properties (e.g., reducing the heat of hydration). A contributing study was undertaken for LCC used as subgrade fill. This study found adding fly ash contributed to the strengthening of the LCC. The strengthening effect was due to pozzolanic and hydration reactions, which aided the densification of the structural skeleton (Liu et al. 2020). Liu et al. (2020) recommend a fly ash content of 25 percent to optimize this admixture. Using fly ash as an admixture in LCC has also been shown to create a more uniform air void distribution and consistent air voids (Nambiar and Ramamurthy 2007). Nambiar and Ramamurthy (2007) have also shown that the air void shape in LCC does not necessarily significantly affect LCC properties. Overviews of the data and relationships in the literature are provided by Narayanan and Ramamurthy (2000) and Ramamurthy et al. (2009).

Tiwari et al. (2017) published a technical note that summarized many geotechnical-based test results for LCC. These methods and tests included casting and curing, unconfined compressive strength, direct shear, direct simple shear, undrained and drained triaxial compression, K0 consolidation, hydraulic conductivity, and 1-D consolidation. The study incorporated Class II and Class IV LCC with a range of 19.7 pcf to 47.7 pcf unit weights. As expected, the compressive strength exhibited a dependency on the unit weight of the test specimens. The effective friction angle obtained from the saturated test specimens' direct simple shearing mode averaged 35° with an effective cohesion intercept of 750 psf. The effective friction angle obtained from the consolidated drained and undrained triaxial compression shearing mode of the saturated test specimens averaged 34° with an effective cohesion intercept of 1,630 psf. The results from the K0 consolidation testing showed a range from 0.2 to 0.5, which corresponds to Poisson's ratio values from 0.2 to 0.3, respectively. Class II LCC exhibited significant deformation with vertical stresses higher than 6,250 psf, while Class IV LCC showed significant deformation with vertical stresses higher than 14,600 psf. The data generated by the study seems to indicate the strength and stiffness of the LCC generally decreases with saturation. The hydraulic conductivity testing was performed using ASTM D5084 (ASTM D18 Committee 2016), which is commonly known as the flexible-wall permeability or back-pressure saturated permeability. The hydraulic conductivity results ranged from 1.7 x 10-4 cm/sec to 1.2 x 10-3 cm/sec and indicated no decrease in permeability with an increase of effective confining stress.

As LCC is used more in geotechnical applications, the performance of LCC during earthquakes has been an area of research interest. Tiwari et al. (2018) undertook a study to investigate the response of LCC under dynamic loading under cyclic simple shear testing. Specimens utilized in the study were Class II and Class IV LCC. Data sets and models were generated for dynamic backbone curves, maximum shear modulus curves, modulus reduction curves, and damping curves.

Song and Lange (2021) presented data on the dynamic Young's modulus measurement using the resonant column test per ASTM C215 (ASTM C09 Committee 2019b). Unit weights of the LCC considered in the study ranged from 25.5 pcf to 123.5 pcf. As expected, the dynamic Young's modulus exhibited a dependence on the unit weight of the LCC as an exponential increase in stiffness with an increase in unit weight.

To date, the studies of Hardy et al. (2004); Song and Lange (2021); Tiwari et al. (2017, 2018) show the most comprehensive material property evaluations applicable to the geotechnical implementation of LCC.

Geotechnical Engineering Applications

According to ACI Committee 523 (2006), geotechnical engineering applications have been used for embankments, roadway bases, pipeline and culvert backfills, void space and tank infills, and insulation and isolation fills. In most cases, LCC offers advantages over other earthen commonly used materials in geotechnical engineering. These advantages include low density, ease of excavation, and a relatively controllable strength. Teig and Anderson (2012) suggest the following benefits of the use of LCC: (1) Lighter and stronger than conventional compacted soil, (2) Small equipment used in construction leading to lower environmental impacts, (3) Bridge abutments may experience little lateral earth pressures and small live load surcharges. (4) Block-like behavior (similar to geofoam) and reduced inertial effects in seismic conditions, (5) Reduced imposed settlements compared to conventional compacted soil fill, and (6) Up to 30% cost savings as compared to conventional cast-in-place concrete walls with soil fills. Additionally, Taylor and Halsted (2021) listed the following alternate advantages: (1) LCC provides for aggregate conservations. (2) Resistance to freeze-thaw. (3) Self-leveling and consolidation. (4) Energy dissipation and damping. (5) LCC is very excavatable. (6) LCC is considered inert and non-flammable. (7) Materials may be locally sourced. (8) LCC is easily pumpable. (9) Construction with LCC requires less transportation costs and reduces emissions, and finally, (10) LCC construction offers worker safety advantages.

Backfill

LCC has been placed adjacent to bridge abutments and retaining walls as a lightweight fill to reduce settlement, and due to the cementitious nature, it requires no compaction. According to ACI Committee 523 (2006), the general fill should consist of 30 pcf material, but the upper two to three feet of the fill should consist of 42 pcf material so that this material is less susceptible to frost damage and provides a solid base for pavement or approach slabs.

Several instances are demonstrated where LCC may be used as mechanically stabilized earth wall (MSE) fill (Bartlett 2015; Pradel and Tiwari 2015; Sutmoller 2020; Teig and Anderson 2012; Tiwari et al. 2017, 2018).

Bartlett (2015) suggested using Rankine Theory for lateral earth pressures using the effective friction angle obtained from direct simple shear tests and a relatively low cohesion intercept. Tiwari et al. (2017) suggest using a stress-dependent effective friction angle and zero cohesion for MSE external stability calculations. Also, numerical analyses of LCC used as MSE wall fill reinforced with geogrid behave as a semi-rigid body under cyclic conditions and perform well (Pradel and Tiwari 2015).

Teig and Anderson (2012) reported an embankment fill over the Colton railway flyover that utilized LCC due to settlement and right-of-way constraints imposed on the project. The project required a relatively high seismic design acceleration criterion. A numerical evaluation method was developed for this project based on previous work performed in similar geomaterials and applications by Bartlett et al. (2011) and Bartlett and Lawton (2008).

Roadways

LCC has been used in roadway construction as a base over soft soils. When used as such, LCC has been shown to span localized settlements up to 3.2 ft (ACI Committee 523 2006). Sutmoller (2020) and Taylor and Halsted (2021) have noted advantages when LCC has been used for subgrade modifications and improvements. Also, work has been undertaken by Decký et al. (2016) to back-calculate the modulus of LCC by in-situ testing of a sand subgrade and LCC base material. The study was based on the theoretical 2-layer Sojuzdornii equivalent deformation model. Lastly, Averyanov (2018) undertook an extensive study evaluating the use of LCC in soft soil conditions as a base material in a pavement section. The study showed many advantages to using LCC as a base material, particularly a reduction in the depth of over-excavation and the replacement of poor subgrade materials.

Inti et al. (2021) suggest the advantageous use of PLCC in pervious parking lot sections as a replacement for the granular subbase. Testing indicated the PLCC demonstrated sufficient strength and permeability with infiltration rates on the order of 700 in./hr. These authors found the density of the PLCC is critical when considering the strength, infiltration rate, and water storage. Effluents from infiltration typically showed a higher pH and alkalinity compared to conventional granular permeable pavement sections.

Pipeline and Culvert Fills

Allen and Meade (1984) discuss an embankment fill on I-275 in Kentucky where LCC was utilized as an embankment material spanning an existing box culvert. The vertical stresses caused by conventional fill (soil) would exceed the box culverts' structural capacity. Hence, LCC was employed as a lightweight material for embankment construction that reached heights up to 47 feet. The dry LCC density used for the project was 25 to 30 percent of conventional fill, but saturated LCC densities were on the order of 60 to 70 percent of conventional fill. The report details construction methods, laboratory test results, and instrumentation. Class II test specimens were subjected to 20 cycles of temperature changes from 0 to 70 °F. Unfortunately, some specimens completely disintegrated under these test conditions. The instrumentation data seems inconclusive and merits more evaluation.

Void Fills

LCC has shown to be an effective material for large void fills where flowability is a factor and a reduction in dead load is desired. Examples of void fills are abandoned swimming pools, abandoned pipelines, excavations, annular spaces around pipelines, undemolished structures, tunnels, and underground fuel or oil tanks (ACI Committee 523 2006; Sutmoller 2020). Federal regulations indicate LCC is an inert substance for abandonment applications (ACI Committee 523 2006).

Insulation and Isolation Fills and Miscellaneous Applications

Regions that experience permafrost conditions have typically employed crushed-rock air convection embankment (ACE) technologies as a method to permafrost from thawing in road constructions. ACE acts as an insulator in summer while it acts as a convection cooler in winter conditions. Wu et al. (2020) undertook a study in which numerical simulations were performed comparing the performance of typical ACE embankments and replacement of crushed rock with LCC. The study indicates LCC has better performance in thermal conductivity and heat capacity with a reduced cost. Advantages, as seen elsewhere, are the reduction of the environmental impact resulting from the installation. Additional insulation and isolation applications are possible for utility protection and geothermal utility insulation (Sutmoller 2020).

LCC has been used in conjunction with expanded polystyrene foam (EPS) for a potential fault crossing. The LCC and EPS system was designed to absorb fault offset over a water pipeline in a rupture event (Taylor 2015).

Lastly, LCC blocks have been used as an energy dissipation system for runaway truck ramps and particularly for airplanes which has been adopted by the FAA (Taylor and Halsted 2021). Other applications presented by Taylor and Halsted (2021) include lightweight dam and levee structural fills, landslide repair, and slope stabilization.

Durability

Durability of LCC from a highway/roadway perspective is the ability of the material to last through the design life of the application under conditions of varying water content, chemical attack from both natural water sources as well as potential roadway surface contaminates and resisting damage from repetitive traffic loading. The degree of durability of LCC is dependent on the location of the material within the pavement section as a direct function of the traffic loading, confinement, and strains. The location of the LCC in a pavement structure may also help identity the importance of the freeze-thaw durability characteristics when temperature changes may not be large or when the material is beneath the regional frost depth.

Lannen et al. (2018) undertook a testing program to address the strength and abrasion testing of cellular grout. Abrasion testing protocols were in accordance with ASTM C1138M-19 Standard

Test Method for Abrasion Resistance of Concrete (Underwater Method) (ASTM C09 Committee 2019c). Their study consisted of cellular grout samples with unit weights ranging from 90 pcf to 110 pcf, which represents the high end of cellular grout densities typically encountered that are on the order of 20 pcf to 70 pcf.

The general testing protocol set forth in ASTM C1138M-19 involves agitation of a concrete specimen submerged under water with the use of rotating agitator that moves a set of hardened chrome steel grinding balls of varying prescribed sizes. The results of the testing are the mass or volume loss as a result of the abrasion which occurs after a prescribed duration of agitation. Lannen et al. (2018) have also reported the average depth of abrasion.

The data presented by Lannen et al. (2018) is very brief and, as previously mentioned, specific to high end of the LCC density range. The data in the report is only loosely applicable to the durability of highway/roadway applications of LCC since LCC will not undergo direct abrasion from surface traffic loading. Applicability of the data and method in ASTM C1138M-19 is more likely to be encountered at the interface of the LCC with other pavement components or the subgrade. The pavement interfaces with the LCC are likely to encounter traffic induced strains on the order of 10^{-5} to 10^{-7} and are not simulative by the abrasion action from ASTM C1138M-19.

A selection of durability influencing factors has been studied by Liu et al. (2019) to include the following:

a. Wet density
b. Compressive strength
c. Filling aspect ratio
d. Safety factor
e. Slope rate of connecting surface
f. Steel wire mesh setting
g. Production equipment
h. Agitation sufficient degree
i. Flow valve
j. Single layer pouring thickness
k. Single layer pouring time
l. Interlayer pouring interval time
m. Construction environment
n. Curing time
o. Vehicle load
p. Drainage condition
q. Chemical corrosion
r. Temperature change

Although the highlight of the paper is the application of fuzzy logic utilizing the method of Analytical Hierarchy Process (AHP) and Fuzzy Comprehensive Evaluation (FCE), the inputs to the method are of interest from a durability standpoint. Referencing the list above, items *c* – *m* are project specific durability concerns and are not likely to have significant research impacts with respect to highway/roadway applications. Item *n*, curing time, is an important consideration when developing research or a testing program for durability as the results of any testing will vary due to the mechanical and chemical behavior of LCC being dependent on the rate of reaction cure time. Of most importance to the application of LCC to highway/roadway durability are items *a*, *b*, and *o* – *r*, wet density, compressive strength, vehicle load, drainage condition, chemical corrosion, and temperature change, respectively.

The total density of the LCC will largely be a function of the project specification but the wet density will be a function of the natural wetting induced water content changes. Tiwari et al. (2017) have suggested that LCC has a low water absorption ability, indicating that research has been undertaken to address absorption. Tiwari et al. (2017) have reported hydraulic conductivities of LCC from 10^{-3} to 10^{-6} cm/sec, which supports the notion that absorption may be relatively low. The low hydraulic conductivity and coupled with an open vesicular pore structure suggests that absorption is likely to occur via diffusion rather than advective flow. The drainage condition of LCC is a quasi-project-specific aspect but may be addressed with absorption and permeability research.

Compressive strength of the LCC has been demonstrated in the literature to be a direct function of the cast density and will always be an important parameter in the design and engineering in projects involving LCC. Kozłowski and Kadela (2018), Namsone et al. (2017), and Tiwari et al. (2017), among many others, have suggested relationships in the form of regression equations for the compressive strength as a function of the unit weight or density.

Durability of LCC as a function of temperature change is an important aspect to consider in the highway/roadway application. Tiwari et al. (2017) have indicated LCC has a high freeze-thaw resistivity which suggests research has been done on the subject. This subject has also been addressed by the research represented by Kozłowski and Kadela (2018).

A Latvian study on LCC durability was conducted and reported by Namsone et al. (2017) that included the durability aspects of strength, density, water absorption, carbonization, and frost resistance. One unique durability aspect explored by Namsone et al. (2017) is the tendency of LCC to exhibit shrinkage. The authors argue that shrinkage is due to the cement hydration as well as water loss. Namsone et al. (2017) also argue that shrinkage causes strength reduction, increases the thermal conductivity, and increases the susceptibility of freeze-thaw cycles. Additionally, carbonation, a process which transforms $Ca(OH)_2$ to $CaCO_3$ does not necessarily affect compressive strength, but does influence shrinkage. The results indicate the depth of carbonation is typically less than six mm.

Namsone et al. (2017) suggested that analyzing the experimental data shows a correlation between water absorption, carbonation depth and compressive strength, but do not present any form of correlation between the parameters. Independently, the frost resistance and carbonation were qualitatively observed. It is apparent that additional research to correlate the durability parameters presented in the paper to compressive strength would increase the value of the research.

As typical with most research papers involving LCC, Kozłowski and Kadela (2018) have reported on testing conducted to address the apparent density and compressive strength. Additionally, Kozłowski and Kadela (2018) have reported on the modulus of elasticity, flexural strength and degradation under freeze-thaw cycles. Both the modulus of elasticity and flexural strength are important factors to consider when including LCC as a structural component in a pavement section but are not necessarily a direct component of durability. The data and analysis looking at the degradation from freeze thaw cycles has been done by comparing the compressive strength after 25 freeze-thaw cycles. Kozłowski and Kadela (2018) have reported an approximately 15 percent reduction in strength after being subjected to the freeze-thaw cycles, which is relatively modest from a durability standpoint.

To date, the most comprehensive study on the mechanical properties of LCC has been published by Tiwari et al. (2017). Their published data set includes laboratory testing on Class II and Class IV LCC specimens (as defined by CALTRANS). The test methods in the study include cast and cured unit weight, unconfined compressive strength, direct shear strength, direct simple shear strength, isotropically consolidated-drained and consolidated-undrained triaxial compressive strength, K_0 consolidation, hydraulic conductivity, and one-dimensional consolidation. The test data presented is largely applicable to the general geotechnical design aspects to be encountered in a project involving LCC, particularly for backfill of MSE retaining walls. It was noted that the strain rate used in the unconfined compressive strength testing was 0.5%/hr, which is exceptionally low and would tend to grossly underestimate the strength of the LCC cylinders. Also noted was the mention that the hydraulic conductivity test results showed no appreciable change when subjected to varying effective confining stresses, which is contrary to intuition and experience. Admittedly, Tiwari et al. (2017) have identified the hydraulic conductivity is an area that requires additional research. Durability information derived from the paper is interpretive from the reader's standpoint and is limited on the stress-controlled strength limit-state aspect.

Summary and Conclusions

Previous research has been conducted on LCC to include a history and characterization of various engineering parameters. Geotechnical applications presented include its use as backfill, roadways, pipeline and culvert fills, void fills, insulation and isolation fills, and durability.

An important subject that is not directly addressed in any of the previous literature is the point at which the mechanical and durability behavior of the LCC has reached a steady state. The steady state point may be defined by sufficient hydration reaction having been achieved where no appreciable strength gain is demonstrated with additional curing time. Strength and durability test data are not comparable when the hydration reaction is not complete. Likewise, at a construction project the LCC product will not be put into service until a certain level of curing has taken place. This aspect of steady state is a deficient point of research and requires further study and consideration.

One aspect of durability that requires more research attention is the effect of the degree of saturation or water content on the mechanical behavior. Data presented by Tiwari et al. (2017) suggest that the increase in saturation yields a decrease in strength, but is not by any means sufficient in drawing conclusive results from a durability standpoint.

An important engineering property in the design of pavement in a highway/roadway application is the stiffness or modulus of the material in consideration. It is apparent in the literature the modulus available is derived from the stress-strain data of testing that involves monotonic loading. Traffic loading impulses are time-dependent and vary in magnitude from various vehicle types. The modulus of a pavement material is also dependent on the state of stress, particularly the confinement of the material. An additional identifiable engineering parameter that appears to be missing in the current state of research for LCC is the resilient modulus. The resilient modulus is an input for engineering design of pavement and the testing is performed in a triaxial cell which is commonly used in geotechnical soil testing. The testing protocol for the resilient modulus is performed in accordance with AASHTO Technical Subcommittee: 1a, Soil and Unbound Recycled Materials (2017). The axial load is applied to a cylindrical test specimen using a haversine-shaped load pulse, which simulates traffic loading. The confinement and load amplitude are varied throughout the test that ultimately yields a stress-dependent modulus of elasticity. Since the loading roughly simulates traffic loading, it is also directly applicable to address the durability of LCC.

LCC, although its primary matter constituent is Portland cement, does not necessarily behave as a typical concrete. Most projects involving LCC do not incorporate steel reinforcement or aggregates in the construction of the product like typical concrete. Much of the research in the development of the engineering properties of LCC are undertaken as a hybrid approach from soil, rock, and concrete testing. LCC is not technically a soil or rock material and is not a conventional concrete. With this classification in mind, LCC should be considered an intermediate material from a geotechnical standpoint.

Finally, it is important to consider the method of production, the LCC class, the mix design, any additives when utilizing the data from the literature as it appears as though there are many varieties of LCC presented in the literature.

References

AASHTO Technical Subcommittee: 1a, Soil and Unbound Recycled Materials. (2017). *T 307-99 Standard Method of Test for Determining the Resilient Modulus of Soils and Aggregate Materials*. AASHTO, Washington D.C.

ACI Committee 523. (2006). *Guide for Cast-in-Place Low Density Cellular Concrete*. Cellular Concrete, American Concrete Institute.

Aerix Industries. (n.d.). "Clarification on Classes of LDCC." Aerix Industries.

Allen, D. L., and Meade, B. W. (1984). *An Evaluation of Elastizell Concrete as a Lightweight Fill Material*. Research Report, Kentucky Transportation Research Program, College of Engineering, University of Kentucky.

Amran, Y. H. M., Farzadnia, N., and Abang Ali, A. A. (2015). "Properties and applications of foamed concrete; a review." *Construction and Building Materials*, 101, 990–1005.

ASTM C09 Committee. (2011a). *C513/C513M-11 Test Method for Obtaining and Testing Specimens of Hardened Lightweight Insulating Concrete for Compressive Strength*. ASTM International.

ASTM C09 Committee. (2011b). *C869/C869M-11 Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete*. ASTM International.

ASTM C09 Committee. (2012). *C495/C495M-12 Test Method for Compressive Strength of Lightweight Insulating Concrete*. ASTM International.

ASTM C09 Committee. (2015). *C666/C666M-15 Test Method for Resistance of Concrete to Rapid Freezing and Thawing*. ASTM International.

ASTM C09 Committee. (2019a). *C796/796M-19 Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Preformed Foam*. ASTM International.

ASTM C09 Committee. (2019b). *C215-19 Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens*. ASTM International.

ASTM C09 Committee. (2019c). *C1138M-19 Test Method for Abrasion Resistance of Concrete (Underwater Method)*. ASTM International.

ASTM C16 Committee. (2019a). *C177-19 Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*. ASTM International.

ASTM C16 Committee. (2019b). *C1363-19 Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*. ASTM International.

ASTM C16 Committee. (2021). *C518-21 Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*. ASTM International.

ASTM D18 Committee. (2016). *D5084-16a Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*. ASTM International.

ASTM D18 Committee. (2019). *D2434-19 Test Method for Permeability of Granular Soils (Constant Head)*. ASTM International.

ASTM E05 Committee. (2020). *E119-20 Test Methods for Fire Tests of Building Construction and Materials*. ASTM International.

Averyanov, S. (2018). "Analysis of construction experience of using lightweight cellular concrete as a subbase material." University Of Waterloo, Waterloo, Ontario, Canada.

Bartlett, S. F. (2015). "Application of Caltrans mechanically stabliized earth wall design requirements to lightweight cellular concrete backfill."

Bartlett, S. F., and Lawton, E. C. (2008). "Evaluating the Seismic Stability and Performance of Freestanding Geofoam Embankment." *6th National Seismic Conference on Bridges and Highways*, Charleston, SC.

Bartlett, S. F., Trandafir, A. C., Lawton, E. C., and Lingwall, B. N. (2011). "Applications of EPS Geofoam in Design and Construction of Earthquake Resilient Infrastructure." *EPS 2011*, Oslo Norway.

Cabrera, J. G., and Lynsdale, C. J. (1988). "A new gas permeameter for measuring the permeability of mortar and concrete." *Magazine of Concrete Research*, 40(11), 177–182.

Chica, L., and Alzate, A. (2019). "Cellular concrete review: New trends for application in construction." *Construction and Building Materials*, 200, 637–647.

Decký, M., Drusa, M., Zgútová, K., Blaško, M., Hájek, M., and Scherfel, W. (2016). "Foam Concrete as New Material in Road Constructions." *Procedia Engineering*, 161, 428–433.

Galle, C. (2001). "Effect of drying on cement-based materials pore structure as identified by mercury intrusion porosimetry A comparative study between oven-, vacuum-, and freeze-drying." *Cement and Concrete Research*, 11.

Hardy, R., Lee, M., and Bronowski, D. (2004). *Laboratory constitutive characterization of cellular concrete*.

Inti, S., Evans, T. W., Flores, M., Solanki, J. S., and Chandramouli, C. V. (2021). "Permeable low-density cellular concrete (PLDCC) as a replacement for aggregate layers in permeable parking lots." *Developments in the Built Environment*, 8, 100060.

Jones, M. R., and McCarthy, A. (2005). "Preliminary views on the potential of foamed concrete as a structural material." *Magazine of Concrete Research*, 57(1), 21–31.

Kearsley, E. P., and Wainwright, P. J. (2001). "The effect of high fly ash content on the compressive strength of foamed concrete." *Cement and Concrete Research*, 31(1), 105–112.

Kearsley, E. P., and Wainwright, P. J. (2002). "The effect of porosity on the strength of foamed concrete." *Cement and Concrete Research*, 32(2), 233–239.

Kozłowski, M., and Kadela, M. (2018). "Mechanical Characterization of Lightweight Foamed Concrete." *Advances in Materials Science and Engineering*, 2018, 1–8.

Lannen, T., Skinner, N. D., and Keim, J. S. (2018). *Strength and Abrasion Testing of Cellular Grout*. U.S Department of the Interior, Bureau of Reclamation, Research & Development Office, Great Plains Regional Office, Billings, MT, 12.

Liu, X., Ni, C., Meng, K., Zhang, L., Liu, D., and Sun, L. (2020). "Strengthening mechanism of lightweight cellular concrete filled with fly ash." *Construction and Building Materials*, 251, 118954.

Liu, X., Ni, C., Zhang, L., Sheng, K., and Hong, B. (2019). "Durability Assessment of Lightweight Cellular Concrete in Subgrade by the Method of Analytic Hierarchy Process Combined with Fuzzy Comprehensive Evaluation." *Mathematical Problems in Engineering*, 2019, 1–10.

Nambiar, E. K. K., and Ramamurthy, K. (2007). "Air-void characterisation of foam concrete." *Cement and Concrete Research*, 37(2), 221–230.

Namsone, E., Šahmenko, G., and Korjakins, A. (2017). "Durability Properties of High Performance Foamed Concrete." *Procedia Engineering*, 172, 760–767.

Narayanan, N., and Ramamurthy, K. (2000). "Structure and properties of aerated concrete: a review." *Cement and Concrete Composites*, 22(5), 321–329.

Pradel, D., and Tiwari, B. (2015). "The use of MSE walls backfilled with Lightweight Cellular Concrete in soft ground seismic areas." *3rd International Conference on Deep Foundations*, Mexican Society for Geotechnical Engineering, Mexico, 8.

Ramamurthy, K., Kunhanandan Nambiar, E. K., and Indu Siva Ranjani, G. (2009). "A classification of studies on properties of foam concrete." *Cement and Concrete Composites*, 31(6), 388–396.

Sandler, I. S., and Rubin, D. (1979). "An algorithm and a modular subroutine for the CAP model." *International Journal for Numerical and Analytical Methods in Geomechanics*, 3(2), 173–186.

Song, Y., and Lange, D. A. (2021). "Measuring dynamic Young's modulus of low-density foam concrete using resonant frequency test." *Journal of Testing and Evaluation*, 50(1).

Sutmoller, N. (2020). "An Introduction to Low-Density Cellular Concrete and Advanced Engineered Foam Technology." *Geo-Congress 2020*, American Society of Civil Engineers, Minneapolis, Minnesota, 630–640.

Taylor, S. (2015). "Cellular Concrete: A Cushion Over A Fault Line - Tunnel Business Magazine.pdf." *Tunnel Business Magazine*.

Taylor, S., and Halsted, G. (2021). *Guide to Lightweight Cellular Concrete for Geotechnical Applications*. National Concrete Pavement Technology Center, Iowa State University, Ames, IA, 62.

Teig, J., and Anderson, J. (2012). "Innovative Design for the Colton Flyover Grade Separation of UPRR and BNSF, Colton, CA." *AREMA 2012 Annual Conference & Exposition*, Chicago, IL.

Tikalsky, P. J., Pospisil, J., and MacDonald, W. (2004). "A method for assessment of the freeze–thaw resistance of preformed foam cellular concrete." *Cement and Concrete Research*, 34(5), 889–893.

Tiwari, B., Ajmera, B., Maw, R., Cole, R., Villegas, D., and Palmerson, P. (2017). "Mechanical Properties of Lightweight Cellular Concrete for Geotechnical Applications." *Journal of Materials in Civil Engineering*, 29(7), 06017007.

Tiwari, B., Ajmera, B., and Villegas, D. (2018). "Dynamic Properties of Lightweight Cellular Concrete for Geotechnical Applications." *Journal of Materials in Civil Engineering*, 30(2), 04017271.

Wu, H., Liu, J., and Zhang, X. (2020). "Feasibility study on use of cellular concrete for air convection embankment on permafrost foundations in Fairbanks, Alaska." *Transportation Geotechnics*, 22, 100317.