An Introduction to Low-Density Cellular Concrete and Advanced Engineered Foam Technology

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ABSTRACT: Low-density cellular concrete (LDCC) was first introduced to the market in the early 1900s and since then has made continuous technological advances. There are two primary types of LDCC: permeable and non-permeable. Both types of cellular concrete offer advantages in different types of geotechnical engineering applications. Because of its unique characteristics of low density, high compressive strength, and high fluidity during placement, LDCC offers an effective solution for a wide variety of engineering applications, and in many cases provides a more cost-effective, labor saving alternative to traditional fill materials. This paper will review the history, characteristics, and technological advances of LDCC, highlighting multiple real-world case studies that showcase the high-performance capabilities of both permeable and non-permeable LDCC.

INTRODUCTION

According to the American Concrete Institute (ACI) 523 Guide for Cast-in-Place Low-Density Cellular Concrete, low-density cellular concrete (LDCC) is defined as "concrete made with hydraulic cement, water, and preformed foam to produce hardened material with an oven dry density of 50 pounds (22.7 kg) per cubic foot or less" (ACI 2007).

First introduced in the early 1900s, the engineered technologies in cellular concrete have advanced exponentially, and they continue to advance to meet new construction challenges. Because of its unique properties, LDCC offers a performance and environmental stability that is unique when compared to alternative products in many geotechnical applications. This paper will explore what LDCC is and the cutting-edge geotechnical solutions it provides to the engineering and construction industries.

HISTORY OF LOW-DENSITY CELLULAR CONCRETE

The technology used in the production of LDCC was first introduced in Sweden in the early 1900s, where it was used in a variety of commercial applications. After the mid-1940s, the technology gained traction throughout Europe and began to spread across the globe. Shortly after this spread, hydrolyzed, proteinbased foam liquid concentrates were introduced into the production of LDCC. The introduction of these concentrates increased the density control of LDCC due to the stability of the air cells in the liquid concentrates.

Then in the early 1990s, synthetic-based foam liquid concentrates were introduced to replace these proteinbased liquid concentrates. This introduction of synthetic-based concentrates was a significant advance in cellular concrete technology. With highly stable air cells, these synthetic-based concentrates significantly enhanced the longevity and stability of LDCC. The next step in this technology occurred in the early 2000s, when manufacturers began creating hybrid foam concentrates—unique mixtures of protein-based concentrates and synthetic-based concentrates. With the introduction of hybrid foam concentrates came the introduction of permeable lowdensity cellular concrete (PLDCC), adding a new type of cellular concrete to the market. The cellular concrete market consists of two types of concrete: permeable cellular concrete and non-permeable cellular concrete. In the following sections of this paper, we will explore the characteristics of both permeable and non-permeable LDCC and their implications for geotechnical applications.

CHARACTERISTICS OF LOW-DENSITY CELLULAR CONCRETE

It is important to note that there are two types of hybrid foam used in LDCC: preformed and agitated. The preformed foam is created by the dilution of a liquid foam concentrate with water in a predetermined ratio. This mixture is then processed through a foam generator, which is then used to create a cellular concrete. Agitated foam, in contrast, is produced by the processing of an engineered liquid concentrate into a concrete mixture, creating a controlled low-strength mixture (CLSM) also known as flowable fill.

While both preformed and agitated foam types conform to ACI industry standards, preformed foam conforms to ACI 523, while agitated foam conforms to the ACI 229 Report on Controlled Low-Strength Materials. Due to its lower density, preformed cellular concrete is a more flexible material than CLSM. CLSM generally has a density of 50 pcf or greater, while LDCC, by definition, features a density of less than 50 pcf. Therefore, according to ACI 229, while cellular concrete is considered a flowable fill material, CLSM by definition cannot be considered a lowdensity cellular concrete material (ACI 2013).

Due to its self-leveling and self-compacting characteristics—as well as its high compressive strength and low density—LDCC presents a viable, long-term solution for a wide range of geotechnical applications.

Compressive Strength and Density

LDCC differs from conventional aggregate concrete in a number of ways, including method of production, material density, compressive strength, and variety of applications.

Because it is produced using a foam generator, LDCC features a comparatively high compressive strength. It contains air cells that replace the coarse aggregate found in a traditional fill material. These air cells withstand the mixing and pumping inherent in the application process and provide the same structural stability as a solid material. When the concrete is cured, the cementitious materials encapsulate the air bubbles and then dissipate, leaving a void structure that replaces traditional aggregate material.

It is important to remember that LDCC replaces traditionally compacted backfill and is not designed to be the wearing surface of a project. Traditionally compacted backfill has a compressive strength of 50 to 80 psi (0.34 to 0.55 MPa) at best. In comparison, a 30 pcf (481 kg/m^3) LDCC will provide an average strength of 140 psi (0.97 MPa) at 28 days, exceeding traditionally compacted backfill (Aerix Industries 2013).

Environmental Stability

The use of LDCC provides many environmental benefits when compared to traditional, alternative materials. First, LDCC enables the addition of ground, granulated blast-furnace slag or fly ash into the design of the cement slurry mixture without adversely affecting the performance of the cellular concrete. The incorporation of these post-industrial byproducts can offer substantial cost savings, reduce the amount of material entering landfills, and eliminate the need for the use of virgin materials in cellular concrete production.

In addition, the use of LDCC significantly reduces jobsite carbon dioxide emissions when compared to compacted lightweight aggregate fill or rigid cellular polystyrene lightweight foam alternatives.

Because it is easy to install, LDCC requires fewer pieces of equipment on the jobsite, which means that it also minimizes the use of fuel. With less equipment, jobsites are more easily navigable and less congested.

In addition, when used in certain underlayment applications, LDCC can reduce the amount of excavation required, eliminate compaction requirements, minimizing jobsite disruption and saving labor time and cost.

MIX DESIGN, BATCHING, AND INSTALLATION REQUIREMENTS FOR LOW-DENSITY CELLULAR CONCRETE

Mix Design Requirements

The quantity of foam that is introduced into the cement slurry determines the density, strength, and thermal conductivity of the LDCC. Therefore, a vital part of the concrete batching and mixing process is the accurate calculation of the mix design, which determines how much foam should be added to the cement slurry. Mix design calculations must be determined before the batching process begins. The required foam volume, along with the foam generator output, is used to calculate the length of time for which foam must be injected into the mixer.

Refer to Table 1 (ACI 2007) below for strength and density properties of typical cellular concrete mix materials. This table illustrates the typical, industrystandard guidelines for cellular concrete mixes. Each of these materials features a high compressive strength with a volume that is, on average, comprised of 70% to 75% foam (30 pcf [481 kg/m^3]).

Table 1. Cellular concrete material strength and density

Oven-Dry Density		Usual Range of Compressive Strength at 28 Days		Modulus of Elasticity	
lb/ft^3	kg/m^3	psi	MPa	10^3 psi	GPa
20 to 25	320 to 400	70 to 125	0.48 to 0.86	30 to 52	0.21 to 0.36
25 to 30	400 to 480	125 to 225	0.86 to 1.55	52 to 89	0.36 to 0.61
30 to 35	480 to 560	225 to 350	1.55 to 2.41	89 to 135	0.61 to 0.93
35 to 40	560 to 640	350 to 450	2.41 to 3.10	135 to 183	0.93 to 1.26
40 to 50	640 to 800	450 to 750	3.10 to 5.17	183 to 320	1.26 to 2.21

Batching Process

There are two methods for mixing LDCC: batching and continuous inline injection. In the batching process, the base cement slurry is prepared in a mixer and then externally produced foam is added to the mixed slurry, at which point the mixture is pumped to the point of placement. Quality control is easily maintained between batches as the proportions of foam, water, cement, and aggregate can be precisely duplicated.

The second type of mixing system is a continuous generating system, which continually draws the foaming agent concentrate from its shipping container and automatically mixes it with water and compressed air in fixed proportions. This type of system is typically used with continuous concrete mixing and placing equipment, or for applications that require large volumes of foam that make jobsite storage ineffective. Continuous generating systems are also more frequently used on jobsites where the LDCC is being placed through a pipe or flexible hose.

Installation Equipment

As mentioned previously, the installation of LDCC requires minimal jobsite equipment. Types of onsite installation equipment typically required include: a high-production, self-contained unit for larger-volume projects; mobile mixing units; and/or a self-contained trailer wet batch system. The equipment needed at the jobsite depends on the batching process being used for the particular project and the volume of LDCC required for the project.

TESTING PROCEDURES FOR LOW-DENSITY CELLULAR CONCRETE

There are multiple American Society for Testing and Materials (ASTM) testing standards that apply to lowdensity cellular concrete. These testing standards must be followed when using LDCC in field applications, and quality control must be measured in the field. The use of ASTM testing standards in the field ensures that the mix design requirements have been met for the LDCC production, and that the LDCC meets the jobspecific performance standards for each project. Performing compressibility testing is one method of jobsite quality control. This paper will briefly review the ASTM standards applicable to LDCC.

ASTM Test Methods

There are three ASTM test methods that apply to cellular concrete: ASTM C869 "Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete"; ASTM C796 "Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete using Preformed Foam"; and ASTM C495 "Standard Test Method for Compressive Strength of Lightweight Insulating Concrete."

All three of these ASTM standards enable quality control with the application of LDCC. ASTM C869 and ASTM C796 both provide measures by which to evaluate the performance of the foaming agent used in the production of the cellular concrete. ASTM C796 and ASTM C495 both measure the compressive strength of lightweight insulating concrete. In addition, ASTM C796 also provides a standard for tensile splitting strength, density, and water absorption.

TYPICAL APPLICATIONS OF LOW-DENSITY CELLULAR CONCRETE

Due to its characteristics of high compressive strength, low density, and environmental stability, LDCC is an ideal material for a wide variety of geotechnical applications. This paper will explore a few applications for which LDCC has proven to be extremely effective.

Tunnel Backfills and Annular Fills

LDCC is an ideal solution for tunnel backfill and annular fill projects, in part because it is a highly flowable material that is able to fill the entirety of the empty space. In addition, because it is lightweight, LDCC can be easily pumped long distances at very low pressures, which means that installation is quick and efficient. Because the compressive strength and density of LDCC is customizable for each project, it can be engineered to meet the project's specific fill requirements, and has a shrinkage rate of less than 0.3%, which means that it will provide long-term performance. Another important feature of LDCC that is specifically relevant for tunnel backfill and annular fill projects is that it is designed to minimize and, in many cases, eliminate damage caused to tunnel lining or slip-lining materials.

There have been a number of projects that have highlighted the effectiveness of LDCC in these types of applications. In Honolulu, HI, the Kaneohe Kailua Tunnel was recently built to transport wastewater between the cities of Kaneohe and Kailua. This 10foot-diameter tunnel would carry wastewater a total of three miles, using gravity to maintain a constant flow. The first step in this project was to drill a 13-footdiameter tunnel and install a 10-foot-diameter pipe. That left a substantial annular space between the pipe and the surrounding soil that needed to be filled and stabilized. 28,000 cubic yards of 50 pcf LDCC was installed using a four-inch injection line. The material was pumped for a total of 2.84 miles, chilling the water, adding a retarder and maintaining 18-to-24-inch controlled lifts due to the jobsite climate.

LDCC has also been used effectively in an Atlanta Gas Light (AGL) gas pipe line abandonment site. In this project, one section of abandoned gas line was filled using LDCC. A 12.5-mile section, 6,500 cubic yards of non-permeable 40-pcf LDCC was installed in 1,000- to 1,500-foot placement points using a 40-pcf LDCC.

In addition to these highlighted projects, LDCC has been used in a multitude of utility tunnel abandonment projects as well as several types of backfill applications.

Subgrade Modifications and Tremie Applications

The use of LDCC is effective in subgrade modification or soft soil remediation applications because of its light weight and high compressive strength. LDCC can decrease the bearing capacity of surrounding soil and reduce the dead loads placed on utilities, creating enhanced seismic stability and reducing the potential for future soil settlement. LDCC is a stronger, more cost- and labor-efficient solution compared to traditional fill materials.

One example of this type of LDCC application was executed at the University of Connecticut, where a football stadium was constructed on top of unstable soils. In this application, LDCC was used to replace the underlying soft soils, equally distributing the load of the stadium to minimize potential soil settlement. A total of 40,000 cubic yards of 35-pcf LDCC was placed at a rate of 150 cubic yards per hour.

Another project that highlights the capabilities of LDCC is a State Route 50 road-widening construction project in Ocoee, FL. State Route 50 was constructed on soft soil in marshy conditions. LDCC was used to lighten the load of the roadway and stabilize surrounding soils to stay within acceptable settlements.

For tremie applications, the application of a higher density concrete mix is required in order to displace water. If a project can be dewatered, it is generally recommended to dewater, place a lower density cellular concrete, and then place the appropriate amount of overburden over the LDCC to counteract any buoyancy concerns.

Bridge Approaches and Retaining Wall Backfills

Due to its high fluidity and low density, LDCC is also a feasible solution for bridge approaches and retaining wall backfill applications. In addition, LDCC reduces and, in some cases, eliminates lateral loads, allows for increased lift heights and enhanced design flexibility, creates engineered permeability, and provides easy placement.

LDCC has also been effectively used in segmental wall configurations and lane expansion projects because of its ability to shorten the strapping configurations. With LDCC, any strappings used are placed to prevent the wall from overturning, not to hold the mass of traditional fill material in place. For example, LDCC was installed in a segmental wall configuration on the Illinois Department of Transportation (IDOT) Lake Shore Drive and I-55 Interchange. In this project, 22,000 cubic yards of LDCC (24–30 pcf) were placed to drastically reduce lateral and vertical loads and enable the construction of three new ramps for lane change requirements. In another IDOT project, the IDOT Circle Interchange, 18,000 cubic yards of LDCC (24–30 pcf) were placed at a circle interchange for the reduction of lateral loads.

Underground Utility Protection

The protection of underground utilities is a construction challenge, and one of vital importance. LDCC provides an ideal alternative to controlled lowstrength material (CLSM) in these types of applications. Figure 1 illustrates a geothermal model of utility protection. This diagram illustrates how LDCC can be used in underground utility protection applications. LDCC has a significant insulation value; greater than any other cementitious backfill material. The insulating values are proportional to the density and the insulating values increase as the density decreases. When a layer of LDCC is placed on top of the underground utilities, it provides insulation and protection when the frost line (as indicated on the illustration) penetrates into the ground. Without this protective layer, the performance of the underground utility could be compromised as it is exposed to frost and colder temperatures. A slab of LDCC over any utilities will reduce the dead loads as well as the lateral loads upon them.

Fill for Underground Tanks, Pipelines, Abandoned Mines, and Conduits

LDCC can also provide an ideal cost-saving alternative to the use of CLSM in various below-grade fill applications around pipelines, tanks, conduits, and

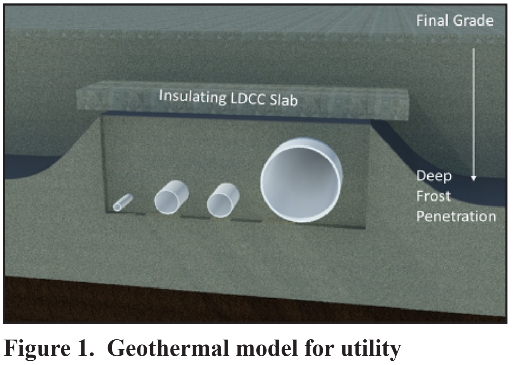

Figure 1. Geothermal model for utility protection

abandoned mines. LDCC was used in a water main abandonment fill application as part of an Illinois Tollways project. The high fluidity, light weight and elevated compressive strength of LDCC made it an ideal choice for this type of application. In this project, a total of 13,000 cubic yards of LDCC (24–30 pcf) was installed into 13,400 linear feet of abandoned water mains along three Illinois tollways.

ADVANCEMENT OF CELLULAR CONCRETE TECHNOLOGY

The engineering and technology behind the production of LDCC is always advancing. One of the most important recent advances in this technology occurred with the introduction of permeable low-density cellular concrete (PLDCC) to the market.

Much of this paper has discussed the characteristics of LDCC in general, but it is important to distinguish the two types of low-density cellular concrete: permeable and non-permeable. The difference between the permeable characteristics of these two types of LDCC relates to the air bubble composition in the concrete. PLDCC contains coalesced (compacted) air molecules that have joined together; nonpermeable LDCC maintains the original, closed cell structure of the air molecules.

Advantages of Permeable Low-Density Cellular Concrete

Due to its unique composition and permeable, open-cell, lightweight characteristics, PLDCC provides many unique advantages for geotechnical engineering applications. For example, PLDCC can be customized for project-specific density, strength, and drainage requirements. In projects where free-draining, lightweight material is required, PLDCC is a highperforming solution. PLDCC is ideal for projects that are located on marginal land with areas of soft soils that are unable to support aggregate loads. With PLDCC, engineers are able to control and customize both load-bearing and drainage capacities.

PLDCC is highly permeable when compared to soil and other traditional fill materials. Table 2 illustrates the permeability of PLDCC compared to other traditional fill materials.

Depending on its density, which ranges from 25 to 35 pcf, PLDCC features a permeability drainage rate of 162 to 1,600 inches per hour. A study completed by the University of Missouri–Kansas City (UMKC 2018), illustrated in Figure 2, shows the direct correlation between the density of LDCC and the rate at which it absorbs water (its level of infiltration).

One of the unique properties of PLDCC is that its permeability does not negatively affect its compressive strength. With some permeable materials, permeability can reduce compressive strength as the material becomes more saturated. That is not the case with PLDCC, which maintains its compressive strength over time and through various levels of saturation, as is evident in Figure 3 (UMKC 2018). The compressive strength of the PLDCC tested in this ASTM 28-day compressive strength study remains constant when the material is dry, partially saturated, and fully saturated. Testing in this study was completed per ASTM C495/C495M-12 Standard Test Method for Compressive Strength of Lightweight Insulating Concrete. The black lines on the chart indicate the average ASTM strength requirement, which is exceeded in every case.

Table 2. Coefficient of permeability

	Coefficient of Permeability k (cm/sec) (log scale)			
	10^{2} 10^{1}	1.0 10^{-1} 10^{-2}	10^{-3} 10^{-4} 10^{-5} 10^{-6}	10^{-7} 10^{-8} 10^{-9}
Drainage	Good		Poor	Practically Impermeable
Backfill Type	Clean gravel	Clean sands, dean, sand and gravel mixture, PLDCC	Very fine, sand, organic and inorganic silts, mixtures of sand silt and clay, glacial till, stratified day, LDCC	"Impermeable" soils, e.g., homogeneous clays below zone of weathering

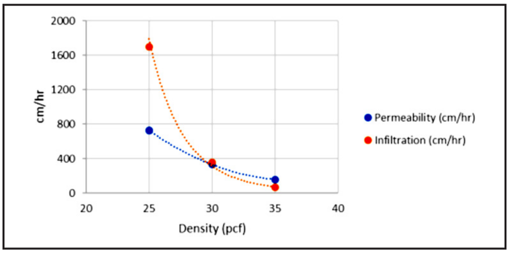

Figure 2. PLDCC permeability and density

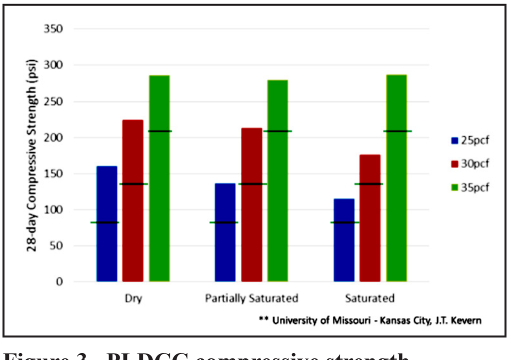

Figure 3. PLDCC compressive strength

The compressive strength and stability of PLDCC has been evidenced in many geotechnical engineering soil stabilization projects.

PLDCC was used for a soft soil remediation project at the Louis Armstrong International Airport in New Orleans, Louisiana. This project included the construction of an airfield lighting vault, which housed all the high-voltage cables, current regulators, and control panels that facilitate the operation of the airfield lighting system.

One of the challenges with this construction was that the lighting vault was to be built on top of soil that consisted of a moldable black clay with an extremely high water table. The fill material used around the vault's pavement needed to facilitate significant stormwater drainage and stabilize the soft soil. To mitigate silt infiltration, a silt fabric was placed before the 28-pcf PLDCC was installed in two lifts of two feet for a total depth of four feet and a total volume of 3,000 cubic yards.

The permeable characteristics of PLDCC contribute to significant reduction in below-grade hydrostatic pressure. Hydrostatic pressure decreases relative to the infiltration rate, which decreases relative to the permeability of the below-grade fill product.

The hydrostatic pressure reduction capabilities of PLDCC have been proven in its application as a sinkhole remediation fill material. Sinkholes are often caused by changes in hydrostatic pressure—when moisture is suddenly removed from soil. PLDCC, with a statistically high permeability and infiltration rate, reduces hydrostatic pressure and stabilizes soil, preventing the formation of sinkholes. These characteristics were illustrated in a recent project completed by the Pennsylvania Department of Transportation on Route 30 in Chester County. This sinkhole was remediated with the use of 1,200 cubic yards of PLDCC pumped through a three-inch hose and installed using four-foot lifts underneath the roadway and adjacent median.

Typical Applications of Permeable LowDensity Cellular Concrete

Because of its characteristic of high permeability, PLDCC is effective for a variety of applications. Typical applications for PLDCC include sports field sub-base fills; bridge approach fills; retaining wall backfills; foundation fills; permeable pavement sub-base fills; pipeline bedding fills; pool deck sub-base fills; and pervious concrete and paver sub-base fills.

One of the more prevalent applications of PLDCC is sub-base fill applications underneath sports fields. PLDCC was used in this capacity at the New York Mets Citi Field ballpark. The use of PLDCC allowed for proper drainage and stabilization of subbase soft soils to maintain acceptable settlement issues and saved the owners over a half-million dollars.

Another ideal application for PLDCC is at bridge approaches. PLDCC is an ideal choice for these types of applications because of its permeability and ability to allow water infiltration and prevent buoyancy concerns. At the Rose Coulee Bridge in Fargo, North Dakota, the use of PLDCC in the bridge approach allowed increased drainage of flood waters, which alleviated pooling water and potential bridge deterioration. In this bridge approach, 2,600 cubic yards of 25-pcf PLDCC with a permeability of 1x102 cm/second was installed.

Finally, PLDCC can also be used in permeable green roof applications, installed above the waterproofing membrane and below the silt fabric, to enable customized elevations in the green roof that allow for proper drainage. The use of PLDCC in green roof applications provides the opportunity to create elevation changes and can significantly reduce labor costs and shorten construction schedules.

SUMMARY AND CONCLUSIONS

Since its introduction in the early 1900s, the technology behind the production of permeable lowdensity cellular concrete has advanced significantly. With the technological advance of engineered foam production, low-density cellular concrete provides a viable, higher-performing alternative to the use of controlled low-strength materials in many applications. Both permeable and non-permeable lowdensity cellular concrete offer a unique combination of high compressive strength, low density, and environmental stability, which make them ideal solutions for a wide variety of geotechnical applications.

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