GUIDE TO

Lightweight Cellular Concrete for Geotechnical Applications

PCA Since 1916
America's Cement Manufacturers™

National Concrete Pavement Technology Center
Tech Center

Iowa State University
Institute for Transportation

JANUARY 2021

About the CP Tech Center

The mission of the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.

About the PCA

The Portland Cement Association (PCA) is a nonprofit organization founded in 1916 that serves America's cement manufacturers through policy, research, education, and market intelligence. PCA members represent 91 percent of US cement production capacity with facilities in all 50 states. PCA promotes safety, sustainability, and innovation in all aspects of construction, fosters continuous improvement in cement manufacturing and distribution, and generally promotes economic growth and sound infrastructure investment.

Disclaimers

Neither Iowa State University nor the Portland Cement Association nor this document's authors, editors, designers, illustrators, distributors, or technical advisors make any representations or warranties, expressed or implied, as to the accuracy of information herein and disclaim liability for any inaccuracies.

This publication is provided solely for the continuing education of qualified professionals. This publication should only be used by qualified professionals who possess all required licenses, who are competent to evaluate the significance and limitations of the information provided herein, and who accept total responsibility for the application of this information.

Iowa State University does not discriminate on the basis of race, color, age, ethnicity, religion, national origin, pregnancy, sexual orientation, gender identity, genetic information, sex, marital status, disability, or status as a US Veteran. Inquiries regarding nondiscrimination policies may be directed to the Office of Equal Opportunity, 3410 Beardshear Hall, 515 Morrill Road, Ames, Iowa 50011, telephone: 515-294-7612, hotline: 515-294-1222, email: eooffice@iastate.edu.

About this Guide

This document, *Guide to Lightweight Cellular Concrete for Geotechnical Applications*, provides information on the materials, properties, design, proper handling, and applications of lightweight cellular concrete (LCC) for geotechnical applications.

While this document may not address all of a project's specific details, it provides information for construction professionals and design engineers on the use of LCC in geotechnical applications, including common uses, conceptual guidance, and design guidelines. The applications presented in this guide have exhibited good long-term performance, providing cost-effective solutions and better and safer designs for projects across North America.

This document includes, as an appendix at the end of it, a guide specification covering materials, equipment, construction inspection, and testing requirements for constructing LCC fills.

Reference Information for this Guide

Taylor, S. and G. Halsted. 2021. *Guide to Lightweight Cellular Concrete for Geotechnical Applications*. Portland Cement Association, Washington, DC, and National Concrete Pavement Technology Center at Iowa State University, Ames, IA.

© 2021 Portland Cement Association

Front Cover Image Credits

Top: Throop Lightweight Fill, used with permission

Center: Cell-Crete Corporation, used with permission

Bottom: Portland Cement Association

For More Information

For technical assistance regarding cement-based concrete paving, contact the Portland Cement Association or the CP Tech Center:

Greg Halsted, Manager
Pavements and Geotechnical Markets
Portland Cement Association
200 Massachusetts Avenue NW, Suite 200
Washington, DC 20001
847-972-9058
info@cement.org
https://www.cement.org/

Peter Taylor, Director
National Concrete Pavement Technology Center
Iowa State University
2711 S. Loop Drive, Suite 4700
Ames, IA 50010-8664
515-294-5798
cptech@iastate.edu
https://cptechcenter.org

Technical Report Documentation Page

1. Report No. PCA Special Report SR1008P	**2. Government Accession No.**	**3. Recipient's Catalog No.**	
4. Title and Subtitle Guide to Lightweight Cellular Concrete for Geotechnical Applications		**5. Report Date** January 2021	
		6. Performing Organization Code	
7. Author(s) Scott Taylor and Greg Halsted		**8. Performing Organization Report No.**	
9. Performing Organization Name and Address National Concrete Pavement Technology Center Iowa State University 2711 South Loop Drive, Suite 4700 Ames, IA 50010-8664		**10. Work Unit No.**	
		11. Contract or Grant No.	
12. Sponsoring Organization Name and Address Portland Cement Association 200 Massachusetts Avenue NW, Suite 200 Washington, DC 20001		**13. Type of Report and Period Covered** Guide	
		14. Sponsoring Agency Code	
15. Supplementary Notes Visit https://cptechcenter.org for color pdfs of this and other publications.			

16. Abstract

The primary purpose of this guide is to provide information on the materials, properties, design, proper handling, and applications of lightweight cellular concrete (LCC) for geotechnical applications.

LCC is a mixture of portland cement and water slurry, combined with preformed foam to create air voids, that can act as a strong, lightweight, durable, and inexpensive alternative to soil or fill replacement for many geotechnical applications. LCC's lightweight property reduces ground settlement and improves the bearing capacity and the static and seismic stability of embankments. Given that an LCC mix is highly flowable, it can be efficiently and safely placed in confined or problematic spaces such as in pipes, trenches, tunnels, wall backfills, and other areas where the routine placement of earthen fill is difficult, if not impossible. These attributes make LCC a low-cost solution for many geotechnical applications.

While this document may not address all of a project's specific details, it provides information for construction professionals and design engineers on the use of LCC in geotechnical applications, including common uses, conceptual guidance, and design guidelines. The applications presented in this guide have exhibited good long-term performance, providing cost-effective solutions and better and safer designs for projects across North America.

Among other topics, this guide provides examples of both mix design preparation and field installation, geotechnical evaluation, and the design, construction, and field testing of LCC. Throughout, this guide addresses the importance of geotechnical oversight at the beginning of a project, during the mix design stage, and during construction to ensure that the project meets its intended purpose.

17. Key Words geotechnical solutions—LCC design guidelines—LCC geotechnical examples—LCC geotechnical guidance—lightweight cellular concrete		**18. Distribution Statement** No restrictions.	
19. Security Classification (of this report) Unclassified.	**20. Security Classification (of this page)** Unclassified.	**21. No. of Pages** 58	**22. Price** NA

Guide to Lightweight Cellular Concrete for Geotechnical Applications

January 2021

Authors

Scott M. Taylor, P.E.

Greg E. Halsted, P.E., Portland Cement Association

Managing Editor

Oksana Gieseman

Graphic Design, Layout, and Production

Alicia Hoermann

Copyeditors

Sue Stokke and Peter Hunsinger

Sponsored by

© 2021 Portland Cement Association

A guide from

National Concrete Pavement Technology Center

Iowa State University

2711 South Loop Drive, Suite 4700

Ames, IA 50010-8664

Phone: 515-294-5798 / Fax: 515-294-0467

https://cptechcenter.org

Contents

Acknowledgments viii
Executive Summary 1
Chapter 1. Introduction 3
Background of Lightweight Cellular Concrete 3
Definition of LCC 3
Scope of This Guide 3
Benefits 3
Applications 4
Lightweight Road Subbases and Fills 4
Bridge Approach Embankments 5
Void and Cavity Filling 6
Abandoned Pipe and Culvert Filling 6
Annular Space Grout Filling 7
Foundation Fills 8
Energy Arresting Systems 8
Retaining Walls and Precast Wall Panels 8
Lightweight Dam and Levee Structural Fills 9
Landslide Repair and Slope Stabilization 9
Controlled Density Fill 10
Chapter 2. Physical Properties 11
Fresh Properties 11
Cast Density 11
In-Place Density 11
Oven-Dry Density 11
Viscosity 12
Lateral Fluid Pressure 12
Set Time 12
Hardened Properties 13
Hardened Description 13
Strength 13
Cohesion and Friction Angle 14
Modulus of Elasticity 15
Air Content 15
Drying Shrinkage 15
Permeability/Sorption 16
Heat of Hydration 16
Thermal Conductivity 18
Resistance to Aggressive Environments 19
Chapter 3. Geotechnical Design Considerations 20
Settlement Reduction/Weight Reduction 20
Net Load Design Method for Settlement Reduction 20
Bearing Capacity 22
Punching Shear 23
Buoyancy 24
Pavement Bases and Subbases 26
Retaining Wall Backfill Soil Pressures 26
Drainage 26
Chapter 4. Mixture Design 27
Ingredients 27
Portland Cement 27
Water 27
Air 28
Foaming Agents 28
Water/Cement Ratio 28
Mix Design Example (Trial and Error Procedure) 28
Laboratory Sample Preparation 30
Chapter 5. Construction 32
Specifications 32
Property Requirements 32
Subgrade and Subbase Preparation 32
Field Observations 33
Reinforcement 33
Transportation 33
Placement and Consolidation 34
Finishing 34
Surface Finishes 34
Curing and Protection 35
Weather Conditions 35
Timing 35
Field Equipment 35
Batch Mixing 36
High-Shear Batching 36
Auger Mixing/Mobile Volumetric Mixers 36
Cement Delivery 37
Ready-Mixed Concrete Plants 37

Pumping Devices....37
Progressive Cavity Pump....38
Peristaltic Pump....38
Piston Pump....38
Chapter 6. Inspection, Testing, and Maintenance....39
Field Quality Control Testing....39
Field Quality Control Observation....40
Post-construction Inspection and Testing....40
Compressive Strength Testing....41
Maintenance....41
References....43
Appendix. Guide Specification for Construction of Lightweight Cellular Concrete Fill....45

Figures

Figure 1.1. Pavement structure comparison..... 4
Figure 1.2. Lightweight road subbases and fills (Ohio)....5
Figure 1.3. Bridge approach embankments (Indiana).....5
Figure 1.4. Void and cavity filling (Alberta)..... 6
Figure 1.5. Pipe and culvert abandonment filling (Michigan).....6
Figure 1.6. Annular space grout filling (Maine).....7
Figure 1.7. Ungrouted and grouted annular spaces.....7
Figure 1.8. Foundation fills (Florida).....8
Figure 1.9. Energy arresting systems (West Virginia).....8
Figure 1.10. Placing LCC backfill behind precast wall panels (California).....9
Figure 1.11. Lightweight dam and levee structural fills (California).....9
Figure 1.12. Landslide repair and slope stabilization (California).....9
Figure 1.13. Controlled density fill.....10
Figure 2.1. Vesicles/air voids.....13
Figure 3.1. Net load design method for settlement reduction.....21
Figure 3.2. Bearing capacity and spread of compressive forces in LCC.....23
Figure 3.3. Punching shear resistance in LCC layer.....24
Figure 3.4. Buoyancy considerations in an LCC layer....25
Figure 4.1. Preformed foam generator..... 31
Figure 5.1. Prepared subgrade awaiting LCC placement..32
Figure 5.2. Welded wire mesh in an LCC placement....33
Figure 5.3. How foam is introduced into a ready-mixed concrete truck-based pumping system..... 34
Figure 5.4. Surface of in-place LCC fill..... 35
Figure 5.5. Batch mixer.....36
Figure 5.6. Mobile volumetric mixer..... 36
Figure 5.7. Inline foam additive system..... 37
Figure 5.8. Ready-mixed concrete truck..... 37
Figure 5.9. Progressive cavity pump..... 38
Figure 6.1. Sampling/testing LCC in the field (Michigan).....39
Figure 6.2. Surface of recently placed LCC.....40
Figure 6.3. Unconfined compressive strength testing of LCC.....41

Tables

Table 2.1. Physical properties of LCC.....13
Table 2.2. Friction angles and cohesion values for LCC....14
Table 2.3. Modulus of elasticity relationships of LCC....15
Table 2.4. Summary of cellular concrete hydraulic conductivity testing..... 16
Table 2.5. Calculated heat capacity and thermal conductivity of foamed concrete mixes, 300 kg/m^3 portland cement content, silica sand fine aggregate.....17
Table 2.6. Thermal properties of LCC at different densities.....18
Table 4.1. Portland cement types.....27
Table 4.2. Blended hydraulic cement types..... 27
Table 4.3. Hydraulic cement performance attributes....27

Acknowledgments

The authors, the National Concrete Pavement Technology (CP Tech) Center, and the Portland Cement Association gratefully acknowledge the contributions of the technical contributors and the technical advisory committee (TAC) members, who helped establish the technical direction for the guide and reviewed several drafts. Their feedback and suggestions were invaluable.

- Wayne Adaska, Portland Cement Association (formerly) *
- Steven Bartlett, University of Utah *
- Steve Bent, CEMATRIX
- Jacques Bloomfield, The Reinforced Earth Company *
- Tyler Bodnar, California Nevada Cement Association
- Tony Borglum, Richway Industries, Ltd.
- Jesse Downs, Strong Manufacturing
- Milton Gomez, Aerix Industries *
- Ray Henn, RW Henn LLC *
- Craig Hrkal, Cellular Concrete Inc. *
- Jon (Ike) Isaacson, Brierley Associates Corporation
- James Krstulovich, Illinois Department of Transportation
- Tarja Kyllönen, Runway Safe Group
- Roberto Montemayor, University of Illinois at Urbana-Champaign
- Gordon Smith, National CP Tech Center *
- Nico Sutmoller, Aerix Industries
- Binod Tiwari, California State University, Fullerton *
- Trevor Towery, Elastizell Corporation of America *
- Diego Villegas, Cell-Crete Corporation
- Jeff Wykoff, California Nevada Cement Association (formerly) *

* TAC members

Executive Summary

The primary purpose of this guide is to provide information for construction professionals and design engineers on the materials, properties, design, proper handling, and applications of lightweight cellular concrete (LCC) for geotechnical applications, including common uses, conceptual guidance, and design guidelines. This guide does not cover the properties or uses of LCC for roof deck systems, autoclaved aerated cellular concrete for creating lightweight precast items, or lightweight structural concrete for reducing the dead loads to concrete elements. This guide also does not discuss the use of permeable low-density cellular concrete or cellular concrete having an oven-dry density greater than 50 lb/ft³ (800 kg/m³).

Initially used as a construction product for flooring systems in both Europe and the United States during the first part of the 20th century, LCC was eventually granted a patent in 1934. Since then, the commercial use of LCC has grown into the industry it is today, with many types of applications in a variety of fields.

LCC is a mixture of portland cement and water slurry, combined with preformed foam to create air voids, that can act as a strong, lightweight, durable, and inexpensive alternative to soil or fill replacement for many geotechnical applications. Its lightweight property reduces ground settlement and improves the bearing capacity and the static and seismic stability of embankments.

Given that an LCC mix is highly flowable, it can be efficiently and safely placed in confined or problematic spaces such as in pipes, trenches, tunnels, wall backfills, and other confined areas where the routine placement of earthen fill is difficult, if not impossible. These attributes make LCC a low-cost solution for many geotechnical applications.

While this document may not address all of a project's specific details, this guide provides examples of both mix design preparation and field installation, geotechnical evaluation, and the design, construction, and field testing of LCC, among other topics. Throughout, this guide addresses the importance of geotechnical oversight at the beginning of a project, during the mix design stage, and during construction to ensure that the project meets its intended purpose.

The six chapters in this guide cover the following information:

- **Chapter 1. Introduction**
  Chapter 1 covers the scope of the guide, provides a definition of and background for LCC, describes the benefits of using LCC for geotechnical applications, and lists many of those applications.
- **Chapter 2. Physical Properties**
  Chapter 2 covers both the fresh and hardened properties of LCC and the importance of these properties in geotechnical applications.
- **Chapter 3. Geotechnical Design Considerations**
  Chapter 3 covers the important engineering design principles required for consideration of LCC on geotechnical projects.
- **Chapter 4. Mixture Design**
  Chapter 4 covers the ingredients of LCC and the process used to determine the proper cement, water, and air content for LCC and includes information on laboratory sample preparation.
- **Chapter 5. Construction**
  Chapter 5 discusses the requirements and process for constructing an LCC fill, the equipment and procedures required, and field observations to ensure quality.
- **Chapter 6. Inspection, Testing, and Maintenance**
  Chapter 6 provides information on field quality control testing and observation, post-construction inspection and testing, and maintenance.

The following appendix is included at the end of this guide:

- **Appendix. Guide Specification for Construction of Lightweight Cellular Concrete Fill**
  The appendix provides a guide specification covering materials, equipment, construction inspection, and testing requirements for constructing LCC fills.

Chapter 1. Introduction

Background of Lightweight Cellular Concrete

Initially used as a construction product for flooring systems in both Europe and the United States during the first part of the 20th century, lightweight cellular concrete (LCC) was eventually granted a patent in 1934 (Bayer v. Rice 1934). Since then, the commercial use of LCC has grown into the industry it is today, with many types of applications in a variety of fields.

Definition of LCC

LCC is a mixture of portland cement and water slurry, combined with preformed foam to create air voids, that can act as a strong, lightweight, durable, and inexpensive alternative to soil or fill replacement for geotechnical applications. The American Concrete Institute (ACI) Committee 523, which provides information on materials, fabrication, properties, design, and handling of the product, defines this material in its *Guide for Cast-in-Place Low-Density Cellular Concrete* as follows:

> Concrete made with hydraulic cement, water, and preformed foam to form a hardened material having an oven-dry density of 50 lb/ft³ (800 kg/m³) or less. These mixtures may include aggregate and other material components including, but not limited to, fly ash and chemical admixtures. (ACI 2006)

The key is obtaining a homogenous and stable air void or cell structure. The cellular structure is attained essentially by the inclusion of macroscopic voids (air bubbles) resulting from the mechanical incorporation of air or other gases.

In addition to LCC, many other terms are often used to describe this material, including low-density cellular concrete (LDCC), foam concrete, and controlled low-strength material (CLSM) (ACI 2006). To avoid confusion and be consistent, the term used throughout this document, unless specifically noted otherwise, is LCC, as it is the best descriptor for the product, is not brand specific, and clearly and appropriately identifies the material.

Scope of This Guide

This guide provides information for construction professionals and design engineers on the materials, properties, design, proper handling, and applications of LCC for geotechnical applications, including common uses, conceptual guidance, and design guidelines. This guide does not cover the properties or uses of LCC for roof deck systems, autoclaved aerated cellular concrete for creating lightweight precast items, or lightweight structural concrete for reducing the dead loads to concrete elements. This guide also does not discuss the use of permeable low-density cellular concrete or cellular concrete having an oven-dry density greater than 50 lb/ft³ (800 kg/m³).

Benefits

The four primary benefits of LCC for geotechnical applications are as follows:

- Significantly lighter in weight than soil
- Highly flowable and able to fill spaces of any size or shape
- Often less expensive than many alternative systems
- Can accelerate construction schedules

The lightweight property of LCC reduces ground settlement and improves the bearing capacity and the static and seismic stability of embankments when used as a lightweight fill placed on top of soft, compressible soils. Also, given that an LCC mix is highly flowable (even over long distances), it can be efficiently and safely placed in confined or problematic spaces such as in pipes, trenches, tunnels, wall backfills, and other areas where the routine placement of compacted earthen fill is difficult, if not impossible. These attributes make LCC a low-cost solution for many geotechnical applications.

The rapid placement and reasonably fast setting time of LCC expedite construction operations. Many other attributes of LCC provide additional advantages for specific challenges, including the following:

- Aggregate conservation
- Insulation
- Freeze-thaw resistance
- Self-leveling and consolidating
- Energy dissipation and damping
- Density, strength, and permeability control
- Ability to be excavated
- Inert/nonflammable
- Local availability
- Ease of pumping
- Dynamic properties
- Reduced transportation costs and emissions
- Increased worker safety

This guide discusses the segments of the geotechnical marketplace where LCC has been successfully used and reviews the above properties, functions/advantages, and benefits. The LCC applications presented in this guide have exhibited excellent long-term performance, providing cost-effective solutions and better and safer designs for projects across North America.

Applications

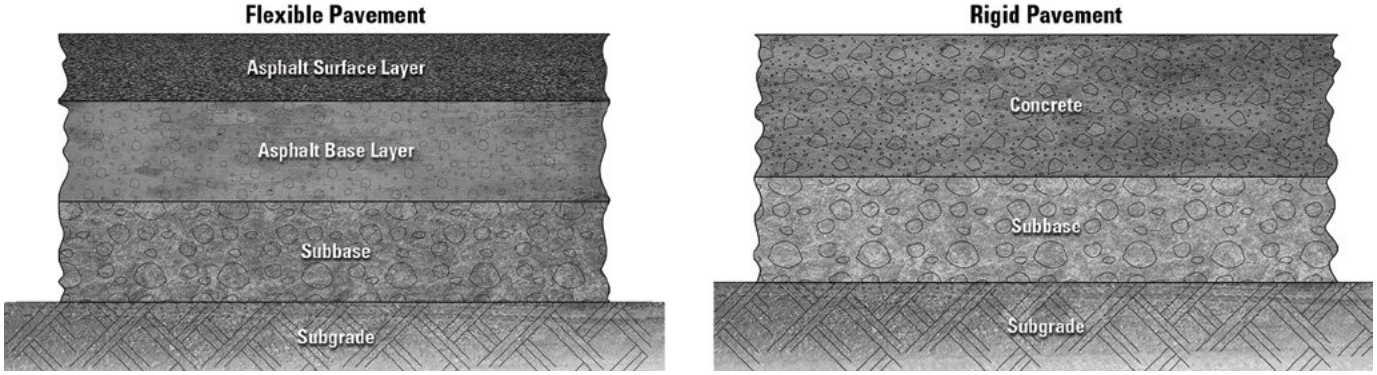
Lightweight Road Subbases and Fills

Most modern roadways consist of a structural pavement section comprised of a concrete or asphalt riding/wearing course at the surface, placed over base and/or subbase layers (typically crushed stone or stabilized materials), and underlaid by a compacted earthen subgrade (see Figure 1.1).

These pavement systems have proven to work successfully in stable soil and foundation conditions, providing a pavement that is durable and long-lasting. However, when the soil and site conditions are less than optimal, placing a layer of strong, lightweight LCC can strengthen and overcome many of the challenges posed by poor subgrade materials (soft or expansive clays, collapsible or reactive soils, etc.). The primary design consideration for use of LCC in these situations is weight compensation.

The displacement of soft compressible soil is generally due to excessive loads applied to these soils. LCC can be utilized as a full or partial replacement for the subbase layer in these applications to produce a zero or low net load increase to the foundation soil.

Geotechnical engineers perform pavement thickness, weight reduction, and embankment stability calculations, obtained primarily from laboratory testing, using representative material properties and unit weights for the respective materials and soils. These calculations must also account for possible roadway elevation and groundwater changes from seasonal cycles or construction dewatering in addressing construction and long-term loading configurations. In this document, this determination of load balancing of the pavement/embankment system is referred to as the net load design method and is further described in Chapter 3. This method is used to ensure the short- and long-term stability and settlement performance of the roadway system.



National CP Tech Center

Figure 1.1. Pavement structure comparison

© 2002 Elastizell Corporation of America, used with permission

Figure 1.2. Lightweight road subbases and fills (Ohio)

The benefits of this geotechnical structural solution for an actively settling roadway begin with its expected long-term performance with little or no settlement. By installing an inert, engineered, lightweight cementitious layer or embankment of material with an unconfined compressive strength that is up to 5 to 10 times stronger than a typically compacted soil or granular material, the subbase is both strengthened and reduced in weight. In addition, this practical solution produces a relatively strong, self-consolidating roadway subbase material that increases the pavement life and greatly diminishes the potential for significant settlement (see Figure 1.2).

Another benefit of installing LCC as opposed to other alternatives is that it typically takes less time and equipment to install, which can result in significant cost and time savings, especially when compared to a solution requiring massive surcharge loadings of embankment foundations, which can take many months. Because LCC is a highly flowable material that is also self-consolidating and self-leveling, it eliminates the need to compact and level the subgrade before it is placed. These properties reduce the need for extra equipment and labor at a jobsite.

Lastly, this application of LCC is also environmentally friendly, in that the imported LCC fills provide 130 yd^3 (100 m^3) per delivered load of dry cement while soil and granular fills provide only 10 to 15 yd^3 (8 to 11 m^3) per load. The reduced trucking significantly reduces CO_2 emissions and traffic congestion, pavement wear, and noise. It also reduces the use of scarce natural resources.

Bridge Approach Embankments

Bridge approaches are elevated pavement sections coming up to the edge of a bridge abutment. The corresponding LCC approach embankments are designed using the net load design method, often using strict design criteria and performance requirements. The challenge is that the typical height of the approach embankment slopes upward as it nears the bridge, causing the likelihood of settlement to increase and warranting a higher factor of safety (FOS) and greater designed LCC thickness to resolve the settlement potential. If not addressed during the design and construction phases, long-term differential consolidation settlement of the foundation soils can occur, often creating a bump at the bridge, which is typically found between the abutment and the approach slab. This settlement can lead to potential safety hazards and cause comfort issues for drivers, as well as lead to an increasing rate of structural deterioration and long-term maintenance costs for the roadway.

Estimates show that bridge approach slab problems affect about 25% of the bridges in the US (Briaud et al. 1997). A more recent report (2017) from the Federal Highway Administration (FHWA) states that about 9% of the over 600,000 bridges in the US are structurally deficient. Undoubtedly, many of these bridges are affected by approach settlement, or the bump. Fortunately, when soft and compressible ground conditions are encountered, the weight reduction function of LCC can resolve the soil issues, eliminating the bump at the bridge without the need for more costly soil remediation methods.

Just like road subbases and fills, another benefit of installing LCC for bridge approach embankments is that installation typically takes less time and equipment than alternative solutions, which can result in significant cost and time savings.

Other design and construction considerations when selecting LCC are the width of the embankment and whether side slopes for vegetation or retaining walls are used. Sloping LCC embankments are typically constructed with a stepped surface below the finished grade (see Figure 1.3) and capped with about 2 ft (0.6 m) of soil placed over the top to create a vegetative landscape surface.

© 1993 Elastizell Corporation of America, used with permission

Figure 1.3. Bridge approach embankments (Indiana)

When designing retaining walls or abutments with LCC backfill, the lateral loads on the structures are reduced, allowing for the use of less costly systems. This load reduction can often lead to significant cost savings on the walls, foundations, and internal reinforcement.

The use of LCC as an embankment fill has been proven successful in many situations. Typical projects include large freight rail grade separation structures constructed using large volumes of LCC paired with precast concrete panel systems. On these types of projects, LCC is used as the "lightweight soil" replacement in the structural and geotechnical designs.

Void and Cavity Filling

One of the most common reasons for using LCC is its highly flowable property. The air bubbles added to the cement paste act like tiny ball bearings within a void or cavity, allowing the material to flow rapidly into all available spaces. Once all water has been removed from the voids prior to starting, the highly flowable nature of LCC allows for easy pumping and long-distance transportation in hoses, which results in easy installation in difficult locations (see Figure 1.4).

Abandoned Pipe and Culvert Filling

Frequently, utility companies, public agencies, and private owners require upgrades to their network of underground pipes. While many pipes are left in place after their service lives, requirements by many local agencies state that these pipes cannot be left empty due to safety and/or settlement concerns. The solutions are to either pay for the pipe to be removed or to fill the decommissioned pipe. If filling the pipe is the option selected, LCC can be produced onsite and pumped directly into the abandoned pipe through installer-provided bulkheads and inlets (see Figure 1.5).

These bulkheads serve to block the highly flowable LCC material from going the wrong direction and can be made of many products that provide a watertight seal. Once all water has been removed from the voids, a 2, 3, or 4 in. (50, 75, or 100 mm) injection pipe is placed through these bulkheads, through which the LCC is pumped. The LCC then fills the pipe from one end to the other, expelling all the air through the vent pipe(s) located at the high points.

CEMATRIX, used with permission

Figure 1.4. Void and cavity filling (Alberta)

© 2017 Elastizell Corporation of America, used with permission

Figure 1.5. Pipe and culvert abandonment filling (Michigan)

While many different materials, including sand, CLSM, and polyurethane foam, can be used to fill abandoned pipes, the ability to install the material efficiently is critical. With LCC, most pipes can be pumped from one end to the other in a single operation. The ability for LCC to fill a pipe should be evaluated not only based on length or absolute volume but also based on the time it takes to fill the cavity. A basic approach is that a pipe should not be pumped into for longer than four hours due to cement hydration (cure) time, unless a set retarding admixture is used.

For instance, with nonrestrictive conditions, a target application rate for a typical LCC installer to achieve is about 100 yd^3 (75 m^3) per hour. At this rate, the pipe to be filled should not exceed 400 yd^3 (300 m^3). Equipment sizes and production rates can vary greatly, so this quantity is not necessarily a requirement or restriction. Ambient temperatures have an effect, and admixtures and mix designs may be adjusted to accommodate pumping times longer than four hours.

Once the required material properties of the fill are determined (typically equivalent to or better than the adjacent soil is sufficient), it is a simple decision between the various types of flowable products. A typical product that is often specified is a flowable fill material or CLSM, which is a one- or two-sack (94 or 188 lb [43 or 85 kg]) cement and sand and/or fly ash mixture creating a low-strength concrete product with unconfined compressive strengths between 50 and 150 lb/in² (0.34 and 1.03 MPa). However, these mixes can be extremely difficult to pump. Pumping distances over 200 ft (60 m) often require additional excavations to allow for dividing the pipe into small enough fill segments. In many instances, the cost of these additional excavations, backfill, and patch paving is higher than the cost of doing the work in one continuous operation using LCC. Another issue with a standard flowable fill or CLSM is that the compressive strength is not as consistent as it is with LCC. Likewise, flowable fill and CLSM often continue to gain strength over time, resulting in a material that is very difficult to remove should future excavation be necessary.

Annular Space Grout Filling

Annular space is the area between an object and another object that is inserted into that object, such as a pipe or culvert (see Figure 1.6).

Aerix Industries, used with permission

Figure 1.6. Annular space grout filling (Maine)

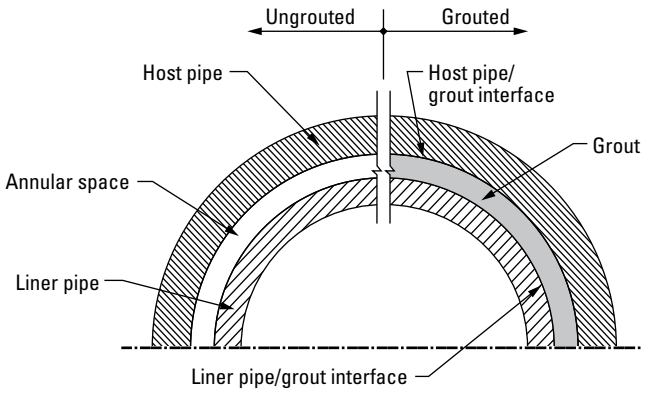
Annular space tunnel grout is a standard LCC installation and is a subset of the pipe fills previously described. The same benefits apply, but the distances are often much longer. The purpose of an annular space tunnel grout is to fill the open space outside a new pipe that is installed in a new tunnel or channel. These are typically medium- to large-diameter pipes.

A special excavation method is used to create a tunnel with its supporting systems. This method is fine for holding the void open but not for containing pressurized fluids. Specified pipes are installed in the opening to transmit the final product (sewage, water, gas, etc.). This installation leaves a void between the pipe and tunnel casing that needs to be filled (see Figure 1.7).

Water should be removed from annular spaces before grouting. Venting at the high point(s) is required for complete grouting and removal of air pockets.

The highly fluid nature of LCC is extremely helpful in tunnel grouting due to the long distances often involved. Tunnels can be grouted in several common ways according to the lengths and volumes required, as follows:

- Install similarly to an abandoned pipe filling from bulkhead to bulkhead (least expensive method)
- Transport the grout from outside the pipe through pre-installed grout tubes to the section to be grouted
- Transport the grout in hoses from inside the pipe and then inject the grout into the void through the pipe by grout ports (most expensive method)



Note: Blocking not shown for clarity

Brierly Associates Corporation, used with permission

Figure 1.7. Ungrouted and grouted annular spaces

With all three of these procedures, the LCC installer should be heavily involved in determining the best method based on experience, equipment, and personnel to ensure a complete fill with properly specified materials.

Storage tank and mine fills are very similar to pipe and annular space fillings but with the potential for much larger volumes of LCC.

Foundation Fills

Sometimes a foundation has unacceptable settlement issues or voids that require filling (see Figure 1.8).

The concepts of void filling and the net load design method are utilized for foundation fills as well, depending on the intent of use. Here are some examples of types of foundation fills:

- Perimeter Fill/Backfilling—New structures are often installed closely adjacent to a shored hole in the ground. When the building is complete, the gap between the building and the shoring needs to be filled. LCC, with its large volume capability and flowable nature, fills this void quickly and inexpensively.
- Settlement Reduction/Mat Foundation—The entire foundation area is excavated based on the net load design method and replaced with LCC. The foundation is then installed on top of the LCC surface.
- Difficult to Access Location—In foundation repair work, fill is sometimes needed in a basement that is difficult to access. With the long-distance pumping abilities of LCC, a hose can be run from the LCC production site to the dispensing location with little difficulty.
- Insulation Fill—A layer of LCC is placed below a foundation to increase the insulation value between the earth and the structure.

Sea level rise and elevation raise fills are similar to foundation backfills but may be entirely above grade. Elevated LCC seawalls and bulkheads are a type of coastal armoring that can protect shorelines from strong wave action. These types of fills can protect existing development from rising water due to storm surge and baseline sea level rise. This geotechnical application involves formwork and buoyancy considerations. As mentioned, LCC can be an effective material in simplifying foundation designs for numerous applications.

Energy Arresting Systems

In this application, LCC blocks or panels are used as a kinetic energy dissipating system. While essentially forming a runaway truck ramp for airplanes (see Figure 1.9), this system is a bed of engineered LCC built at the end of a runway to reduce the severity of the consequences of a plane leaving the end of the paved runway that has been adopted by the Federal Aviation Administration (FAA) for use in airports around the country (FAA 2012).

© 1988 Elastizell Corporation of America, used with permission

Figure 1.8. Foundation fills (Florida)

Runway Safe Group, used with permission

Figure 1.9. Energy arresting systems (West Virginia)

Many years of design, testing, and approvals are required before the manufacturing of these precast elements.

Retaining Walls and Precast Wall Panels

When used as a lightweight backfill in place of granular soil, LCC is ideally suited for retaining wall applications where lightweight vertical embankments are required. When used in conjunction with precast wall panels, these systems are designed based on the geotechnical properties of the soil being retained. When LCC is substituted for soil backfill, current practice is to conservatively design the walls as if the LCC was a granular material using its specific unit weight and internal friction angle. Cohesive strength in the LCC is conservatively ignored in soil retaining wall designs; however, the appreciable cohesion in LCC is permanent and provides an additional FOS in such designs.

Throop Lightweight Fill, used with permission

Figure 1.10. Placing LCC backfill behind precast wall panels (California)

Cell-Crete Corporation, used with permission

Figure 1.11. Lightweight dam and levee structural fills (California)

Precast concrete wall systems have been used extensively on LCC embankment installations (see Figure 1.10). These systems are typically reinforced with lateral metal or plastic reinforcement extending from the back of the walls to the design embedment. Walls of this style are proprietary and typically designed by the manufacturer of the wall system according to its proprietary testing and system parameters but following the design rules for mechanically stabilized earth (MSE) walls stipulated by the American Association of State Highway and Transportation Officials (AASHTO). LCC is treated as soil for MSE wall design purposes, with unit weight and friction angles dependent on the class or estimated absolute volume design mix of LCC. These walls made of LCC are a very cost-effective method of creating vertical faces, especially if soft soils are involved, accelerated construction is necessary, or adjacent utilities or structures are present.

Lightweight Dam and Levee Structural Fills

Lightweight dam and levee structures are often installed in regions of deep soft sediments where settlement can be a major problem. LCC can address this challenge by being installed in the section of the levee below the surface while repairing a levee and filling it back to the design grade (see Figure 1.11).

Calculations pertinent to this LCC application again use the net load design method to avoid increasing the weight on the deep soft soils. The LCC section can be placed at any level to achieve the weight reduction, and it is important to investigate its buoyancy effect to determine the appropriate location within the levee or dam to place the LCC. The LCC layer is placed under a designed amount of heavy soil, incorporating helical anchors or pavement to keep the structure stable during high water, with the advantage of achieving weight reduction year-round, thereby reducing or eliminating any future settlement. Due to the low permeability and monolithic nature of LCC, failures due to scour, piping, and wash-out are decreased in a levee structure.

Landslide Repair and Slope Stabilization

Landslides can be rapid, dangerous failures causing extreme issues for those involved. If a slide is small, traditional and simple methods of soil excavation and slope regrading are likely to be applicable. However, if a slide is massive, unstable soil removal becomes inapplicable and too expensive. One method of dealing with large slides is to stabilize the site (through piers, tiebacks, dewatering, etc.) and leave the soil in place. Alternatively, LCC can be used at the crown/head scarp of the slide area to reduce the driving force from the weight of the existing soil (see Figure 1.12).

By removing the top of the slide area and replacing it with LCC, the mass is reduced, the grade is restored, and the driving force acting on the slide mass is significantly reduced.

© 2019 Cell-Crete Corporation, used with permission

Figure 1.12. Landslide repair and slope stabilization (California)

Controlled Density Fill

Controlled density fill (CDF), including CLSM, flowable fill, slurry cement, two-sack slurry, or sand slurry, is supplied all over the country by ready-mixed concrete providers as a compacted backfill replacement in trenches or under foundations (see Figure 1.13).

PCA

Figure 1.13. Controlled density fill

Typical unconfined compressive strengths are between 50 and 150 lb/in² (0.34 and 1.03 MPa), making CDF stronger and more stable than soil but still excavatable with conventional construction equipment. LCC makes an excellent CDF material because it can be used in many of the same applications.

LCC is increasingly cost-effective as the installed volume increases. When comparing the applicability of LCC against that of CDF, the following should be considered:

- Price
- Flowability
- Distance to ready-mixed concrete plant
- Availability of water
- Pumping requirements
- Buoyancy of fill
- Project size
- Placement time
- Traffic access to site

Chapter 2. Physical Properties

While LCC is usually comprised of only portland cement, water, and air provided through a preformed foam, a vast number of possible mix designs can achieve the desired engineering properties. The introduction of supplementary cementitious materials like fly ash or slag, along with chemical admixtures and aggregate (fine, coarse, or lightweight), into the LCC to change the fresh and hardened properties adds to the complexity of characterizing its physical properties.

The material properties discussed in this chapter are based on research conducted throughout the world over many years. Proper mix design and construction plays an important role in determining these engineering properties. Chapter 4 of this guide, Mixture Design, provides some guidance on mix design specifics.

Fresh Properties

LCC is normally made by combining portland cement, water, and air through preformed foam (with additives occasionally incorporated) in a mixing chamber. Once mixed and in its fresh state, the LCC material is self-consolidating and highly fluid, with water/cement (w/c) ratios ranging from 0.45 to 0.80. Foam manufacturers provide recommendations given that water content significantly affects many properties of LCC, and especially its strength and viscosity.

Cast Density

Field measurements of the unit weight, or density (mass per unit volume), along with the known w/c ratio of the fresh LCC mixture, are the primary quality control mechanisms (Hoff 1972). LCC is typically sampled from a flowing hose using a sample bucket, and measurements are taken frequently during production. The wet density of placed material may be evaluated using the recommendations in ASTM International (ASTM) C796, Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Preformed Foam.

This measurement of the wet LCC is referred to as the cast density and is the density that should be used in the specification and design of the LCC project. The installer may also take samples of fresh LCC material from the placement area, where material pools, or at the end of the hose within 30 minutes of installation to ensure densities are in accordance with the design and that air voids are not dissipating, which can result in an unexpected increase in density.

Within 8 to 24 hours, depending on the ambient conditions (temperature, precipitation, wind, etc.) and mix design, the placed LCC changes from a fluid to a solid. The density of the hardened LCC is approximately the same as its cast density, but due to the process of cement hydration and water loss through evaporation, the hardened density may be slightly lower. The solids in the placed LCC are permanent, but the moisture content does vary. The cast density is utilized to represent the density of the LCC provided. Wetting or drying over the lifetime of the product changes its actual field density. While drainage by itself will not completely prevent density fluctuation, when these fluctuations are unacceptable, providing a sealed surface that does not allow additional water in may be required. Any sealer used should be approved by its manufacturer for use with LCC.

In-Place Density

The term dry density is undefined in LCC applications and should be avoided due to its potential ambiguity. Specification writers often incorrectly refer to the final in-place density of the LCC after it cures as its dry density. While geotechnical engineers want to know how much the overall fill weighs in long-term conditions for settlement and consolidation calculations, the LCC installer can only control the density at the time of placement. The designer can control the changes in moisture content over the lifetime of the product by specifying sealers, the finish slope on grade, and drainage systems.

Because the installer can only be responsible for density measuring during LCC placement, the installer should not be held responsible for final long-term density after placement. While long-term density may change depending on, for example, whether proper drainage or surface sealing has been incorporated into the system, initial and long-term densities do not vary dramatically in the field when compared to cast densities.

Oven-Dry Density

The term oven-dry density can be useful, but it is not typically reported unless requested. While it is never recommended to oven-dry samples of LCC that are to be tested for unconfined compressive strength analysis, the oven-dry density can be a useful parameter to back-calculate the cast density. During cement hydration, the oven-dry density will increase slightly; however, once the cement has completely hydrated, the oven-dry density will be constant over the lifetime of the LCC. Oven-dry density can be determined as follows (Equation 1):

Oven-dry Density (lb/ft³) = Cast Density (lb/ft³) ÷ (1 + Moisture Content (%))
Oven-dry Density (kg/m³) = Cast Density (kg/m³) ÷ (1 + Moisture Content (%)) **(1)**

As an example, the oven-dry density for a 24 lb/ft³ (384 kg/m³) sample of LCC could be as light as 16 lb/ft³ (256 kg/m³). Determining LCC oven-dry density through testing provides an indication of the cement content and can be useful to the engineer who is overseeing the placement operation or as an investigative tool should problems arise.

Viscosity

One of the primary reasons for using LCC is its ability to flow, or its viscosity. Low viscosity allows for long-distance placements and nearly self-levelling installations. The viscosity of LCC, like any cement-based product, is primarily based on its water content. However, in LCC, the air bubbles are also considered. It is generally understood that the air bubbles increase flowability by acting as tiny ball bearings within the fill.

The viscosity of LCC is often incorrectly specified and measured utilizing grout measurement tools that are not appropriate for LCC from the U.S. Army Corps of Engineers (USACE) or ASTM International. These flowability measurements are often referred to as viscosity measurements and include ASTM C939, Standard Test Method for Flow of Grout for Preplaced-Aggregate Concrete (Flow Cone Method); ASTM C1611, Standard Test Method for Slump Flow of Self-Consolidating Concrete; and ASTM D6103, Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM).

While these procedures are excellent measurements of flowability for normal-weight flowable fill and grouts and are traditionally used to accept a product before attempting to pump into long pipes or similarly constricted locations, LCC does not fit well with these established tests. Gravity is a key component to the accuracy of these tests, and LCC has a density of ⅓ to ¼ of cement slurry, for which the tests are designed. The tests often provide higher viscosities than would be expected due to gravity not pulling the lightweight product through the hole or spreading it thoroughly enough.

Ultimately, the true test of flowability for LCC is the measurement of pumping pressure as the product is pushed through a hose. Maximum pumping pressure allowances for project conditions should be developed and monitored during placement. Maximum pumping times for placements into constricted areas such as abandoned pipes and annular spaces should be closely monitored. Additional information on proper construction practices is given in Chapter 5.

The viscosity of LCC is variable because of its thixotropic properties (having a viscosity that decreases when a stress is applied, as when agitated). The fresh cement pastes in LCC become fluid when agitated but restore their structural form when at rest. This is because cement pastes experience microstructural changes with time due to the particles' flocculation and cement hydration (Quanji 2010). With LCC, the flowability can be maintained for extended periods if agitation continues, as with continuous pumping on a single line where the entire mass is moving. However, there is a limit to how long the LCC remains stable with time and agitation. Segregation, where the cement slurry settles and leaves the foam at the surface, can occur on extended placements and should be avoided. Segregated areas are often found the next day by the observation of a crunchy/foamy top, and the segregated areas should be removed and replaced.

Lateral Fluid Pressure

LCC is placed as a fluid. During placement, the hydrostatic force exerted should be based on the actual cast density of the LCC. If a wall or shoring is being backfilled with LCC, it should be designed to ensure that it can support the wet fluid. LCC is typically placed in 4 ft (1.2 m) deep lifts; however, thicker and thinner lifts are also common. Given that LCC stiffens over time, the hydrostatic force completely disappears as the product solidifies into its final form. Formwork may be removed after the material has fully solidified into a homogenous mass.

Set Time

LCC is a concrete product, and most of the studies appropriate for types of cement and concrete also apply to LCC. LCC may perform differently in varying conditions, with the change factors being agitation, temperature, and mix design. Fresh concrete is a thixotropic material that liquefies when energy is applied. Just as ready-mixed concrete trucks continually spin their load to keep the concrete in a fluid state, LCC also benefits from agitation.

While an exact set time does not exist for LCC, a practical set time of two to four hours may be assumed for a fill such as a foundation placement or other large-volume, low-energy, open-top fills. Low-energy fills are large areas where the entire mass is not in motion and subareas can start setting up prior to completion.

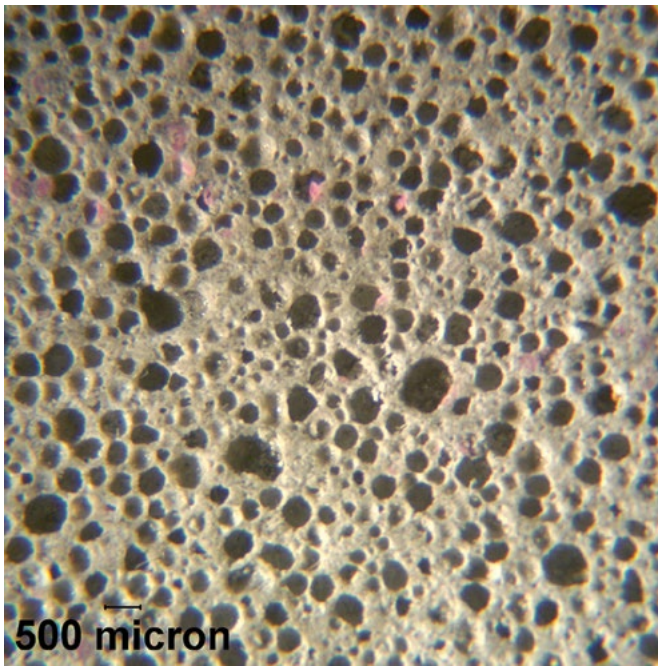
In pipe work, the entire mass is being agitated because the pump is pushing the LCC; therefore, set issues do not occur until pumping stops. If the set time is a critical factor, the installer should evaluate the placement size, specific mix, and techniques and compare them to the project specifications. This challenge is often resolved by creating smaller cells for placement or by incorporating set retarding admixtures that are compatible with the LCC.

Hardened Properties

The hardened properties of LCC are the properties that the engineering community uses for the service life of the project. These are the properties of the final product and indicate how the product performs when in the structure. The most common hardened properties are unit weight and unconfined compressive strength, which should be measured on every job. Most of the other hardened properties, such as air content, permeability, sorption, modulus of elasticity, and others, are typically not tested unless specifically requested by the design engineer.

Hardened Description

Once LCC has been in place for 8 to 24 hours and the final set has taken place or the LCC has hardened, it looks like pumice or volcanic tuft (uniform lava rock). It is gray colored and consists of a portland cement matrix filled with tiny, round, stable air voids, or vesicles, approximately 0.04 in. (1.0 mm) in diameter (see Figure 2.1).



© 2014 Elastizell Corporation of America, used with permission

Figure 2.1. Vesicles/air voids

The actual diameter of the air voids in fresh LCC depends on the mixing techniques and materials employed. Held in the hand, it is noticeably lightweight, and density differences among samples are readily apparent. The strength of the residual matrix creates the beneficial properties found in the final product. The water is utilized during cement hydration, and the preformed foam is absorbed into the mix, leaving air voids visible to the naked eye. The cured LCC appears either wet or dry, which varies with drying, depending on its water content.

Strength

LCC is very strong compared to the material, typically soil and compacted aggregates, that it replaces in the geotechnical environment. A 30 lb/ft³ (480 kg/m³) sample of LCC has a minimum unconfined compressive strength of 40 lb/in² (0.28 MPa), which corresponds to a 2.9 ton/ft² (0.28 MPa) bearing capacity. Table 2.1 provides a summary of industry-accepted values for maximum cast density, 28-day minimum unconfined compressive strength, and bearing capacity that can be expected for typical LCC mixes used in the US.

Actual LCC mix properties should always be tested prior to installation.

The compressive strength, shear strength, resilient modulus, and California bearing ratio (CBR) of LCC vary due to factors such as cement quality, type of cement, density, foam quality, w/c ratio, mixing equipment, sand-cement ratio (if sand is added), mix intensity, production and placement temperatures, and additives or admixtures. Several other factors can be added to this list because, while LCC has only three primary components (cement, water, and air), the number of mix variables is immense.

Table 2.1. Physical properties of LCC

Maximum cast density		Minimum compressive strength		Bearing capacity	
lb/ft³	kg/m³	lb/in²	MPa	ton/ft²	MPa
24	385	10	0.07	0.7	0.07
30	480	40	0.28	2.9	0.28
36	575	80	0.55	5.8	0.56
42	675	120	0.83	8.6	0.82
50	800	160	1.10	11.5	1.10

Source: ACI 2006

The large number of mix variables leads to an inability to make design decisions based entirely on material property values from the tables, figures, and equations provided in this document. The information presented is given to provide guidance only, and the engineer is encouraged to conduct the necessary testing and consultation with the installer and/or manufacturer to determine the appropriate mixture design for achieving the specified material property requirements.

A study was conducted in California to evaluate a large data set of more than 3,000 LCC test samples under many different conditions (Siebold and Tootle 2016). The raw data were evaluated, and the unconfined compressive strengths ranged from one to three times for the same density (i.e., 30 lb/ft³ [481 kg/m³] density equated to 50 to 150 lb/in² [0.34 to 1.03 MPa] unconfined compressive strength). This is acceptable for a geotechnical fill when a minimum strength is all that is required. However, this might not be acceptable in applications when the actual strength and its accompanying failure mechanism must be known.

The study was conducted to simply evaluate the ability of LCC material to be consistent enough for structural applications. The intent of the study was to show that 60 samples, all from the same batch, would consistently test the same. This would prove that LCC mixes with near-identical strengths could be repeatedly made if required and that variables, when held constant, could produce a consistent product.

The study divided the 60 samples into six groups of 10. The six groups were then cured in three different ways. Half of the groups were sulfur capped and half were not; 20 were cured wet, 20 were cured dry, and 20 were cured per the procedure in ASTM C495. Each of the six groups tested consistently for strength, proving that a uniformly made/cured LCC could obtain an anticipated strength. The most informative part of the results was that the curing process was critical. The strength values obtained from the wet- and dry-cured samples were very similar, while the samples cured with the ASTM C495 procedure achieved nearly twice the strength of the others. This showed that properly following the ASTM C495 procedure is critical for laboratories measuring LCC samples for unconfined compressive strengths.

Cohesion and Friction Angle

In one study, laboratory soil tests were conducted on LCC samples having four different densities; shear strength parameters, coefficients of permeability, and at-rest earth pressure coefficients were measured (Tiwari et al. 2017). Unconfined compressive strength and undrained strength properties (total friction angle and cohesion intercept) of partially saturated materials were found to be dependent on the density of the LCC sample. However, the effective friction angle and cohesion intercept of the saturated materials were independent of the test unit weight over the range of stresses tested. The effective friction angle and cohesion values of the LCC materials determined from direct simple shear tests were 35 degrees and 36 kPa (5.2 lb/in²), respectively, as shown in Table 2.2.

Table 2.2. Friction angles and cohesion values for LCC

Material	Unconfined compressive strength (kPa)	Friction angle for partially saturated conditions (degrees)	Cohesion for partially saturated conditions (kPa)	Friction angle for saturated conditions (degrees)	Cohesion for saturated conditions (kPa)
Class II-Batch 1	265–1,657	19	408	35	36
Class II-Batch 2		20	187	35	36
Class IV	628–2,765	21	615	35	36
7.1 kN/m³ cast unit weight	8,979–10,845	22	820	35	36
8.6 kN/m³ cast unit weight	10,729–13,406	21	1,174	35	36

1 kPa = 0.145 lb/in²
1 kN/m³ = 6.423 lb/ft³
Source: Tiwari et al. 2017

Table 2.3. Modulus of elasticity relationships of LCC

Author and year	Relationship	Remarks
Tada 1986	$E = 5.31 \times W + 853$	Density from 200 to 800 kg/m^3
McCormick 1967	$E = 33W^{1.5}fc^{.5}$	Pauw's equation
Jones and McCarthy 2005a	$E = 0.42fc^{1.18}$	Sand as fine aggregate
	$E = 0.99fc^{0.67}$	Fly ash as fine aggregate

E = modulus of elasticity (KN/mm^2)
W = in-place density of LCC (kg/m^3)
fc = compressive strength (N/mm^2)

1 KN/mm^2 = 145,037.738 lb/in^2
1 kg/m^3 = 0.062 lb/ft^3
1 N/mm^2 = 145.038 lb/in^2

Source: Ramamurthy et al. 2009

Modulus of Elasticity

Several mathematical models have been developed and reported in the literature relating the density or compressive strength of LCC to the modulus of elasticity. Table 2.3 summarizes these.

A simple measurement of the stress-strain curve could also be used to determine if these formulas are accurate for proposed mix designs.

The modulus of elasticity values obtained from the relationship equations in Table 2.3 compare favorably for LCC mixes, including those from the California study (Siebold and Tootle 2016).

Air Content

The air content in a typical 30 lb/ft^3 (481 kg/m^3) LCC mixture is in the range of 70% to 75%. Air content measurements are sometimes required in project specifications. Unfortunately, the standard procedure for determining the air content of concrete is not applicable when the air content is very high, like it is with LCC. Instead, the air content can be calculated by measuring the density of the cement and water slurry and then measuring the cast density of the final product. Equation 2, which is derived from ASTM C796, can be used to approximate the air content as a percentage of volume.

Equation 9, which is found in Chapter 6, provides information on computing slurry densities.

A more exact analysis could include the mass/density of the foam.

Drying Shrinkage

All portland cement products experience some amount of autogenous shrinkage when moisture is lost. This is referred to as drying shrinkage. The drying shrinkage exhibited by LCC can be up to 10 times greater than that observed for normal-weight concrete (Narayanan and Ramamurthy 2000, Ramamurthy et al. 2009).

Shrinkage occurs in the cement paste and is restrained in normal-weight concrete by the inert materials such as gravel and sand. In LCC, the aggregates are replaced with open voids that allow the cement paste to shrink without restriction. Shrinkage is primarily caused by the change in water content, which can be reduced by decreasing the water in the initial mix or by reducing the amount of drying that occurs over time. The shrinkage of LCC decreases as density increases (ACI 2006). This shrinkage is attributed to the decreasing water content in the cement paste.

In the geotechnical fill environment, LCC shrinkage is not generally observed in the field due to its location in the ground and the lack of drying that occurs. If the likelihood of shrinkage is a concern, covering the fill to reduce evaporation or adding curing water will minimize the moisture loss. The long-term moisture condition for both density and shrinkage should be designed to stay consistent, either wet or dry. Shrinkage can be assumed to be between 0.5% and 1.0% for most mix designs. The actual field mix should be tested prior to installation if excessive shrinkage is a concern.

$$\text{Air}(\%) = 100 \times (\text{Slurry Density}(\text{lb/ft}^3) - \text{Cast Density}(\text{lb/ft}^3)) \div \text{Slurry Density}(\text{lb/ft}^3)$$
$$\text{Air}(\%) = 100 \times (\text{Slurry Density}(\text{kg/m}^3) - \text{Cast Density}(\text{kg/m}^3)) \div \text{Slurry Density}(\text{kg/m}^3) \quad \textbf{(2)}$$

Permeability/Sorption

The understanding of the permeability of LCC has improved in recent years. Previous studies had shown and general understanding had been that LCC exhibits extremely low permeability. Recently, studies have shown that completely saturated LCC exhibits high permeability characteristics (Maw and Cole 2015); however, when not saturated, LCC is resistant to water passage.

The contradiction stems from the initial wetting. Submerging a completely dry sample in water will rapidly moisten the cement paste within the sample. The sample then takes on water extremely slowly to ultimately fill the voids. Permeation rates have been reported as shown in Table 2.4, with the recommendation that additional hydraulic conductivity testing be performed due to the variability in referenced hydraulic conductivity, the limited data, and the historic nature of the testing (Tiwari et al. 2017).

While permeability is a standard concept well understood in the geotechnical field, a better mechanism to understand the flow of water through LCC may be sorption. Sorption is a moisture flow measurement that includes the transfer of water vapor and moisture diffusion coefficients, where capillary suction and water permeability characterize water transfer. Engineers looking for a more thorough understanding of water flow within a mass of LCC should review the literature on LCC sorption (Narayanan and Ramamurthy 2000, Nambiar and Ramamurthy 2007).

Heat of Hydration

LCC is comprised of portland cement, water, and air (added through a preformed foaming agent). The curing of cement is an exothermic reaction, commonly known as the heat of hydration. This rapidly occurring chemical reaction has been known to generate temperatures above the boiling point of water. Under normal conditions, the heat of hydration in an LCC fill begins two to four hours after placement. The rate of temperature rise, as well as the maximum temperature reached, are influenced by the type and quantity of cement, the density, and the placement size of the LCC mass (Tarasov et al. 2010).

The heat of hydration can be a significant problem when placing plastic pipes within large masses of LCC undergoing curing and should always be considered when designing an LCC fill. While an LCC fill will always warm up, placement with an open top will not obtain the maximum heat forecasted, which assumes no heat loss and represents the highest temperatures possible. Internal temperatures in large flat fills typically range from 100°F to 150°F (38°C to 66°C).

An extensive study of the heat of hydration of LCC was performed by researchers in South Africa (Tarasov et al. 2010). The study evaluated the effects of the mix constituents and concluded that the amount of cement was the largest indicator of maximum heat attained, followed by the size of the sample. The researchers determined that adding fly ash or other filler materials reduces the maximum temperature attained through increased mass or a slower chemical reaction. Increasing the amount of foaming agent in the LCC was found to slow the reaction and reduce the maximum temperature.

While actual edge conditions cannot be perfectly characterized, the study did present a valuable method for forecasting the maximum heat possible in a large LCC mass. Table 2.5 and Equations 3 and 4 can be used to estimate the maximum possible temperature a mass of LCC could attain.

Table 2.4. Summary of cellular concrete hydraulic conductivity testing

Cellular concrete class	Cast date	Sample ID	Hydraulic conductivity $K_{average}$[a] (cm/sec)	Moist unit weight (lb/ft^3)	Confining stress (psi)
II	July 2014	13	1.9E-4	29.2	5
	July 2014	13	1.7E-4	29.2	12.5
	July 2014	19	7.7E-4	27.1	5
	July 2014	19	7.2E-4	27.1	12.5
IV (low density)	February 2015	213-31	1.2E-3	31.2	5
	February 2015	213-21	9.5E-4	33.5	12.5

[a] *Corrected to 20°C (68°F)*
1 cm/sec = 0.394 in./sec
1 lb/ft^3 = 16.018 kg/m^3
1 lb/in^2 = 6.895 kPa

Source: Tiwari et al. 2017

Table 2.5. Calculated heat capacity and thermal conductivity of foamed concrete mixes, 300 kg/m³ portland cement content, silica sand fine aggregate

Characteristics	Unit	Values for in-place density grades			
		350*	400	800	1,200
Volumetric heat capacity, C_v	kJ/(°C m³)	915.70	966.90	1,479.40	1,997.80
Thermal conductivity, λ_v	W/mK	0.19	0.28	0.53	0.84

** Values valid for foamed concrete mix without aggregate*
1 kg/m³ = 0.062 lb/ft³
1 kj/(°C m³) = 0.027 BTU (th)/ft³
1 W/mK = 0.580 BTU ft / (h ft² °F)
Source: Tarasov et al. 2010

Please note that this study references in-place density and is referring to oven-dry density. Through the mix design, it can be estimated what the oven-dry density should be for this analysis by using Equation 1.

First, using Equation 3, obtain the value for α, which represents the heat generated from the mix design.

$$\alpha = \lambda v \div (Cv \times \rho v) \quad \textbf{(3)}$$

where,

α = thermal diffusivity coefficient (m²/s)

λv = thermal conductivity (W/(m °C))

Cv = volumetric heat capacity (kJ/(m³ °C))

ρv = cast density (kg/m³)

1 m²/s = 10.764 ft²/s

1 W/(m °C) = 0.578 BTU ÷ (h ft °F)

1 kJ/(m³ C) = 0.027 BTU (th)/ft³

1 kg/m³ = 0.062 lb/ft³

Second, calculate the maximum temperature expected from the mix design and sample size. A large, flat placement may be assumed to be a cube equal to the height of the placement, as shown in Equation 4.

$$T_{max} = 120.29\ (a\ Cem^2\ V^2 \div S\ A^2)^{0.17} \quad \textbf{(4)}$$

where,

T_{max} = "maximum" temperature in a sealed box core of LCC (°C)

a = thermal diffusivity coefficient (m²/s)

Cem = cement content in LCC (kg/m³)

V = volume of LCC in a sealed box (m³)

S = mass of all solid ingredients in the given LCC mix (kg/m³)

A = overall surface area of the LCC cube in a sealed box (m²)

°C = (5/9)(°F – 32)

1 m²/s = 10.764 ft²/s

1 kg/m³ = 0.062 lb/ft³

1 m³ = 35.315 ft³

1 kg/m³ = 0.062 lb/ft³

1 m² = 10.764 ft²

Heat evolution is directly related to cement content and placement volume in LCC. The cement-to-solid ratio in the function considers the presence of inert fillers, which are accumulators of evolved heat. The more filler there is in the solid phase, the lower the maximum temperature. The volume of LCC mass represents the influence of cube size on heat evolution. LCC density, heat conductivity, and heat capacity are combined in a term of thermal diffusivity that describes the velocity of temperature change in the mass, which depends on the physical characteristics of the initial ingredients in the mix. Overall surface area is an indirect parameter of heat loss for an LCC mass, with higher surface areas resulting in higher heat losses.

Tarasov et al. (2010) compared actual measured temperatures to temperatures predicted using Equation 4, and the computed temperatures compared well with the measured temperatures. The researchers found that the model as fitted explains 89.3% of the variability in temperatures. More efficient heat insulation of molds would probably have given an even higher correlation. Although this function can only be used to predict temperatures under laboratory conditions, it does reflect the general trend indicating that the most dominant factors influencing temperature development are cement content and volume of placement.

While more study is needed and local constituents affect the applicability of the function, this method is reasonable in estimating the maximum temperature possible during the LCC curing process. Even with the amount of heat generated, there were no reported issues with cracking, as is common with conventional concrete. No precautions need to be taken during construction to minimize the temperature differential between the surface LCC and the inner core, unlike for mass concrete placements.

Thermal Conductivity

The thermal conductivity of LCC is usually proportional to density (the lighter the sample, the higher the insulation factor). In the early 1900s, when various inventors from around the world were applying for patents for LCC (e.g., Bayer v. Rice 1934), the inventors were primarily focused on insulation potential. Insulation patents for LCC products—for walls, floors, and roofing—may be found in many parts of the world. The insulation values found in the research can be limited and confusing due to the wide variety of LCC products made around the world and the differing qualities of the materials. That said, locally available LCC should always be tested for desired properties prior to installation.

Studies of LCC typically make the comparison that its thermal conductivity is dramatically lower than that of traditional concrete (Aldridge et al. 2005). On average, the thermal conductivity of conventional normal strength concrete at room temperature is between 1.4 and 3.6 W/mK (0.81 and 2.09 BTU ft ÷ (h ft² °F)) (Bažant and Kaplan 1996), whereas LCC has a much lower thermal conductivity.

An extensive study in Malaysia showed that the thermal properties of LCC could change based on the mix design and additive ingredients (Mydin et al. 2012). The study created 22 different mixes, prepared at three different densities and with varying amounts of fly ash, lime, and polypropylene fibers as additives. The various thermal properties at different densities for the portland cement-only mixtures are provided in Table 2.6.

A measure of thermal resistance, or R-value, can be calculated for the insulating medium using Equation 5, referenced in ASTM C168, Standard Terminology Relating to Thermal Insulating Materials.

Table 2.6. Thermal properties of LCC at different densities

Density (kg/m^3)	Thermal conductivity (W/mK)	Thermal diffusivity (mm^2/s)	Specific heat (MJ/m^3K)	Porosity (%)
D	k	α	Cp	
600	0.19	0.35	0.54	69
1,000	0.43	0.54	0.81	49
1,400	0.59	0.60	0.98	36
Mortar	1.4	0.96	1.47	–

1 kg/m^3 = 0.062 lb/ft^3
1 W/mK = 0.580 BTU ft / (h ft^2 °F)
1 mm^2/s = 0.002 in^2/s
1 MJ/m^3K = 26.839 BTU/ft^3 °F
Source: Mydin et al. 2012

R-value = L (thickness in feet) ÷ k (thermal conductivity in BTU/h(ft)F)
R-value = L (thickness in meters) ÷ k (thermal conductivity in W/mK) **(5)**

The units of an R-value are given in Fahrenheit feet squared hours per British thermal unit or F-ft²-h/BTU (kelvin meters squared per watt or K-m²/W). Notice that the thicker the material, the higher the R-value. If a higher R-value is desired, adding additional thickness can achieve the increased insulation.

LCC testing at a cast density containing free water will show a relatively lower insulation value; if retested oven-dry, this value will increase dramatically. Mydin et al. (2012) state that the samples were tested in an oven-dry condition. It can be assumed that LCC, when placed in a field-dry condition and allowed to dry out completely, will perform as shown in Table 2.6. Conversely, if LCC is placed in the ground, where long-term moisture is available, the thermal conductivity will increase, resulting in a decrease in the insulating value. Additional testing is required for insulation values in long-term moisture conditions.

Resistance to Aggressive Environments

LCC exhibits good resistance to aggressive environments (Ramamurthy et al. 2009). Most foamed concrete mixtures properly designed at low density, taking into consideration the depth of initial penetration, absorption, and the absorption rate, provide good chemical resistance.

A 12-month study on the sulfate resistance of LCC revealed that LCC has good resistance to aggressive chemical attack (Jones and McCarthy 2005b). A comparison of the performance of mixes with sand and fly ash showed that mixes with fly ash exhibited higher carbonation than those with sand. An accelerated chloride ingress test suggested that the performance of LCC is equivalent to that of normal concrete with enhanced corrosion resistance at lower densities.

The cell-like structure of LCC and the possible porosity of its cell walls do not necessarily make LCC less resistant to moisture penetration than dense concrete, but the air voids appear to act as a buffer preventing rapid penetration and degradation.

Chapter 3. Geotechnical Design Considerations

As with the selection of all construction materials, qualified design engineers should use the appropriate material properties, along with approved design methodologies, and evaluate LCC applications accordingly. The materials described in this guide can be used for many different geotechnical applications. LCC should not be used in structural applications as a substitute for conventional concrete elements.

In many cases, LCC with a higher or lower density or strength, as described in Table 2.1, may be required. All cellular concretes, including LCC, can also be used as versions of traditional lightweight aggregate concretes, which have low densities compared to conventional concrete. The typical design considerations described in this guide involve the geotechnical engineering aspects of the use of LCC.

When LCC is used as a geotechnical material, applications and considerations may include bearing capacity improvement, reduction of hydrostatic pressure, weight reduction, buoyancy, prevention of punching and other improved strength mechanisms, extended design life, seismic improvements, control of temperature rise during hydration, improved drainage or permeability, improved structural number, and higher angle of internal friction.

Settlement Reduction/Weight Reduction

The most common benefit of LCC is weight/load reduction, which is evaluated utilizing the net load design method. This method is intended to estimate changes in the effective soil pressure (or in situ effective vertical stress) that may induce short- and long-term settlement in deep-seated layers of soft soils. To this end, primary and secondary consolidation settlement evaluations should be implemented to determine the allowable net load increase on the compressible soil layers to keep the expected settlement within an allowable amount.

In some cases, a zero net load is desired, which simply means that subexcavated near-surface soil is replaced with LCC backfill and fill so that no net increase in effective vertical stress occurs in the critical sublayer(s). In such cases, the consolidation settlement is generally negligible.

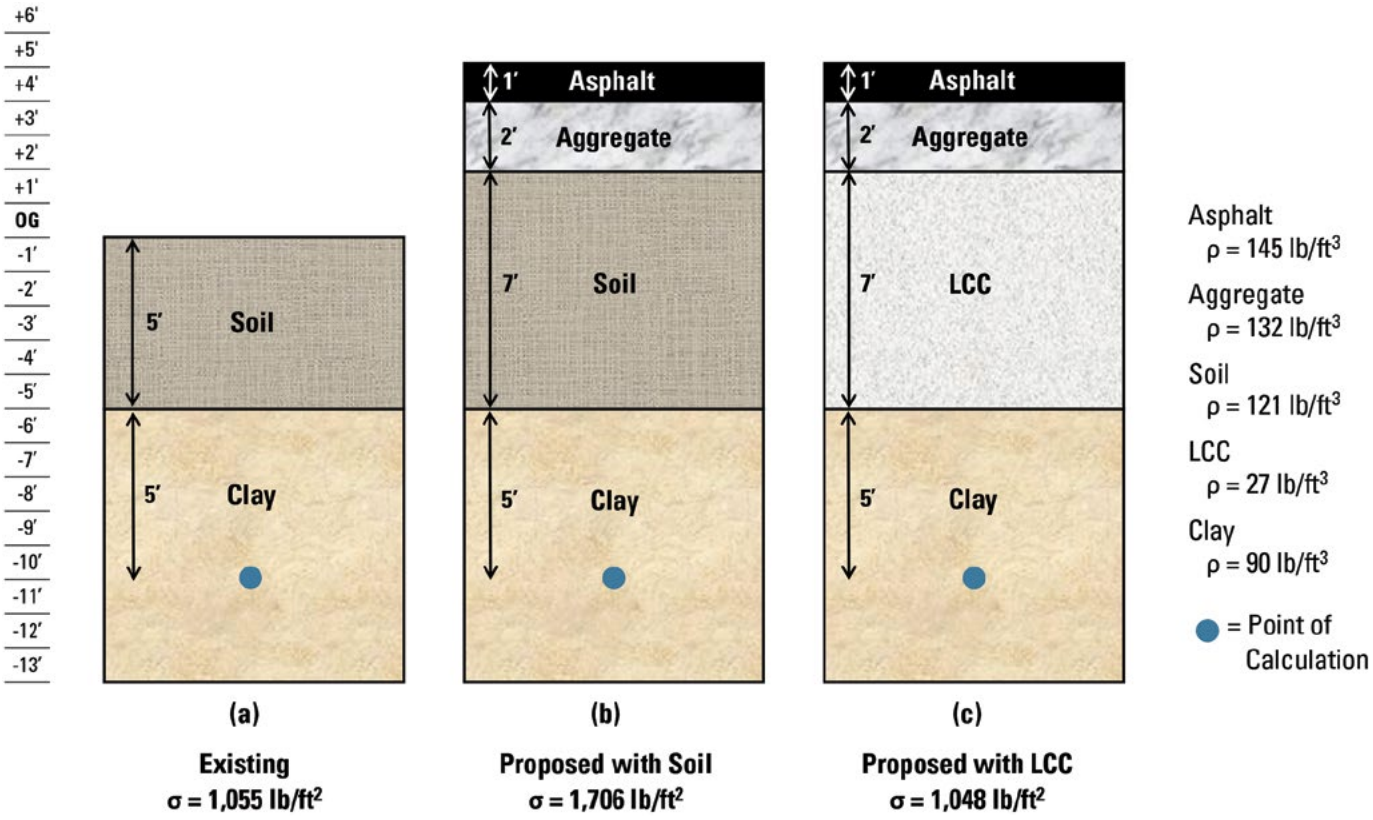
Net Load Design Method for Settlement Reduction

Vital to the net load design method is the removal of a predetermined amount of subgrade soil and its replacement with lightweight backfill, fill, or a lightweight structure. In many cases, the design starts with the goal of not adding any additional weight to the site (or a zero net loading case). However, a zero net loading case is not required in all situations. The project-specific design approach and settlement performance goal are often refined by the geotechnical engineer for actual site conditions and settlement goals.

The following is an example where the final soil and pavement loads are less than the preexisting soil load; therefore, the anticipated settlement is expected to be negligible.

Example: A new flexible pavement section is proposed consisting of 1 ft (0.3 m) of asphalt with a density of 145 lb/ft³ (2,323 kg/m³), over 2 ft (0.6 m) of aggregate base with a density of 132 lb/ft³ (2,114 kg/m³), over 7 ft (2.1 m) of soil with a density of 121 lb/ft³ (1,938 kg/m³), over a deep section of compressible clay with a density of 90 lb/ft³ (1,442 kg/m³). Because the site location is adjacent to the ocean, the new pavement is planned to be 5 ft (1.5 m) higher than the original undisturbed grade.

The top of the compressible layer is located at a point 5 ft (1.5 m) below the original ground surface and will not be disturbed during construction. This layer is shallow and has settlement potential because it is normally consolidated. The water table is below the critical layer, and its anticipated fluctuation will not change the effective vertical stress conditions within the clay. This calculation is performed at a randomly selected depth of 10 ft (3.0 m), as illustrated in Figure 3.1 and detailed further after that.



1 ft = 0.305 m *1 lb/ft³ = 16.018 kg/m³* *1 lb/ft² = 4.882 kg/m²*

PCA

Figure 3.1. Net load design method for settlement reduction

Existing Conditions Calculations (see Figure 3.1 (a)): 5 ft (1.5 m) of soil over 5 ft (1.5 m) of compressible clay to the calculation point at 10 ft (3.0 m) below grade:

Vertical Stress from Soil: 5 ft (1.5 m) soil × 121 lb/ft³ (1,938 kg/m³) = 605 lb/ft² (2,907 kg/m²)

Vertical Stress (Clay Layer): 5 ft (1.5 m) clay layer × 90 lb/ft³ (1,442 kg/m³) = 450 lb/ft² (2,163 kg/m²)

Total Vertical Stress at 10 ft (3.0 m) below Original Grade: 605 lb/ft² (2,907 kg/m²) + 450 lb/ft² (2,163 kg/m²) = 1,055 lb/ft² (5,070 kg/m²)

Proposed Conditions without LCC (see Figure 3.1 (b)): Add 1 ft (0.3 m) of asphalt, 2 ft (0.6 m) of aggregate base, and 7 ft (2.1 m) of soil to the existing subgrade and calculate at 15 ft (4.6 m) below the finished grade:

Vertical Stress from Asphalt: 1 ft (0.3 m) asphalt × 145 lb/ft³ (2,323 kg/m³) = 145 lb/ft² (697 kg/m²)

Vertical Stress from Aggregate: 2 ft (0.6 m) aggregate × 132 lb/ft³ (2,114 kg/m³) = 264 lb/ft² (1,268 kg/m²)

Vertical Stress from Soil: 7 ft (2.1 m) soil × 121 lb/ft³ (1,938 kg/m³) = 847 lb/ft² (4,070 kg/m²)

Vertical Stress from Existing Clay Layer: 5 ft (1.5 m) clay layer × 90 lb/ft³ (1,442 kg/m³) = 450 lb/ft² (2,163 kg/m²)

Total Vertical Stress at 15 ft (4.6 m) below Original Grade: 145 lb/ft² (697 kg/m²) + 264 lb/ft² (1,268 kg/m²) + 847 lb/ft² (4,070 kg/m²) + 450 lb/ft² (2,163 kg/m²) = 1,706 lb/ft² (8,198 kg/m²)

The addition of the asphalt, aggregate base, and soil would result in an increase of 651 lb/ft² (3,178 kg/m²) over the existing condition. In this example, the geotechnical engineer decides that the additional materials would cause unacceptable settlement and recommends that the pressure be brought back to the original existing condition or less.

Proposed Final Conditions with LCC (see Figure 3.1 (c)): Replace the soil with 7 ft (2.1 m) of LCC with a density of 27 lb/ft³ (432 kg/m³):

Vertical Stress from Asphalt: 1 ft (0.3 m) asphalt × 145 lb/ft³ (2,323 kg/m³) = 145 lb/ft² (697 kg/m²)

Vertical Stress from Aggregate: 2 ft (0.6 m) aggregate × 132 lb/ft³ (2,114 kg/m³) = 264 lb/ft² (1,268 kg/m²)

Vertical Stress from LCC Replacement: 7 ft (2.1 m) LCC × 27 lb/ft³ (432 kg/m³) = 189 lb/ft² (907 kg/m²)

Vertical Stress from Existing Clay Layer: 5 ft (1.5 m) clay layer × 90 lb/ft³ (1,442 kg/m³) = 450 lb/ft² (2,163 kg/m²)

Total Vertical Stress at 15 ft (4.6 m) below Original Grade: 145 lb/ft² (697 kg/m²) + 264 lb/ft² (1,268 kg/m²) + 189 lb/ft² (907 kg/m²) + 450 lb/ft² (2,163 kg/m²) = 1,048 lb/ft² (5,035 kg/m²)

By utilizing LCC instead of soil in this example, the total vertical stress is reduced by 7 lb/ft² (34 kg/m²) when compared to the existing conditions. This negative amount results in a slight net weight reduction at this location and indicates that the LCC option is a viable alternative for producing negligible settlement.

The above example does not consider groundwater fluctuation. If this is possible during the life-cycle of the project, total vertical stress calculations should be replaced with effective vertical stress calculations that consider the amount of water table changes. Additionally, buoyancy calculations, as discussed later in this chapter, may be required depending on the amount of water table fluctuation.

Since the final design pressure at the calculation point is less than the original pressure where the soil has been in place undisturbed, the calculation indicates that the design will not cause settlement, and the design is ready to send to the geotechnical engineer for approval. Using a properly characterized profile, the geotechnical engineer may be able to reduce costs at the site by allowing for some net positive weight and, hence, less excavation and lightweight fill. The engineer may also know that the site soils are extremely sensitive and that a negative net weight is required to achieve an appropriate FOS. It is important to note that this net load design method does not incorporate traffic loads, only soil replacement loads.

Bearing Capacity

LCC is a rigid cement-based product that behaves similarly to structural concrete at much lower densities and strengths. Failure is typically observed as crushing but also could be from fracturing or shearing. The allowable bearing capacity of a section is calculated based on the minimum required compressive strength of the LCC provided. The use of this specified minimum strength only serves to increase the final FOS realized by using the actual strength of the LCC as tested on the job. This bearing capacity is then carried through the layer of LCC, widening with depth at an approximately 45 degree angle (depending on LCC density) to distribute the load to the subgrade below. It is important to note that the angle of shear failure and the angle of load distribution are not the same values.

Example: In Figure 3.2, a 10,000 lb (4,536 kg) load is placed on a steel plate measuring 2 ft (0.6 m) square.

This loaded plate sits on a 4 ft (1.2 m) thick layer of 30 lb/ft³ (481 kg/m³) of LCC having a minimum compressive strength of 40 lb/in² (28,123 kg/m²). The soils below the LCC have an allowable bearing capacity of 1,000 lb/ft² (4,882 kg/m²). The following calculations are used to determine the FOS with LCC.

Compressive Stress: 10,000 lb bearing on 2 ft² = 10,000 lb ÷ (2 ft × 2 ft) = 10,000 lb ÷ 4 ft² = 2,500 lb/ft²

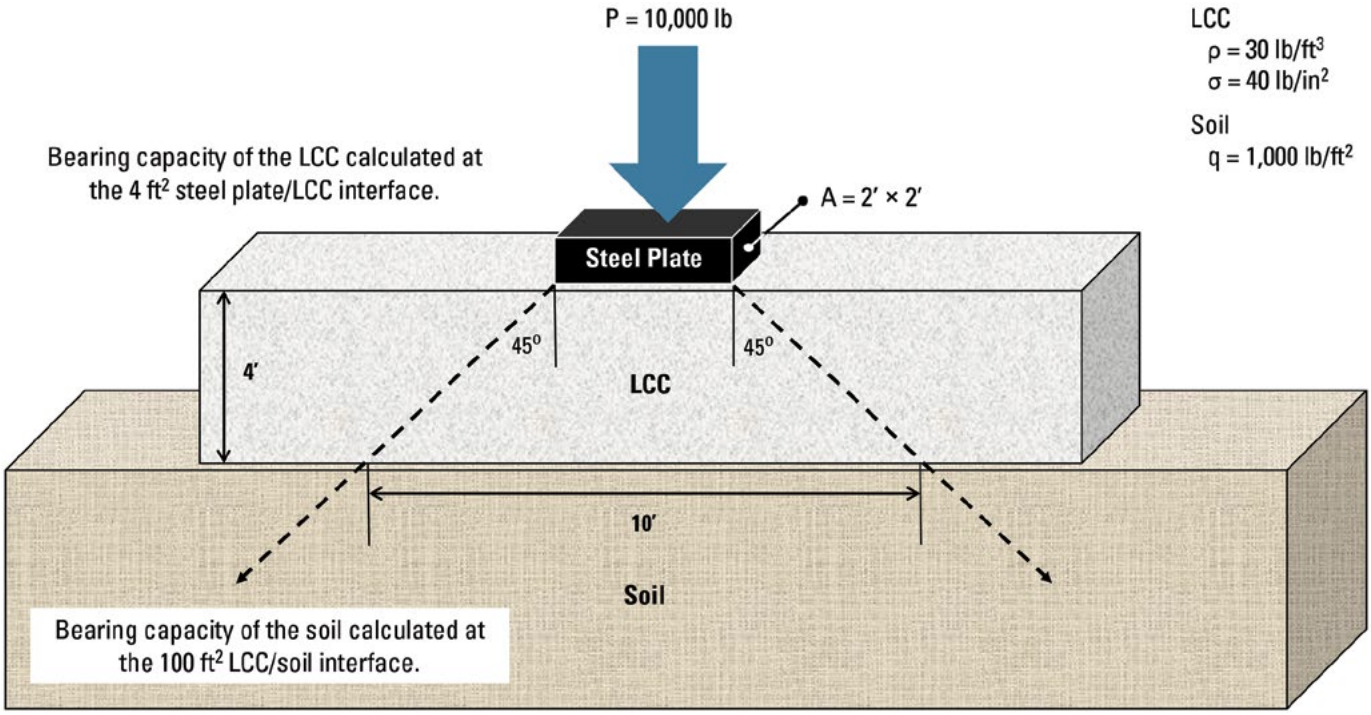
Compressive Stress: 4,536 kg bearing on 0.6 m square = 4,536 kg ÷ (0.6 m × 0.6 m) = 4,536 kg ÷ 0.36 m² = 12,600 kg/m²

Compressive Strength: 40 lb/in² × (12 in./ft × 12 in./ft) = 40 lb/in² × 144 in²/ft² = 5,760 lb/ft²

Compressive Strength: 28,123 kg/m²

Depending on design safety factors, the results indicate that the pressure (compressive stress) from the load of 2,500 lb/ft² (12,600 kg/m²) can be supported by the bearing capacity (compressive strength) of the LCC, which is 5,760 lb/ft² (28,123 kg/m²).

The bearing pressure on the underlying soil is calculated over a 10 ft by 10 ft (3.05 m by 3.05 m), or 100 ft² (9.30 m²), area based on the 2 ft (0.6 m) square load, spread at a 45 degree angle, to a depth of 4 ft (1.2 m).



1 ft = 0.305 m *1 lb = 0.454 kg* *1 lb/ft³ = 16.018 kg/m³* *1 lb/in² = 0.007 MPa* *1 lb/ft² = 4.882 kg/m²*

PCA

Figure 3.2. Bearing capacity and spread of compressive forces in LCC

Soil: 10,000 lb ÷ 100 ft² = 100 lb/ft²

LCC: 30 lb/ft³ × 4.0 ft = 120 lb/ft²

Total Pressure: 100 lb/ft² + 120 lb/ft² = 220 lb/ft²

Design FOS: Bearing Capacity ÷ Total Pressure = 1,000 lb/ft² ÷ 220 lb/ft² = 4.5

Soil: 4,536 kg ÷ 9.30 m² = 488 kg/m²

LCC: 481 kg/m³ × 1.2 m = 577 kg/m²

Total Pressure: 488 kg/m² + 577 kg/m² = 1,065 kg/m²

Design FOS: Bearing Capacity ÷ Total Pressure = 4,882 kg/m² ÷ 1,065 kg/m² = 4.6

The results show that the total pressure from the load of 220 lb/ft² (1,065 kg/m²) can be supported by the bearing capacity of the soil, which is 1,000 lb/ft² (4,882 kg/m²).

The lowest design FOS is at the plate-to-LCC interface, as follows:

Design FOS: 5,760 lb/ft² ÷ 2,500 lb/ft² = 2.3

Design FOS: 28,123 kg/m² ÷ 12,600 kg/m² = 2.2

As a note, it is also equally as important to check deflections and other project criteria.

Punching Shear

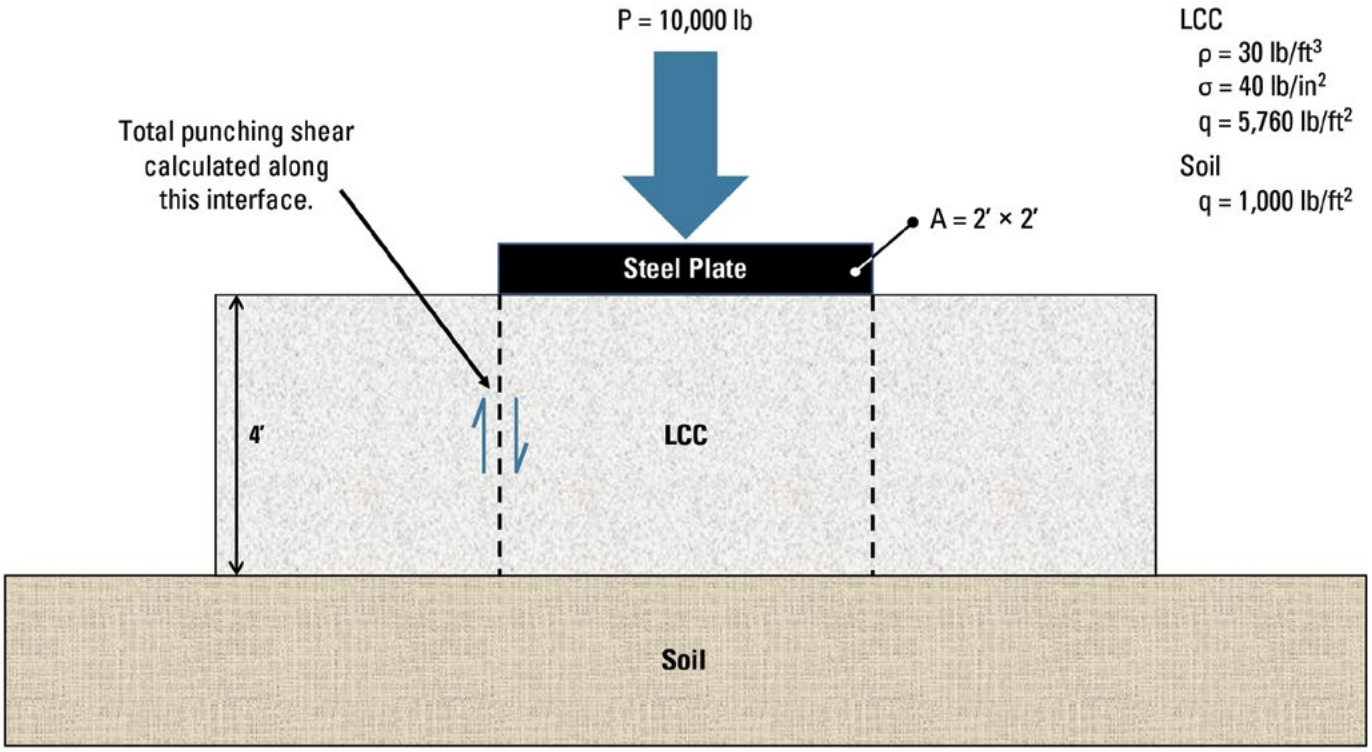
When LCC is used in a bearing layer, the punching shear should be checked at the perimeter to ensure that the layer is thick enough to support the load in shear. For the previously discussed bearing capacity example and results, the punching shear would be calculated along the edge of the steel plate, as shown in Figure 3.3 and detailed after that.

Shear Resistance per Side: 2 ft wide by 4 ft deep = 2 ft × 4 ft = 8 ft²

Shear Resistance per Side: 0.6 m wide by 1.2 m deep = 0.6 m × 1.2 m = 0.72 m²

Total Shear Resistance: Shear Resistance per Side × 4 sides = 8 ft² × 4 = 32 ft²

Total Shear Resistance: Shear Resistance per Side × 4 sides = 0.72 m² × 4 = 2.88 m²



1 ft = 0.305 m *1 lb = 0.454 kg* *1 lb/ft³ = 16.018 kg/m³* *1 lb/in² = 0.007 MPa* *1 lb/ft² = 4.882 kg/m²*

PCA

Figure 3.3. Punching shear resistance in LCC layer

Conservatively, if the shear strength of LCC is assumed to be one-half of its compressive strength, total punching shear capacity can be determined as follows:

Total Punching Shear Capacity: Total Shear Resistance × (Compressive Strength ÷ 2) = 32 ft² × (5,760 lb/ft² ÷ 2) = 92,160 lb

Total Punching Shear Capacity: Total Shear Resistance × (Compressive Strength ÷ 2) = 2.88 m² × (28,123 kg/m² ÷ 2) = 40,497 kg

Buoyancy

One of the primary reasons LCC is used is its low density. Its density is typically far less than the density of water, and buoyancy can sometimes be a significant challenge. To account for buoyancy, the level of the worst-case water table, as well as the amount of the LCC that will be submerged, must be determined. A weight balance calculation is then performed to ensure that the weight above the LCC fill is enough to overcome any buoyancy effects. This is typically performed over a 1 ft² (or 1 m²) column for simple calculations.

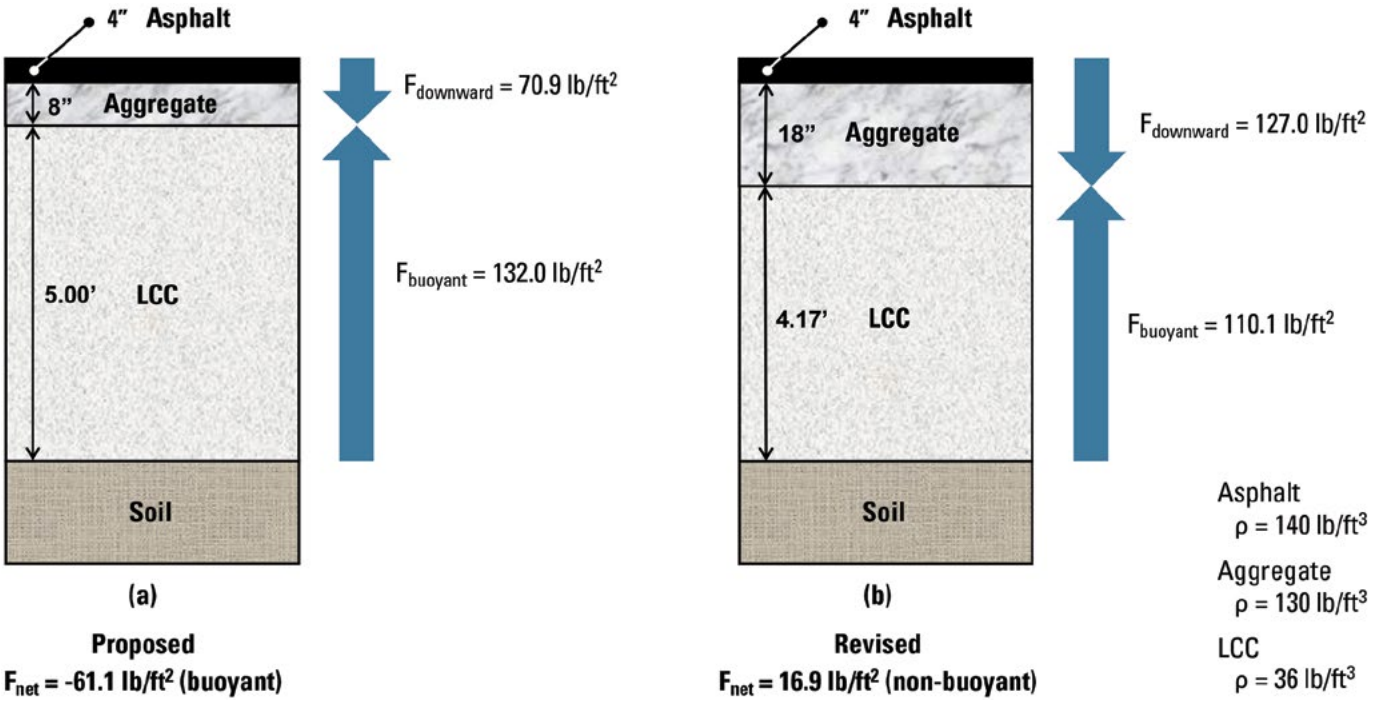
The buoyant force that a submerged section of LCC will experience is calculated based on a worst-case scenario using the LCC's cast density. The buoyant force for a single cubic foot (or cubic meter) is calculated by subtracting the density of the LCC from the density of water. For example, the buoyant force on a submerged 36 lb/ft³ (577 kg/m³) LCC fill is determined as follows:

Buoyant Force: density of water – density of LCC = 62.4 lb/ft³ – 36 lb/ft³ = 26.4 lb/ft³

Buoyant Force: density of water – density of LCC = 1,000 kg/m³ – 577 kg/m³ = 423 kg/m³

The submerged LCC fill is summarized to provide a total uplifting force, and the weight above the water table is also summarized to provide the restraining force. The net buoyancy is then calculated by subtracting the total upward force from the total downward force to provide a positive or negative result. If the upward force is greater than the downward force, the overall mass of the LCC could float out of the ground and the design would need to be revised. The FOS is calculated by dividing the downward force by the upward force.

Example: A 5 ft (1.5 m) thick section of 36 lb/ft³ (577 kg/m³) LCC is to be placed directly beneath a proposed residential pavement section of 4 in. (100 mm) of asphalt with a density of 140 lb/ft³ (2,243 kg/m³) over 8 in. (200 mm) of aggregate base with a density of 130 lb/ft³ (2,082 kg/m³) (see Figure 3.4 (a)).



1 in. = 25.4 mm *1 ft = 0.305 m* *1 lb/ft³ = 16.018 kg/m³* *1 lb/ft² = 4.882 kg/m²*

PCA

Figure 3.4. Buoyancy considerations in an LCC layer

The area is known to flood, so the worst-case water table is at the surface. The buoyant condition is determined as follows:

Buoyant Force: 5 ft × (density of water – density of LCC) = 5 ft × (62.4 lb/ft³ – 36 lb/ft³) = 5 ft × 26.4 lb/ft³ = 132.0 lb/ft²

Buoyant Force: 1.5 m × (density of water – density of LCC) = 1.5 m × (1,000 kg/m³ – 577 kg/m³) = 1.5 m × 423 kg/m³ = 634.5 kg/m²

In this example, the pavement section is also submerged, so its submerged density is included by subtracting the weight of the water from the section's in-place density, as follows:

Downward Force: [(4 in. ÷ (12 in./ft)) × (density of asphalt – density of water)] + [(8 in. ÷ (12 in./ft)) × (density of aggregate – density of water)] = [0.33 ft × (140 lb/ft³ – 62.4 lb/ft³)] + [0.67 ft × (130 lb/ft³ – 62.4 lb/ft³)] = (0.33 ft × 77.6 lb/ft³) + (0.67 ft × 67.6 lb/ft³) = 25.6 lb/ft² + 45.3 lb/ft² = 70.9 lb/ft²

Downward Force: [(100 mm ÷ (1,000 mm/m)) × (density of asphalt – density of water)] + [(200 mm ÷ (1,000 mm/m)) × (density of aggregate – density of water)] = [0.1 m × (2,243 kg/m³ – 1,000 kg/m³)] + [0.2 m × (2,082 kg/m³ – 1,000 kg/m³)] = (0.1 m × 1,243 kg/m³) + (0.2 m × 1,082 kg/m³) = 124.3 kg/m² + 216.4 kg/m² = 340.7 kg/m²

This results in a buoyant condition because the upward force of 132.0 lb/ft² (634.5 kg/m²) is greater than the downward force of 70.9 lb/ft² (340.7 kg/m²). In order to keep the final roadway elevation constant and avoid the expensive excavation of any in-place soil, the thicknesses of the LCC and aggregate base layers are adjusted. The revised pavement section will have 4.17 ft (1.27 m) of LCC and 18 in. (457 mm) of aggregate base (see Figure 3.4 (b)). A revised buoyant force is calculated as follows:

Revised Buoyant Force: 4.17 ft × (density of water – density of LCC) = 4.17 ft × (62.4 lb/ft³ – 36 lb/ft³) = 4.17 ft × 26.4 lb/ft³ = 110.1 lb/ft²

Revised Buoyant Force: 1.27 m × (density of water – density of LCC) = 1.27 m × (1,000 kg/m³ – 577 kg/m³) = 1.27 m × 423 kg/m³ = 537.2 kg/m²

Likewise, a new buoyant condition is calculated as follows:

Revised Downward Force: [(4 in. ÷ (12 in./ft)) × (density of asphalt – density of water)] + [(18 in. ÷ (12 in./ft)) × (density of aggregate – density of water)] = [0.33 ft × (140 lb/ft³ – 62.4 lb/ft³)] + [1.50 ft × (130 lb/ft³ – 62.4 lb/ft³)] = (0.33 ft × 77.6 lb/ft³) + (1.50 ft × 67.6 lb/ft³) = 25.6 lb/ft² + 101.4 lb/ft² = 127.0 lb/ft²

Revised Downward Force: [(100 mm ÷ (1,000 mm/m)) × (density of asphalt – density of water)] + [(457 mm ÷ (1,000 mm/m)) × (density of aggregate – density of water)] = [0.1 m × (2,243 kg/m³ – 1,000 kg/m³)] + [0.46 m × (2,082 kg/m³ – 1,000 kg/m³)] = (0.1 m × 1,243 kg/m³) + (0.46 m × 1,082 kg/m³) = 124.3 kg/m² + 497.7 kg/m² = 622.0 kg/m²

The adjustment of the LCC and aggregate base layers overcomes the buoyant condition because the revised upward force of 110.1 lb/ft² (537.2 kg/m²) is now less than the revised downward force of 127.0 lb/ft² (622.0 kg/m²). The FOS in a flood condition can now be determined as follows:

FOS: downward force ÷ upward force = 127.0 lb/ft² ÷ 110.1 lb/ft² = 1.15

FOS: downward force ÷ upward force = 622.0 kg/m² ÷ 537.2 kg/m² = 1.16

A FOS of 1.15 or greater is typically an acceptable value for this type of situation.

Pavement Bases and Subbases

LCC, with its many variations, makes an excellent pavement base and subbase material and should be considered by pavement designers. As previously mentioned, even though it is lightweight, LCC has a high load-bearing capacity that is typically stronger than that of soils or compacted fills. When placed within a pavement structure, LCC results in a significantly stiffer layer that is nonexpansive, nonerodible, and not prone to settlement.

Retaining Wall Backfill Soil Pressures

LCC is placed in its final location as a fluid material that then hardens and sets over the following 8 to 12 hours. During this set period, any formwork or retaining walls must support the entire hydrostatic force of the fluid LCC.

While LCC is light, its horizontal pressure is not reduced, as it is in backfill soil, when it is fully liquid. For example, a 2.0 ft (0.61 m), 30 lb/ft³ (481 kg/m³) cast density LCC would exert a 60 lb/ft² (293 kg/m²) equivalent fluid pressure on the back of a wall. This is just a little below the long-term design load for many soils when designing for active force.

This force may be reduced by limiting the lift height of the LCC placements. It is important to understand that a day after its placement, the LCC has completely solidified and is no longer exerting any fluid pressure against the formwork or wall. In applications where LCC is placed behind precast walls, temporary bracing is required. Long-term anchorage of the walls should be determined using resistance based on full-scale pull-out testing. Any anchor material must be compatible with the LCC for its design service life.

There is more to designing LCC as a backfill than just determining the liquid hydrostatic pressure; there is also the soil pressure next to the LCC, as the LCC is not thick enough to restrain the soil and water movement. When designing a retaining structure with LCC backfill, a designer should evaluate the loads from the LCC layer along with any loads applied to the LCC layer from the soil behind it. A standard practice to eliminate or reduce this force is to slope the soil interface that is to be buried at an angle determined to be stable. LCC can then be placed on the slope (preferably in steps), thereby creating a zero lateral load condition.

Drainage

Given that LCC must be protected from traffic and weathering, appropriate drainage should be provided for LCC fills even though it has low permeability and can easily shed water. When LCC is placed behind precast walls, vertical drainage with weep holes or other continuous pathways to grade are necessary to prevent excessive hydraulic pressure against the walls. Additionally, weep holes or other discharge must flow away from traffic areas.

Chapter 4. Mixture Design

LCC consists of portland cement, water, and air (added through a preformed foaming agent). Additional ingredients may be incorporated into the mixture if they do not adversely affect the quality, size, and distribution of the air matrices. Some common examples include fly ash, slag cement, silica fume, fibers, accelerators, retarders, and other cement modifiers. While LCC mixes are usually designed by LCC installers, this guide describes how to create a simple mix design to achieve the correct density at a known w/c ratio. All ingredients and additives should be tested for their compatibility with the LCC mix and their effects on the fresh and hardened properties of the LCC before being utilized on a project.

Ingredients

Portland Cement

All types of portland cement are acceptable in LCC. ASTM C150, Standard Specification for Portland Cement, describes the portland cement types, as listed in Table 4.1.

Blended hydraulic cements, produced by intimately and uniformly intergrinding or blending two or more types of fine materials, can also be used in LCC. ASTM C595, Standard Specification for Blended Hydraulic Cements, recognizes four primary classes of blended cements, as listed in Table 4.2.

Additionally, in light of the interest in the industry for performance-based specifications, ASTM C1157, Standard Performance Specification for Hydraulic Cement, describes cements by their performance attributes, as listed in Table 4.3.

Different types of portland cement are manufactured to meet various physical and chemical requirements for specific purposes (Kosmatka and Wilson 2016), and it is recommended to check local availability and project compatibility.

Table 4.1. Portland cement types

Cement type	Description
Type I	Normal
Type II	Moderate sulfate resistance
Type II (MH)	Moderate heat of hydration/ Moderate sulfate resistance
Type III	High early strength
Type IV	Low heat of hydration
Type V	High sulfate resistance

Source: ASTM C150, Standard Specification for Portland Cement

Table 4.2. Blended hydraulic cement types

Cement type	Description
Type IS	Portland–blast furnace slag cement (up to 95% slag permitted)
Type IP	Portland-pozzolan cement (up to 40% pozzolan [fly ash] permitted)
Type IL	Portland-limestone cement (up to 15% limestone permitted)
Type IT	Ternary blended cement (portland cement plus two additional cementitious materials)

Source: ASTM C595, Standard Specification for Blended Hydraulic Cements

Table 4.3. Hydraulic cement performance attributes

Cement type	Description
Type GU	General use
Type HE	High early strength
Type MS	Moderate sulfate resistance
Type HS	High sulfate resistance
Type MH	Moderate heat of hydration
Type LH	Low heat of hydration

Source: ASTM C1157, Standard Performance Specification for Hydraulic Cement

Water

In an LCC mix, water is mixed with the cement to form a slurry, and water is also mixed with a foaming agent to create the preformed foam. Clean, potable water is important for the function of foam creation. Water quality should meet the requirements of ASTM C1602, Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete. Nonpotable water may be used; however, it is recommended that the mix design be prepared in the laboratory with actual samples of the site water prior to starting the project. Deleterious constituents in water could cause the material to fail and the final mixture to collapse.

Air

The air requirement from the air compressor comprises most of the volume within any LCC mix design. The temperature of the air may affect the cure rates, and any contaminants in the air can cause failure of the foaming agent. A change in the temperature of the trapped air in the voids during the exothermic curing reaction has been known to expand the mixture.

While naturally available air is typically used and little can be done to alter the atmosphere, it is important to understand that the properties, temperature, and cleanliness of this ingredient are important to the success of any LCC mixture. Contamination from air compressors with excessive oil can also cause density variations in the LCC.

Foaming Agents

Foaming agents, or foam concentrates, are chemically formulated to produce and maintain stable air voids within the final LCC product. Most common proprietary formulations of foaming agents contain protein hydrozylates or synthetic surfactants (ACI 2006). Commercially available foaming agents should meet the requirements of ASTM C869, Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete.

The foaming agent and mix design should be tested prior to use to ensure that the required properties are obtained. It is advisable to coordinate with the foaming agent manufacturer to ensure the appropriate properties are obtained for project success.

Water/Cement Ratio

The w/c ratio is the weight of water in the batch divided by the weight of cement in the batch. Any consistent unit of weight will work, such as pounds or kilograms. The higher the w/c ratio, the more fluid the mixture and the lower the strength. Conversely, the lower the w/c ratio, the stronger and thicker the mix.

LCC is typically mixed with a w/c ratio between 0.45 and 0.80, as specified per the foam manufacturer's recommendations. A w/c ratio that is too high can cause segregation and excess bleed water. The weight of water in an LCC mix is derived from all sources, including mixing water, foam water, moisture content of aggregates (if used), and inactive portions of admixtures.

Mix Design Example (Trial and Error Procedure)

Typically performed by the contractor, one approach for the creation of an LCC mix design involves a repetitive process that may require several iterations to obtain the correct quantities of ingredients. The process starts with known constants of target density and w/c ratio, which are typically provided in the project specifications or engineering drawings or by the design engineer, who in many cases is the geotechnical engineer.

While the density of LCC can be varied by adjusting any of the ingredients, for the density to remain at the target density, the increase of one ingredient will require the reduction of another to compensate. Given that these ingredients have different densities, the mix design rapidly changes with the increase or reduction of one ingredient, while the target density never varies and is considered constant. It is the ratios of the components that change as the mix design is modified to achieve the target density.

Before an LCC mix design is specified, all of the design criteria must be known. These include the mix design density, the w/c ratio, and the specific gravity (SG) or densities of all the different ingredients.

For mix design purposes, water is commonly understood to have a density of 62.4 lb/ft³ (1,000 kg/m³) with an SG value of 1.0 depending on its temperature and purity. The production of portland cement is tightly controlled, with consistent mix design densities of 196.5 lb/ft³ (3,148 kg/m³) and with a commonly accepted SG value of 3.15. The density of the preformed foam should be provided by the foam manufacturer and may vary from 2 to 4 lb/ft³ (32 to 64 kg/m³) with a SG value between .032 and .064. Preformed foam should always be produced according to the manufacturer's recommendations.

As noted in Chapter 2, the air content in a typical 30 lb/ft³ (481 kg/m³) LCC sample is in the range of 70% to 75%. Because most of the weight within any LCC mixture is essentially the water and cement, their quantities approximate the target density and account for the remaining 25% to 30% of the total volume.

While the following example mix design was developed to demonstrate how the iterative process works, several LCC mix design calculators are available, as well as simple spreadsheets that can be developed to perform the calculations much more quickly and accurately. If a design calculator is used, it is recommended to double-check the density and volume of the mix using the equations provided in this guide to ensure that the resulting answers are accurate.

Example:

- Target density* = 30 lb/ft³ (481 kg/m³)
- W/c ratio* = 0.55
- Total volume = 1.0 ft³ (1.0 m³)
- Portland cement SG = 3.15
- Foaming agent density** = 3 lb/ft³ (48 kg/m³)
- Foaming agent SG** = 0.048
- Water SG = 1.0
- Water density = 62.4 lb/ft³ (1,000 kg/m³)

* Provided in contract documents, specifications, drawings, or by LCC installer

** Provided by foaming agent manufacturer

The first step is to establish initial trial batch weights for the cement and water ingredients. As was noted, because the majority of the weight of an LCC mix is cement and water, their quantities approximate those used in establishing the target density. The target density in this example is 30 lb/ft³ (481 kg/m³), so the starting point for determining the cement and water weights will be established at 30 lb (481 kg).

Cement (lb) = Target Density (lb/ft³) ÷ (1 ft³ + w/c)
Cement (kg) = Target Density (kg/m³) ÷ (1 m³ + w/c) **(6)**

Water (lb) = Cement and Water Slurry (lb) – Cement (lb)
Water (kg) = Cement and Water Slurry (kg) – Cement (kg) **(7)**

Ingredient Volume = Ingredient Batch Weight ÷ (Ingredient SG × Water Unit Weight) **(8)**

Using Equations 6 and 7, the initial cement and water weights are as follows:

Cement (lb): 30 lb/ft³ ÷ (1 ft³ + 0.55) = 19.35 lb
Cement (kg): 481 kg/m³ ÷ (1 m³ + 0.55) = 310 kg

Water (lb): 30 lb – 19.35 lb = 10.65 lb
Water (kg): 481 kg – 310 kg = 171 kg

Given that the foaming agent used in this mix design example has a density of 3 lb/ft³ (48 kg/m³) and accounts for approximately 70% to 75% of the total volume, its initial batch weight can be determined as follows:

Foaming Agent (lb): 3 lb/ft³ × 0.75 ft³ = 2.25 lb
Foaming Agent (kg): 48 kg/m³ × 0.75 m³ = 36 kg

With the initial trial batch weights established for the three ingredients, the volumes that they make up can be calculated using Equation 8.

The resulting ingredient volumes for the initial trial batch weights are as follows:

Volume of Cement: 19.35 lb ÷ (3.15 × 62.4 lb/ft³) = 0.098 ft³
Volume of Cement: 310 kg ÷ (3.15 × 1,000 kg/m³) = 0.098 m³

Volume of Water: 10.65 lb ÷ (1.0 × 62.4 lb/ft³) = 0.171 ft³
Volume of Water: 171 kg ÷ (1.0 × 1,000 kg/m³) = 0.171 m³

Volume of Foam: 2.25 lb ÷ (0.048 × 62.4 lb/ft³) = 0.75 ft³

Volume of Foam: 36 kg ÷ (0.048 × 1,000 kg/m³) = 0.75 m³

Total Volume: 0.098 ft³ + 0.171 ft³ + 0.75 ft³ = 1.019 ft³

Total Volume: 0.098 m³ + 0.171 m³ + 0.75 m³ = 1.019 m³

While the volumes of both the foaming agent and the cement and water slurry are within the desired ranges after this first iteration, the total weight of the mix, 32.25 lb (517 kg), is above the target of 30 lb (481 kg), and the total volume, 1.019 ft³ (1.019 m³), is slightly above the target of 1 ft³ (1 m³). The addition of the foaming agent pushed the weight higher than desired. If the weights are simply lowered, the total volume will no longer be correct. A downward adjustment must be made to the initial cement and water slurry target weight to accommodate and hold steady the weight of the foaming agent.

By simply adjusting these three weights and holding the w/c ratio constant, additional iterations can be performed to accurately obtain the desired LCC mix design parameters. A second iteration where the weight of the cement is proportionally lowered by 1.0 lb (16 kg), which also results in a corresponding reduction in water, results in the following:

Volume of Cement: 18.35 lb ÷ (3.15 × 62.4 lb/ft³) = 0.093 ft³

Volume of Cement: 294 kg ÷ (3.15 × 1,000 kg/m³) = 0.093 m³

Volume of Water: (Weight of Cement (lb) × w/c) ÷ (1.0 × 62.4 lb/ft³) = (10.09 lb ÷ 62.4 lb/ft³) = 0.162 ft³

Volume of Water: (Weight of Cement (kg) × w/c) ÷ (1.0 × 1,000 kg/m³) = (162 kg ÷ 1,000 kg/m³) = 0.162 m³

Volume of Foam: 2.25 lb ÷ (0.048 × 62.4 lb/ft³) = 0.75 ft³

Volume of Foam: 36 kg ÷ (0.048 × 1,000 kg/m³) = 0.75 m³

Total Weight: 18.35 lb + 10.09 lb + 2.25 lb = 30.69 lb

Total Weight: 294 kg + 162 kg + 36 kg = 492 kg

Total Volume: 0.093 ft³ + 0.162 ft³ + 0.75 ft³ = 1.005 ft³

Total Volume: 0.093 m³ + 0.162 m³ + 0.75 m³ = 1.005 m³

After the second iteration, while the values are more in line with what is desired, the total weight and total volume are still slightly elevated compared to the target values. Performing a third iteration, where the cement weight is proportionally lowered by an additional 0.45 lb (7 kg) and its corresponding water weight is also lowered, results in the following:

Volume of Cement: 17.90 lb ÷ (3.15 × 62.4 lb/ft³) = 0.091 ft³

Volume of Cement: 287 kg ÷ (3.15 × 1,000 kg/m³) = 0.091 m³

Volume of Water: (Weight of Cement (lb) × w/c) ÷ (1.0 × 62.4 lb/ft³) = 9.85 lb ÷ 62.4 lb/ft³ = 0.158 ft³

Volume of Water: (Weight of Cement (kg) × w/c) ÷ (1.0 × 1,000 kg/m³) = 158 kg ÷ 1,000 kg/m³ = 0.158 m³

Volume of Foam: 2.25 lb ÷ (0.048 × 62.4 lb/ft³) = 0.75 ft³

Volume of Foam: 36 kg ÷ (0.048 × 1,000 kg/m³) = 0.75 m³

Total Weight: 17.90 lb + 9.85 lb + 2.25 lb = 30.00 lb

Total Weight: 287 kg + 158 kg + 36 kg = 481 kg

Total Volume: 0.091 ft³ + 0.158 ft³ + 0.75 ft³ = 0.999 ft³

Total Volume: 0.091 m³ + 0.158 m³ + 0.75 m³ = 0.999 m³

After this third iteration, all of the values—cement and water percentage, foaming agent percentage, total weight, total volume, target density, and w/c ratio—are as close as desired to the design requirements. These are the values that should be used for this mix design.

Laboratory Sample Preparation

Using the material quantities obtained from the mix design technique discussed above, laboratory samples should be prepared using approved and suitable equipment. The preparation of material to sample must result in a mix that is as close as possible to the actual mix design intended to be used in the field. If this is not possible, a smaller sample may be prepared and the mix approximated. The energy imparted into the LCC mixture impacts the final properties of the samples and explains why laboratory-prepared samples are only approximations of the samples tested in the field.

The mixture of the three ingredients is just as challenging to correctly incorporate as it is to accurately calculate, especially for small samples. The difficulty is in measuring the foam component, which is too light to weigh accurately. The simplest way is to create a container of a known quantity, such as a 5 gal (19 l) bucket.

First, determine the absolute volume of the bucket to a known level. For example, fill it with exactly 5 gal (19 l) of water and mark the level. Then, adjust the mix design down to the ratio of the 5 gal (19 l) to that for 1 yd^3 or 1 m^3. Using this container size, 5 gal (19 l) equals 0.67 ft^3 (0.019 m^3). This means that the ratio would be 0.67 ft^3 ÷ 27 ft^3, or 0.0248 yd^3 (0.019 m^3 ÷ 1 m^3, or 0.019 m^3). By multiplying each of the three ingredients by 0.0248 (0.019 metric), the mix design proportions are determined for the 5 gal (19 l) batch.

As previously mentioned, the challenge for small batches lies in determining the correct amount of foam. The following steps can be used to provide the correct foam amount for the test batch with a fair degree of accuracy:

- Use a mixing container of known volume
- Determine the ingredients ratio and individual quantities
- Add the determined portion of water to container
- Thoroughly add and mix the determined portion of cement into the container with the water (being careful not to overmix, as additional mixing energy will change the results)
- Create foam per the manufacturer's instructions using a foam generator (Figure 4.1)
- Add the determined portion of foam into the container with the water and cement while mixing until the container is filled to the known volume
- Verify the exact quantity of the foam incorporated and add more if the mixed sample is below the anticipated level

Aerix Industries, used with permission

Figure 4.1. Preformed foam generator

Once the determined quantities of cement, water, and foam are blended together, weigh the full container, subtract the tare weight of the empty container, and calculate the final density of the mixture. The prepared LCC mixture should now be placed in sample containers for testing and curing.

Laboratory testing can be performed by any qualified testing facility; however, the facility must follow the procedures in ASTM C495 in order to provide repetitive and optimum test results. Concrete laboratories are often employed to perform these tests and should be alerted to the fact that standard equipment is not sensitive enough and that the procedures in ASTM C495 differ from those for conventional concrete.

Chapter 5. Construction

This chapter describes the methods, equipment, and operations for a generic LCC fill project. It begins with an overview of the specifications and appropriate field conditions, highlights common construction considerations, and then discusses the methods and equipment employed. These methods vary dramatically depending on region, installer, and time of construction and should always be verified by the specific local installer.

Specifications

Standard specifications for LCC vary widely across the country, with many agencies relying on the expertise of project engineers and LCC installers to understand the materials and prepare appropriate requirements for a particular project. Several agencies have prepared formal standardized construction specifications or special provisions for their states, including California, Florida, Illinois, Iowa, New York, and Texas. In many instances, these requirements for LCC are listed under construction details for flowable fill or CLSM. A suggested set of specifications that could be used for many LCC fill projects and adjusted as necessary is included in the appendix to this guide.

Property Requirements

A common challenge for LCC installers is to ensure that the appropriate material property requirements are included in the project specifications. It is imperative that a design professional matches the desired properties with the correct LCC density. For example, it is unlikely that LCC with a maximum density of 30 lb/ft³ (481 kg/m³) will have a high minimum strength of 1,000 lb/in² (6.89 MPa).

It is recommended that specifications be written to require a certain range of LCC as shown previously in Table 2.1, which provides typical properties for standard ranges of LCC and should be used as a guide. Otherwise, the specifier must work with the local LCC installer to ascertain the blend of density, strength, and possibly other properties to achieve the project goals.

Subgrade and Subbase Preparation

Subgrade and subbase preparation are dependent upon the loads to be applied and the depth of LCC placed. Base materials should always be prepared in accordance with the project requirements (see Figure 5.1).

Throop Lightweight Fill, used with permission

Figure 5.1. Prepared subgrade awaiting LCC placement

The project engineer should consider the layer of LCC as a rigid base material that allows for the spreading of loads over defined areas. LCC is not a flexible base material, and overloading it can result in failure. Occasionally, soft subgrade conditions do not allow for the specified compaction to occur. In such cases, a geotechnical engineer should evaluate the loads designed to be applied to the layer of LCC and the stresses applied to the subgrade/subbase interface at the bottom of the LCC.

Unlike a flexible base material, loads through LCC are spread over a large area, consequently reducing the stresses at the subgrade/subbase interface. At a minimum, the engineer should check the punching shear at point loads and the load distribution from uniform loads as it travels through the LCC mass.

Excessive stresses at the subgrade/subbase interface can occur when site soil is excavated and the bottom is in peat, mud, or similar extremely soft soils where compaction of the bottom is not possible. In these situations, the geotechnical engineer may allow the bottom of the fill to remain in its undisturbed natural state and place the LCC directly over the natural subgrade. Geotextiles can be placed to bridge softer areas that may cause differential settlement. The excavation should be performed with extra care to avoid disturbing the soil that remains.

Field Observations

When observing the placement of LCC on a project, many factors should be noted. Both contractor and project personnel present on site should be trained and able to observe the following aspects of the project to determine whether the material is being produced and placed properly:

- Metered cement content or flow rate
- Metered water content or flow rate
- Density of cement and water slurry
- Density of preformed foam
- Density of final product
- Pumping distance
- Metered pumping pressure
- Time required to fill the area
- Material segregation in the placement
- Depth of daily placement
- Drainage that might lead to buoyancy
- Excessively hot or cold temperatures
- Lumps of cement in mix
- Leakage in the formwork
- Excessively high cure heat
- Location of any bleed water after curing

While many other items may be observed, this list covers most of the potential issues that may arise from an LCC placement operation.

Reinforcement

LCC is a low-strength concrete product and can be reinforced similarly to other concrete products. Reinforcing may consist of steel or other low-strain products, provided they are not damaged or altered during placement and curing of the LCC (see Figure 5.2).

Reinforcing will have negligible bonding at its surfaces. It is imperative that reinforcing be calculated based on a pull-out strength with proper safety factors on the designed unconfined compressive strength. Pull-out strength is determined by pulling the installed reinforcement through the hardened LCC. The unconfined compressive strength of the LCC can be measured by calculating the force required to pull out the reinforcement. Ultimately, the failure mechanism will be the crushing of the LCC in front of the reinforcing members.

California Nevada Cement Association, used with permission

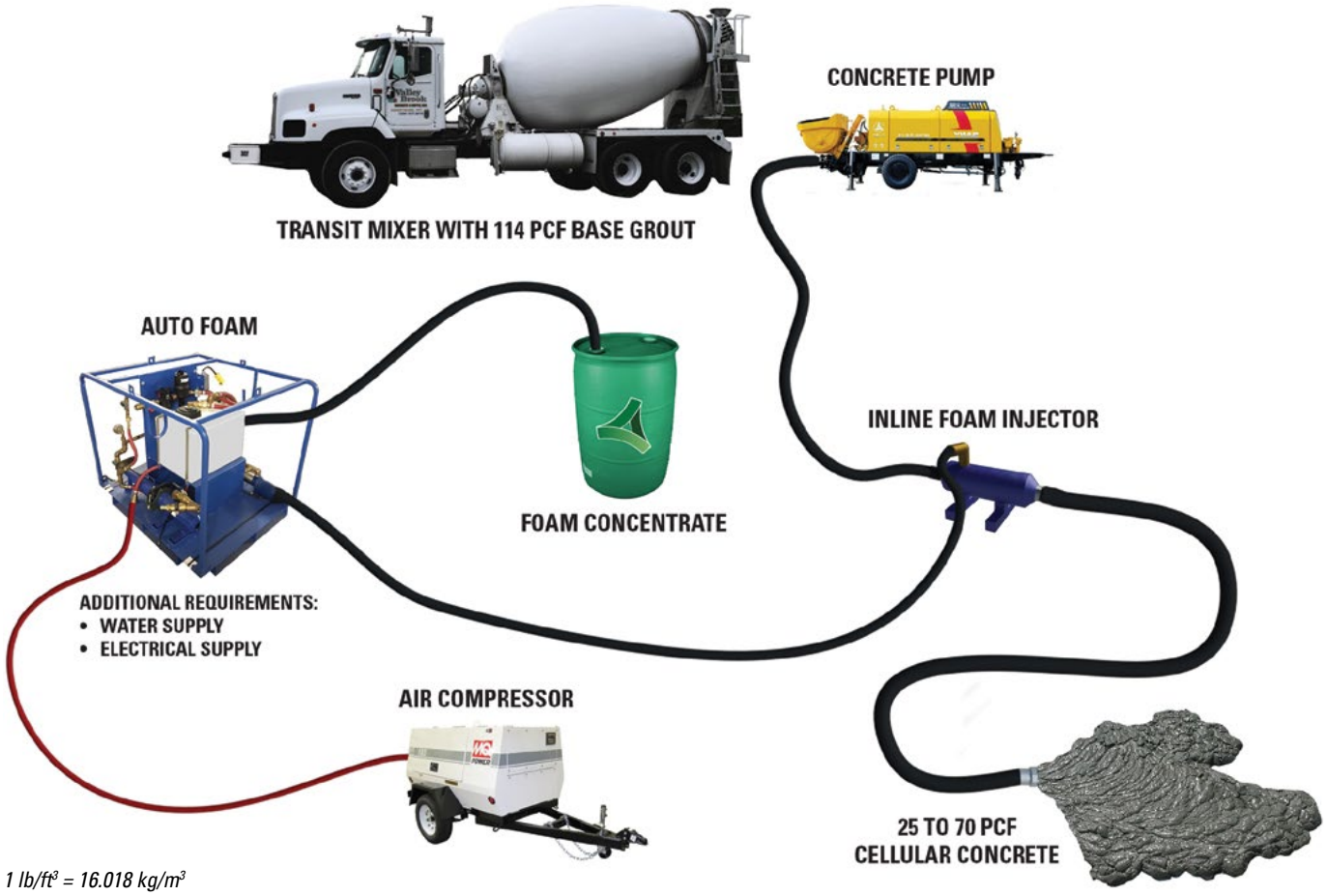
Figure 5.2. Welded wire mesh in an LCC placement

Galvanized welded wire mesh is readily available and recommended for reinforcing material given that each strongly welded intersection of the wire mesh would need to be pulled through the LCC in order for the LCC to fail in resistance to shearing action. Geogrids perform in a similar manner but must be confirmed as acceptable in the extremely high pH environment of the LCC.

Fibers are often used in LCC masses to increase their shear strength. Any fiber that can handle the curing heat and high pH is suitable for this application. Strength gains should be tested prior to application. Both fiber and LCC foam manufacturers should be consulted regarding product compatibility.

Transportation

While delivery of the cement and water slurry to a jobsite is routinely performed, transportation of premixed LCC should always be avoided. Vibrations from movement may displace the entrained air and alter the density of the final product. Prolonged periods of LCC in a ready-mixed concrete truck may also cause the properties to change, and LCC in such situations should be closely monitored prior to placement.



1 lb/ft³ = 16.018 kg/m³

Aerix Industries, used with permission

Figure 5.3. How foam is introduced into a ready-mixed concrete truck-based pumping system

Placement and Consolidation

LCC is typically placed in its final location using a pump and hose (see Figure 5.3).

The LCC is fluid enough to self-consolidate with no vibration required. LCC should not be allowed to set and then be remixed but should instead be kept plastic until allowed to set in its final location. LCC can separate and shear when moved after its curing has started.

Individual fill areas should be contained to allow the installer to maintain a well-mixed fill that is finished in approximately two to four hours before moving on to another location. Installers can limit any segregation or shearing by regularly intermixing the fill with the material coming out of the hose.

It is also important to consider buoyancy on LCC layers placed below grade, given that the LCC could float up after excessive rain events. Any objects encased in the fill should be anchored to prevent movement from flow or buoyant forces.

Finishing

LCC is typically a subsurface product and finishing is not necessary. The surface of a hose-placed layer of LCC will be relatively flat with a slight splatter pattern (see Figure 5.4).

A finished surface can be provided but takes practice. If a smooth and flat surface is desired, additional effort is required to create screeds and provide labor for finishing. Creating a smooth and flat finish on a large fill is challenging given that the LCC continues to move slightly during the finishing process. When a sloped finish is desired, a grade of up to 3% is possible. Each lift under the final lift does not need to be sloped to achieve the final grade.

Surface Finishes

Surface finishes over the top of LCC can be placed at any time once the LCC has achieved the majority of its design strength, typically in as little as three to seven days.

Throop Lightweight Fill, used with permission

Figure 5.4. Surface of in-place LCC fill

Conventional concrete surface courses may be placed earlier if care is taken not to damage the surface of the LCC. Asphalt base and surface courses may take a little longer to place due to the weight of the compaction rollers needed for consolidation. In addition, vibratory rollers should only be used with caution when compacting asphalt on top of LCC, given that the impact action of the equipment could damage the underlying LCC layer.

Curing and Protection

Given that LCC is not a surface product, curing compounds are not necessary. While superficial cracking may occur on the surface of the LCC, it will not detrimentally affect the performance of the LCC. The best way to protect LCC is to install the surface finishes as soon as possible. Until a surface course is applied, the LCC may be covered with a properly installed and maintained durable polyethylene plastic sheet to hold in the moisture needed for curing and reduced shrinkage. If the surface smoothness or concern about LCC surface damage is critical, the LCC surface can be protected from construction traffic using cover boards or fill material.

Weather Conditions

Weather conditions should be monitored before starting the placement of LCC. If heavy rain is imminent, placement of the LCC should be delayed, while light rain will not hurt this product because it is already composed of a significant amount of water. Heavy rain can be described as that which is strong enough to cause segregation if the added water was to push the cement in the mix down and leave foam at the surface. Placement during heavy rain should be avoided and could be cause for closer evaluation and possibly replacement of the LCC layer. If damage from rain does occur, the affected top surface of the LCC may be removed down to the uncompromised LCC (with no need for complete removal or replacement) and the next casting placed on the newly exposed LCC without the need for scouring.

Immediate protection may be appropriate from extreme temperature conditions (either hot or cold). According to ACI 523 (2006), special precautions should be taken if the ambient temperature is below 32°F (0°C) or above 100°F (38°C). High heat can evaporate the water in the LCC and cause it to shrink excessively. Conversely, cold weather can inhibit the cure time and quality of the LCC placed. In both cases, covering the LCC with a layer of plastic sheeting or insulated blankets may be employed, providing these actions do not damage the surface of the LCC.

Timing

LCC placed in moderate temperatures (60°F to 80°F [16°C to 27°C]) will set and harden within about 10 to 14 hours. As a rule of thumb, construction may proceed with the next layer of material as soon as the LCC layer can be walked upon without excessive surface penetration (up to 1.0 in. [25 mm] is acceptable). The average ground pressure from human foot traffic (Terramac 2013) provides a good field indicator at approximately 16 lb/in² (0.11 MPa), which is more than sufficient to proceed on the project. In colder weather, the time range can be up to 20 hours.

Field Equipment

Field equipment for LCC varies, with most major installers developing their own proprietary machines utilizing standard components. LCC is a portland cement-based mixture, and the mixing energy (shearing) imparted to the mixture is known to affect the final properties and is the primary factor in production equipment. The two types of production systems generally used to mix the cement and water together in LCC are called batch mixing and auger mixing.

Strong Manufacturing, used with permission

Figure 5.5. Batch mixer

Throop Lightweight Fill, used with permission

Figure 5.6. Mobile volumetric mixer

Batch Mixing

Batch mixing has long been the industry practice for preparing concrete mixtures (see Figure 5.5).

This system of mixing provides all the ingredients necessary to make one batch of the product. This works for all types of concrete, including LCC, and any type of batch mixer can be used for LCC. It is important with any type of mixer, including batch mixers, that the mixing action be aggressive enough to thoroughly disperse the cement, water, and foaming agent into a homogenous mixture. The batching times should be observed to ensure that enough mixing has occurred to provide a uniform product with no cement lumps or preformed foam visible.

This system allows an installer to prepare individual batches quickly and repeatedly; therefore, the accuracy of the measurement of ingredients should be carefully monitored. Overall, this is the simplest system and provides excellent mix quality at a relatively low production rate. The LCC industry's typical batch mixing equipment produces 30 to 50 yd^3 (22.9 to 38.2 m^3) per hour and is mounted on a trailer for easy mobility.

High-Shear Batching

Among the different batch mixers on the market, many different designs and systems are available. Batch mixers that are used to impart higher mixing energy are referred to as high-shear or colloidal mixers.

This type of batch mixer can be viewed as more of a high-speed blender than a slow, deliberate mixer. The fluid portion of the batch is rapidly mixed within the container, and the cement is incorporated at high velocity. This action results in a higher strength LCC without any increase in cement content. These mixers can produce 50 to 150 yd^3 (38.2 to 114.7 m^3) per hour depending on the size of mixer, mix design, and material feed rates.

Auger Mixing/Mobile Volumetric Mixers

Auger mixing is typically performed in mobile volumetric concrete trucks and involves the use of a rotating shaft and flange (auger) to blend the ingredients (see Figure 5.6).

The auger receives the raw ingredients at one end and then spins and mixes the ingredients together as they are pushed down the auger, typically for a distance of approximately 10 ft (3.0 m). Most augers are in the range of 8 to 12 in. (200 to 300 mm) in diameter and can be used to produce LCC. The mixing energy in an auger is less than that of a batch mixer, and by the nature of an auger's continuous feed operation, additional mixing time cannot be provided. The auger system can be extremely accurate when the equipment is properly calibrated.

There are three ingredients (cement, water, and preformed foam) that must be incorporated into the mixer at the appropriate rates in order to make the specified LCC mix. The operator of the mixer and the project inspector should monitor the mixture exiting the auger for consistent properties and well-blended materials. By paying special attention to the first amounts of material exiting the machine, the operator can make flow and rate adjustments to any of the ingredients.

Volumetric mixing is a convenient and fast method for making large volumes of LCC. Production rates for these inline mixers can vary from a standard 30 yd^3 (22.9 m^3) per hour to up to 500 yd^3 (382.3 m^3) per hour for the largest of the equipment.

Richway Industries, Ltd., used with permission

Figure 5.7. Inline foam additive system

Individual installers develop their own versions of mixer and pump systems to provide LCC in their local markets. These systems are specialized to the type and quantity of LCC work being performed, as well as the installers' geographic locations. Many factors are considered when designing an LCC mobile mixer, including mix designs, production rates, cement storage, dust, drips, mix quality, cleaning, ease of use, weather, and automation. Customized or custom-made mobile systems are typically designed to utilize one of the two production systems described in this guide—batch mixing or auger mixing. In both batch mixing and auger mixing systems, the foam may be added into the mixing chamber or inline into the hose after the pump (see Figure 5.7).

Mobile mixing of any type provides the benefits of the material going directly from initial wetting into the final location immediately after production. This is beneficial for LCC given that the properties rapidly change within the first few minutes and hours after mixing.

Cement Delivery

In a mobile plant mixing operation, dry, powdered portland cement is typically delivered from a cement manufacturer to the mobile batch plant in pneumatic trucks. The dry cement is then discharged from the delivery truck into a storage container or silo located at the jobsite. A single load of 27 tons (24.5 metric tons) of delivered dry cement can be used to produce about 130 yd^3 (99.4 m^3) of 30 lb/ft^3 (481 kg/m^3) LCC. This can be verified by the mix design quantity of cement per cubic yard (cubic meter) and varies with density.

Another advantage of a mobile mixing plant is that the cement tanker truck is the only heavily loaded vehicle delivering product to the project site. Environmentally speaking, this trucking reduction lessens energy use, emissions, fossil fuel consumption, and traffic effects on roadways.

© 2018 Roberto Montemayor, used with permission

Figure 5.8. Ready-mixed concrete truck

Ready-Mixed Concrete Plants

Ready-mixed concrete plants and trucks are typically not used for completely proportioned LCC because their mixing action does not combine all of the ingredients with the correct speed and intensity (ACI 2006). However, ready-mixed concrete trucks may be used to bring just the cement and water slurry component to the project site (see Figure 5.8).

These trucks come in a large variety of types and capacities, and their mixing drums are designed with a rated maximum capacity of 63% of the gross drum volume when used as a mixer (NRMCA 2020). The reason for not filling a ready-mixed concrete truck full of cement and water slurry is that the fluid can spill out during transit. This is especially true on rough roads or when driving on steep grades to get to the jobsite.

The preformed foam is then added to the cement and water slurry in the truck on the jobsite with a foam generator provided by the LCC installer.

Pumping Devices

After LCC is produced in the mixing chambers previously described, it needs to be placed in its final location on the jobsite. When utilizing an auger-style volumetric mixer, the prepared LCC may be placed directly into the final location. For all other types of production, the LCC is typically pumped from the mixer directly onto the jobsite.

Pumping LCC can be challenging at times. It is initially fairly easy to move the lightweight material, and most any style of pump can transport it. The challenge can occur a little later when the cement paste starts to collect on the interior walls of the pumping hoses and pumping equipment and begins to solidify. Controlling the output, along with regular cleaning, will help to avoid damaging the pump and prematurely stopping production. Scheduled end-of-day cleaning should be immediate and thorough.

Pumping pressures should also be closely controlled with LCC given that the preformed foam is an ingredient for which pressure makes a difference. There has been considerable discussion on whether the air void system within the LCC is stable enough to survive pumping pressures. The preformed foam must conform to the properties listed in ASTM C869 when tested following the procedures in ASTM C796. Field monitoring should also be performed by checking the density in accordance with ASTM D6023, Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM), before and after pumping, observing any increase. An increase indicates that the LCC air voids are popping during the pumping process and that adjustments should be made.

The following sections describe the three pumping systems most commonly used for LCC: progressive cavity, peristaltic, and piston pumps. While other pumping systems are available, they typically do not lend themselves to the proper conveying of LCC from the mixer to its location on the jobsite. These other pumping systems include ball valve pumps, centrifugal pumps, and diaphragm pumps.

Whichever LCC production method and pumping equipment is chosen, the fundamental goal is for the installer to produce and place a final product that meets the specified project requirements. These requirements include the correct w/c ratio, foam meeting the manufacturer's requirements, and a specified final in-place density.

Progressive Cavity Pump

Most equipment designed for placing LCC utilizes a progressive cavity pump (see Figure 5.9).

This type of pump is extremely steady with no pulsing and keeps itself clean on the inside while operating. However, care must be taken with this type of pump to avoid dropping rocks or other solids into the hopper, given that they can stop or damage the pump. Progressive cavity pumps are relatively low pressure, with output pressures of about 100 to 300 lb/in² (0.69 to 2.07 MPa).

© 2020 Elastizell Corporation of America, used with permission

Figure 5.9. Progressive cavity pump

This is the correct range of pressure for LCC placement in most situations.

Peristaltic Pump

Peristaltic pumps, also referred to as squeeze pumps, can be used to easily transport LCC. This type of pump has the benefit of separating the cementitious materials from the pumping mechanism. This is very beneficial when pumping a sticky, solidifying mixture and dramatically lowers the cost of any needed repairs. Peristaltic pumps have been used successfully for LCC for many years and were the primary system utilized in the early years. High pressures can be obtained with this type of pump, and peristaltic pumps should therefore be closely monitored.

Piston Pump

Due to their extreme reliability and strength, piston pumps are used for moving many different types of fluids and slurries, including concrete. Piston pumps utilize a check valve and a piston retracting system, drawing in material and then pushing it out. Piston pumps for concrete that are mounted on a trailer are not commonly used in LCC construction due to the large number of surfaces that need to be cleaned and the concern about the high pressures that can be obtained.

With a piston pump system, if there is a blockage in the line, the pump can achieve extremely high pressures in a fraction of a second. This type of pump should be used with great caution because extreme pressures can often break hoses, fittings, or even a pipe in the ground being filled, causing injury or damage and creating quite a mess. LCC has also been observed leaking from broken pipes that are being filled under pressure. Injection ports are typically made from polyvinyl chloride (PVC) pipe leading into underground pipes, and these have the potential to rupture due to high pressure.

Chapter 6. Inspection, Testing, and Maintenance

LCC, as any concrete product, should be carefully observed, inspected, and controlled with the highest quality control available. Small variations in mix design can cause significant differences in the final product, leading to unacceptable materials, failures, and unexpected expenses. The following quality control guidelines will assist the engineer, inspector, and installer in inspecting and observing the placement of properly mixed LCC.

Prequalification of the installer performing the work, based on the manufacturer's approval of processes and equipment, is an important first step in the quality control process. Requirements that should be followed when performing any testing on LCC are well established, including the previously mentioned guidelines in ACI 523 (2006) and the standards in ASTM C495, C796, and C869. The following is only guidance to supplement that provided in the guidelines and standards.

© 2017 Elastizell Corporation of America, used with permission

Figure 6.1. Sampling/testing LCC in the field (Michigan)

Field Quality Control Testing

Quality control is performed by the installer and can be very complicated or relatively simple for LCC. Many installers develop automated equipment to supply high volumes of LCC. While these systems may be both efficient and complex, there is a fairly simple method to test the product, and it can be done with inexpensive tools and utilized with any system. As previously discussed in this guide, the fundamental measurements to be taken are the densities of both the cement slurry and the final placed LCC mix (see Figure 6.1).

Measuring the density of samples on the jobsite is critical because this quality control activity ensures that the mix prepared meets the design specifications of the project. The final product density is measured to ensure that the LCC is being produced to the specified density. Unfortunately, this measurement does not verify whether the correct ratio of water to cement to foam is being used. Therefore, a solitary second measurement is required to verify the density of the cement and water slurry prior to the addition of the preformed foam. If these measurements can be taken, the mix can be evaluated without looking at the mechanical function of the machine.

Cement and water are both highly consistent substances (cement mill reports are available if needed), and the expected density of the water and cement slurry can be measured in the field using Equation 9 and compared to the weight and volume data included in the mix design discussed in Chapter 4.

Because it can sometimes be difficult to adjust the cement, water, and foaming agent all at one time, it is recommended that the w/c ratio be adjusted first by measuring the cement slurry density and then adjusting if necessary until correct. The cement slurry is mixed separately to simplify the density verification. The cement and water slurry density is determined in accordance with ASTM D4380, Standard Test Method for Density of Bentonitic Slurries.

Slurry density checks should be performed regularly to ensure that the flow meters for the cement and water are properly operating. The foam is then added, and measurements of the final product density should be taken as specified. The cement slurry density is typically between 105 and 115 lb/ft³ (1,682 and 1,842 kg/m³), and a trained operator can identify by feel and by visual observation whether the mixing machine is operating in accordance with the project specifications.

In addition to making visual observations, the contractor should regularly take the following two quality assurance field measurements throughout the placement timeframe:

- Slurry density
- Final density

Slurry Density (lb) = (cement (lb) + water (lb)) ÷ (cement (ft³) + water (ft³))
Slurry Density (kg) = (cement (kg) + water (kg)) ÷ (cement (m³) + water (m³)) **(9)**

Slurry density should be tested at a minimum of every two hours. Final density testing should be performed at a minimum of every 30 minutes (and preferably more often) or anytime a change in material is observed from the machine.

This testing schedule ensures that the machine is producing the specified product. This understanding greatly simplifies the work of the project inspector when working around highly sophisticated equipment. This also saves installers from spending time and money to certify their own onboard meters and prove they are working perfectly every day. The amount of raw materials used, unit weights, field samples, and surveys of the jobsite are reliable methods of measuring the volume of LCC being placed.

The collection of LCC field samples for laboratory testing should be in accordance with the recommendations found in ASTM C495 and the project specifications.

Field Quality Control Observation

LCC should flow from the machine into the final location as a thick slurry, looking something like gray pancake batter (see Figure 6.2).

The LCC should lay relatively flat with a defined texture on the surface, typically looking like it was splattered on. Noticeable cracks or fissures should not be forming in the flowing material, as this indicates a placement area that is too large for the placement rate, a needed w/c ratio adjustment, forms that are leaking, or other issues. While cracks or fissures do not typically result in major failures, their causes should be identified and corrected if possible. These challenges can be avoided by limiting the placement time as influenced by fill geometry, mix design, weather, and site conditions.

There should not be any foamy areas at the top of the placed LCC. This may indicate segregation, which produces areas with gray foam at the top and heavy slurry at the bottom and can occur if the LCC is allowed to flow too far a distance. This can be avoided by continuously mixing the final product and limiting the size of the placement areas.

In some cases, LCC that is placed with too much or too little water or improperly made foam or mixing

Throop Lightweight Fill, used with permission

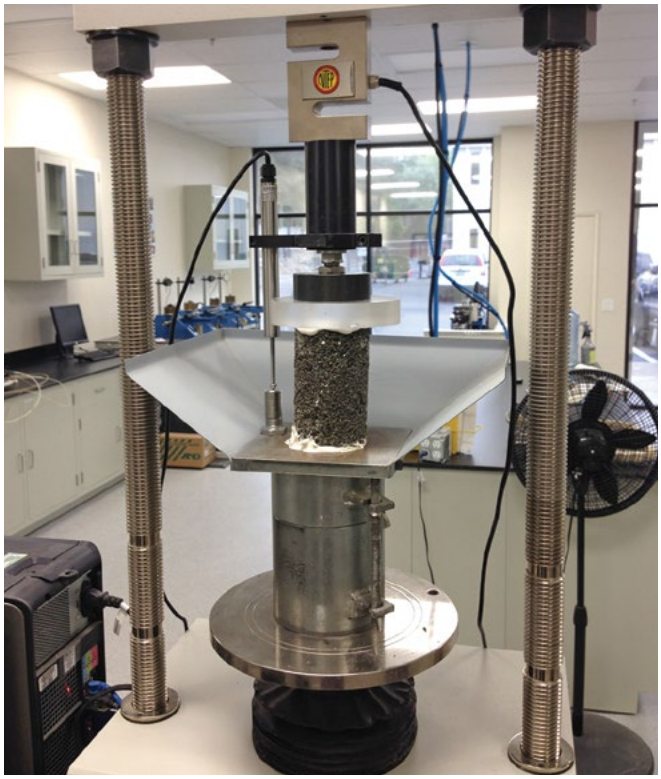
Figure 6.2. Surface of recently placed LCC

procedures may collapse after placement. A sunken surface in placed LCC indicates a collapse of the air void structure due to the material being improperly mixed or placed. It is imperative to ensure that the foam is of good quality throughout the placing operations by measuring its density. Careful observation is also important, as is understanding what the foam should and should not look like. It is important to understand that collapses do not indicate that there is a void below the surface. Collapses actually indicate that there is a higher density, stronger fill than desired, as the air has come out of the slurry.

LCC placed in single lifts exceeding 4 ft (1.2 m) can present challenges. At present, 4 ft (1.2 m) is the industry standard maximum depth; however, installers have successfully placed LCC in single lifts up to 10 ft (3.0 m) under controlled conditions.

Post-construction Inspection and Testing

LCC should be inspected the day after placement. It should be stable enough to be walked upon with limited impressions (no more than 1.0 in. [25 mm]) left on the surface, unless retarders, supplemental cementitious materials, near-freezing temperatures, or other modifications affect the setting time of the mix. The LCC could be warm, possibly steaming, from the chemical reactions (hydration) and have a relatively flat surface at the same elevation as when placed the day before. In short, if the placed LCC made it through the night (initial setting) and passed the previously stated density tests during placement, it is acceptable pending later test results.



Throop Lightweight Fill, used with permission

Figure 6.3. Unconfined compressive strength testing of LCC

Compressive Strength Testing

Post-construction testing of LCC primarily involves testing for unconfined compressive strength (see Figure 6.3).

Laboratory testing of unconfined compressive strength should carefully follow the procedures outlined in ASTM C495. Years of experience and the results of the California study (Siebold and Tootle 2016) mentioned in Chapter 2 provide strong evidence that the procedures provided in ASTM C495 provide the most accurate laboratory results and that variations, such as oven drying or improper curing, can have dramatic effects on test results. Strict standards have not been developed for other properties, and other properties should be tested with the understanding that comparing results may mean comparing significantly different procedures.

Maintenance

There is no recommended maintenance for in-place LCC material itself. The material should be protected after being placed with some form of surface layer, such as concrete, soil, subbase material, a drainage mat, etc. Excessive walking and driving directly on the LCC surface can cause damage and should be avoided.

Due to the insulative properties of LCC, a relatively high thermal differential is possible, causing surface cracking and accelerated wear if left exposed. Moisture should not be allowed to evaporate off the placed LCC too quickly, because this will cause excessive shrinkage (although in most applications, shrinkage cracks are only superficial and will not detrimentally impact the service life of the LCC). Once buried and protected, no additional maintenance is possible or necessary beyond observation of the cover material and the drainage system (if present).

References

Aldridge, D., R. K. Dhir, M. D. Newlands, and A. McCarthy. 2005. Introduction to Foamed Concrete: What, Why, How? *Proceedings of the International Conference on the Use of Foamed Concrete in Construction*, July 5, Dundee, Scotland, pp. 1–14.

ACI. 2006. *Guide for Cast-in-Place Low-Density Cellular Concrete*. ACI Report 523.1R-06. American Concrete Institute Committee 523, Farmington Hills, MI.

Bayer v. Rice. 1934. 75 F.2d 238, U.S. Court of Appeals for the District of Columbia Circuit.

Bažant, Z. P. and M. F. Kaplan. 1996. *Concrete at High Temperatures: Material Properties and Mathematical Models*. Addison-Wesley, London, England.

Briaud, J. L., R. W. James, and S. B. Hoffman. 1997. *NCHRP Synthesis 234: Settlement of Bridge Approaches (The Bump at the End of the Bridge)*. National Cooperative Highway Research Program, Washington, DC.

FAA. 2012. *Engineered Materials Arresting Systems (EMAS) for Aircraft Overruns*. Advisory Circular 150/5220-22B. Federal Aviation Administration, Washington, DC. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_150_5220-22B.pdf.

FHWA. 2017. National Bridge Inventory, Deficient Bridges by Highway System 2017. Federal Highway Administration, Washington, DC. https://www.fhwa.dot.gov/bridge/nbi/no10/defbr17.cfm.

Hoff, G. C. 1972. Porosity-Strength Considerations for Cellular Concrete. *Cement and Concrete Research*, Vol. 2, No. 1, pp. 91–100.

Jones, M. R. and A. McCarthy. 2005a. Preliminary Views on the Potential of Foamed Concrete as a Structural Material. *Magazine of Concrete Research*, Vol. 57, No. 1, pp. 21–31.

Jones, M. R. and A. McCarthy. 2005b. Behaviour and Assessment of Foamed Concrete for Fill and Highway Applications. *Proceedings of the International Conference on the Use of Foamed Concrete in Construction*, July 5, Dundee, Scotland, pp. 61–88.

Kosmatka, S. H. and M. L. Wilson. 2016. *Design and Control of Concrete Mixtures*. 16th edition. Portland Cement Association, Skokie, IL.

Maw, R. and R. Cole. 2015. *Cellular Concrete Laboratory Testing Program, Laboratory Testing Observations and Results, Fall and Winter of 2014–2015*. Technical Memorandum. Gerhart Cole Inc., Draper, UT.

McCormick, F. C. 1967. Rational Proportioning of Preformed Foam Cellular Concrete. *ACI Materials Journal*, Vol. 64, No. 2, pp. 104–110.

Mydin, M. A. O., H. Awang, and A. F. Roslan. 2012. Determination of Lightweight Foamed Concrete Thermal Properties Integrating Various Additives. *Elixir Cement and Concrete Composites*, Vol. 48, pp. 9286–9291.

Nambiar, E. K. K. and K. Ramamurthy. 2007. Sorption Characteristics of Foam Concrete. *Cement and Concrete Research*, Vol. 37, No. 9, pp. 1341–1347.

Narayanan N. and K. Ramamurthy. 2000. Microstructural Investigations on Aerated Concrete. *Cement and Concrete Research*, Vol. 30, No. 3, pp. 457–464.

NRMCA. 2020. *About Concrete*. National Ready Mixed Concrete Association, Silver Spring, MD. https://www.nrmca.org/about-nrmca/about-concrete/.

Quanji, Z. 2010. Thixotropic Behavior of Cement-Based Materials: Effect of Clay and Cement Types. MS thesis. Iowa State University, Ames, IA.

Ramamurthy K., E. K. K. Nambiar, and G. I. S. Ranjani. 2009. A Classification of Studies on Properties of Foam Concrete. *Cement and Concrete Composites*, Vol. 31, No. 6, pp. 388–396.

Siebold, D. and J. Tootle. 2016. *CNCA Cellular Concrete Testing: Unconfined Compression Testing (ASTM C495)*. ENGEO Incorporated, San Ramon, CA, to the California Nevada Cement Association, Yorba Linda, CA.

Tada, S. 1986. Material Design of Aerated Concrete – An Optimum Performance Design. *Materials and Structures*, Vol. 19, pp. 21–6.

Tarasov, A. S., E. P. Kearsley, A. S. Kolomatskiy, and H. F. Mostert. 2010. Heat Evolution Due to Cement Hydration in Foamed Concrete. *Magazine of Concrete Research*, Vol. 62, No. 12, pp. 895–906.

Terramac. 2013. What Exerts More Ground Pressure – A Human or a Crawler Carrier? *TERRAMAC NEWS*. https://www.terramac.com/news/2013/what-exerts-more-ground-pressure-a-human-or-a-crawler-carrier/.

Tiwari, B., B. Ajmera, R. Maw, R. Cole, D. Villegas, and P. Palmerson. 2017. Mechanical Properties of Lightweight Cellular Concrete for Geotechnical Applications. *Journal of Materials in Civil Engineering*, Vol. 29, No. 7, 06017007-1–06017007-7.

Tiwari, B., B. Ajmera, and D. Villegas. 2017. Dynamic Properties of Lightweight Cellular Concrete for Geotechnical Applications. *Journal of Materials in Civil Engineering*, Vol. 30, No. 2, pp. 04017271-1–04017271-10.

Appendix. Guide Specification for Construction of Lightweight Cellular Concrete Fill

January 2021

1. General Provisions

1.1 Description

Lightweight cellular concrete (LCC) shall consist of portland cement, preformed foam, possibly fly ash, slag, or chemical admixtures, and water to form a hardened material having an oven-dried density of 50 lb/ft³ (801 kg/m³) or lower. LCC shall be proportioned, mixed, and placed in accordance with this specification and shall conform to the lines, grades, thicknesses, and typical cross sections shown in the project plans or otherwise established by the engineer.

1.2 Caveat

This specification is intended to serve as a guide to the form and content for typical LCC fill construction. Most projects have features or requirements that should be incorporated into the project documents.

2. Referenced Documents

2.1 ASTM International (ASTM)

C150 Standard Specification for Portland Cement

C494 Standard Specification for Chemical Admixtures for Concrete

C495 Standard Test Method for Compressive Strength of Lightweight Insulating Concrete

C595 Standard Specification for Blended Hydraulic Cements

C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

C796 Standard Test Method for Foaming Agents for Use in Producing Cellular Concrete Using Preformed Foam

C869 Standard Specification for Foaming Agents Used in Making Preformed Foam for Cellular Concrete

C989 Standard Specification for Slag Cement for Use in Concrete and Mortars

C1017 Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete

C1157 Standard Performance Specification for Hydraulic Cement

C1602 Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete

3. Submittals

3.1 Submittal Requirements

The contractor shall submit the following to the engineer at least 30 calendar days before start of any production of LCC:

3.1.1 Certifications. Certifications for portland cement, foaming agents, supplementary cementitious materials, and chemical admixtures as required by the engineer.

3.1.2 Specifications. Manufacturers' product data and specifications for materials listed in Section 4.1 and equipment including capacities listed in Section 5 to be used in mixing and placing LCC.

3.1.3 Proposed LCC Mix Design. If the proposed mix design is developed by the contractor or a change is suggested to the mix design, it must be submitted to the engineer for approval. This mix design shall include quantities for cementitious materials, water, and preformed foam, along with expected compressive strengths and required densities.

3.1.4 Proposed Work Plan. A description of the proposed installation procedure shall address the following:

1. Proposed construction sequence and schedule
2. Locations of the material sources, equipment, and storage and batching areas
3. Type of equipment and tools to be used

4. Products

4.1 Materials

4.1.1 General. All materials to be used for LCC fill construction shall be approved by the engineer based on laboratory tests or certifications of the representative materials that will be used in the actual construction.

4.1.2 Portland Cement. The portland cement shall comply with the latest specifications for portland cement (ASTM C150) or blended hydraulic cements (ASTM C595 and ASTM C1157).

4.1.3 Foaming Agent. The foaming agent shall comply with the latest specifications (ASTM C869) when tested in accordance with ASTM C796.

4.1.4 Fly Ash. If used, fly ash shall comply with the latest specifications (ASTM C618).

4.1.5 Slag. If used, slag shall comply with the latest specifications (ASTM C989).

4.1.6 Chemical Admixtures. If used, chemical admixtures shall comply with the latest specifications (ASTM C494 and ASTM C1017) as applicable.

4.1.7 Water. Water shall comply with the latest specifications (ASTM C1602). Nonpotable water may be used; however, it is recommended that the mix design be prepared in the laboratory with actual samples of the site water prior to starting the project.

4.2 Properties

4.2.1 General. Unless otherwise approved in writing by the engineer, LCC shall meet the following properties for each class as shown in this table:

LCC class	Maximum cast density		28-day minimum compressive strength	
	lb/ft³	kg/m³	lb/in²	MPa
I	30	481	40	0.28
II	36	577	80	0.55
III	42	673	120	0.83
IV	50	801	160	1.10

5. Equipment

5.1 General

All necessary equipment shall be on hand and approved by the engineer before work will be permitted. LCC shall be constructed with any combination of equipment that will produce a final product meeting the requirements for proportioning, mixing, and placing as provided in this specification.

5.2 Mixer

Mixing equipment for the production of LCC shall be as follows:

5.2.1 Capacity. Mixing equipment shall be capable of producing LCC in the proportions defined by the final approved mix design and within the specified tolerances. The capacity of the equipment shall be sufficient to produce a uniform mixture at a rate compatible with the placing equipment.

5.2.2 Batch Plant. If used, a batch plant mixer shall be capable of producing a homogenous mixture that is uniform in color and capable of discharging its contents directly into truck agitators, truck mixers operating at agitating speed, or nonagitating trucks for transport to the jobsite. The plant mixer shall be equipped with batching equipment to meet the following requirements:

5.2.2.1 The amounts of cement, as well as fly ash, slag, and chemical admixtures, if used, entering each batch of LCC shall be measured by direct weighing equipment readily adjustable for changing the proportionate batch weights. The cement, as well as fly ash, slag, and chemical admixtures, if used, may be weighed separately or cumulatively in the same hopper on the same scale, provided the cement is weighed first.

5.2.2.2 Weigh hoppers for bulk cement and fly ash and slag, if used, shall be equipped with vibrators to operate automatically and continuously while weigh hoppers are being dumped.

5.2.2.3 The amount of water entering each batch shall be measured by weight or volume. The equipment shall be capable of measuring the water to within a tolerance of plus or minus 1% and shall be equipped with an accurate gauge or dial measuring device. During batching, water shall be admitted to the mixer only through the water measuring device.

5.2.3 Mobile Volumetric Mixer. Proportioning and mixing equipment shall be of the self-contained, mobile, continuous mixing type subject to the following:

5.2.3.1 The mixer shall be self-propelled and capable of carrying sufficient unmixed dry, bulk cement, fly ash, slag, and chemical admixtures, if used, and water to produce uniform LCC onsite.

5.2.3.2 The mixer shall be capable of accurately measuring and adjusting the cement, water, preformed foam, and any admixtures being introduced into the mix. The flow rates of all LCC components shall be recorded by a meter that is visible at all times.

5.2.3.3 The mixer shall be capable of being calibrated to proportion and blend all components of the indicated composition on a continuous or intermittent basis as required by the placing operation and to discharge the mixture without segregation.

5.2.4 Alternative Mixing Equipment. Other types of batching and mixing equipment and configurations, including dry batch plants and concrete truck mixers, may be used with the approval of the engineer. The contractor must demonstrate that the mixing equipment can produce a consistent, well-blended, nonsegregated LCC mix that meets the minimum capacity requirements of Section 5.2.1.

5.3 Foam Generator

5.3.1 The foam generator shall be approved by the foaming agent manufacturer and used to produce a predetermined quantity or flow rate of preformed foam that shall be injected into the mixer and blended with the cement and water slurry.

5.3.2 The foam generator shall be timer-controlled to repetitively discharge a preselected quantity or to continuously discharge at a steady fixed rate.

5.3.3 The foam generator shall be tested and calibrated daily for dilution percentage, density, and volume output.

5.4 Pump

LCC shall be conveyed by a positive displacement pump (progressive cavity, peristaltic, or piston) capable of handling the volume of LCC to be placed.

5.4.1 All pumps shall operate such that a continuous stream of LCC, without segregation, is conveyed promptly to the location of final placement.

5.4.2 All pumps shall be equipped with safety measures to prevent sudden excessive LCC pressure from developing.

5.4.3 Unless otherwise approved in writing by the engineer, the use of ball valve pumps, centrifugal pumps, diaphragm pumps, and other pumping devices, as well as ready-mixed concrete transit mixers, shall not be permitted for conveying prepared LCC.

5.5 Water Supply Equipment

Water supply equipment shall be of such capacity and design as to ensure an ample supply and adequate pressure simultaneously for all requirements of the machinery, the mixing, placing, and wetting site, and all other features of the work.

5.6 Inspection of Equipment

Before start-up, the contractor's equipment shall be carefully inspected. Should any of the equipment fail to properly operate, no work shall proceed until the deficiencies are corrected and approved by the engineer.

5.7 Access for Inspection and Calibration

Except for any proprietary systems, the engineer shall have access at all times to any plant, equipment, or machinery to be used on the project in order to check calibration, scales, controls, and operating adjustments.

6. Construction Requirements

6.1 Preparation of Site

Preparation of the site to receive LCC is frequently the responsibility of the excavation/grading contractor. Placement of LCC shall not proceed until satisfactory site conditions are established as shown in the plans and approved by the engineer.

6.1.1 Any items to be fully or partially encased in LCC shall be properly set and stable in their final location prior to the installation of the LCC. If a geotechnical fabric for ground stabilization or geomembrane is specified in conjunction with the LCC, it shall be in place prior to placing the LCC.

6.2 Trial Batch (Optional)

6.2.1 At least 30 calendar days before the start of the placing operations, and in the presence of the engineer, the contractor shall produce a trial batch of LCC using the approved mix design. This trial batch will allow the engineer to evaluate the density and strength of the LCC material, methods of construction, and surface conditions for the placed material. A minimum 1.0 yd^3 (0.76 m^3) trial batch shall be produced and placed offsite.

6.2.2 The equipment, materials, and techniques used to produce the trial batch shall be that which will be used to construct the main LCC fill.

6.2.3 The trial batch shall be evaluated and tested by the contractor and the engineer via split samples for as-cast density and compressive strength according to the sampling and testing requirements specified herein.

6.3 Mixing Process

6.3.1 General. Any adjustments to the mix design needed to create LCC in accordance with the project documents due to ambient conditions at the jobsite shall be approved by the engineer. If, during the mixing, there is a change in the type or source of cementitious materials, water, admixtures, or foaming agent, the mixing must be suspended, and a new mix design shall be developed and approved by the engineer.

6.3.2 Batching. Cement slurry shall be batched mechanically in a manner ensuring consistency of the mix. All solids shall be thoroughly wetted before the introduction of the preformed foam. Excessive mixing after the preformed foam has been incorporated shall be avoided in order to reduce the possibility of changes in unit weight.

6.3.3 Mixing. A foam generator meeting the requirements of Section 5.3 shall be used to produce a predetermined quantity or flow rate of the preformed foam that shall be injected into the mixer and blended with the cement slurry. The foaming agent shall be introduced per its manufacturer's recommendations using approved foam-generating equipment. All equipment shall be calibrated to produce consistent preformed foam with a stable, uniform cellular structure.

6.3.4 Daily Reports. The contractor shall supply daily records of production and quantities of materials used each day to the engineer.

6.4 Transportation

LCC shall not be transported. The cement slurry for LCC shall be conveyed promptly to the location of final placement avoiding excessive handling. Cement slurry delivery must be scheduled so that, when mixed with the preformed foam, the LCC material is placed within the specified time limits.

6.5 Placing

6.5.1 Condition of the Site. Prior to LCC placement, the surface of the site shall be clean and free of foreign material, ponded water, and frost. The site must be uniformly moist at the time of LCC placement. If sprinkling of water is required to remoisten certain areas, the method of sprinkling shall not be such that it forms mud or pools of free-standing water. Prior to placement of the LCC, the site shall be checked for proper density and soft or yielding areas, and these areas shall be corrected.

6.5.2 Formwork. Where shown on the plans, all formwork shall be designed and installed to contain the fluid LCC. Formwork may require lining with durable polyethylene plastic sheeting or a similar impermeable membrane to prevent leakage.

6.5.3 LCC shall be placed without excessive handling to prevent segregation. Intermediate lifts shall be horizontally placed, while only the top lift shall be finished to plan grade. The final surface elevation of the LCC fill shall be within ±0.1 ft (±30 mm) of the plan elevation.

6.5.4 The area of LCC placement shall be limited to the volume that can be placed within one hour, up to the maximum lift height as shown on the plans. Placements shall be staggered such that the vertical joints are at least 10 ft (3 m) apart.

6.5.5 All LCC shall be placed with a hose approved by the engineer. The discharge hose shall be periodically moved to homogenously blend the LCC being placed.

6.5.6 LCC shall not be mechanically vibrated or otherwise disturbed.

6.5.7 Construction activities on any recently placed LCC lift shall not be permitted until the LCC mix has attained the minimum compressive strength for its class as shown in Section 4.2.1 or 20 psi (0.14 MPa), whichever is less. However, if any work on the recently placed LCC results in cracking or indentations of more than 0.25 in. (6 mm), the contractor shall discontinue construction, revise their wait time, mix strength, or equipment used, and submit that to the engineer for approval.

6.5.8 Any excavation or sawing required of the LCC for installation of utilities, drains, or other conflicts shall be by methods approved by the engineer.

6.6 Weather Conditions

6.6.1 Cold Weather Precautions. LCC material shall not be placed on any surface containing frost or frozen material or when the air temperature is below, or is expected to fall below, 32°F (0°C). Protection of the LCC layer by covering with insulated blankets may be employed, provided that such action does not damage the surface of the LCC. Any LCC that is damaged by freezing shall be removed and replaced at the contractor's expense.

6.6.2 Hot Weather Precautions. During periods of hot weather (above 100°F [38°C]) or windy conditions, special precautions shall be taken to minimize moisture loss due to evaporation. Under conditions of excessive surface evaporation due to a combination of air temperature, relative humidity, LCC temperature, and wind conditions, the contractor must present to the engineer a detailed proposal for minimizing moisture loss and protecting the LCC. Precautions may include temporary wind breaks to reduce wind effect, cooling of slurry mix water, decreasing the allowable time between mixing and placing, reducing lift heights, and/or applying a protective cover.

6.6.3 Rain Limitations. No placement of LCC shall be performed while it is raining hard enough to be detrimental to the finished product. Placement may continue during light rain or mists provided the surface of the LCC is not washed out or damaged.

6.7 Maintenance

The contractor shall maintain the placed LCC in good condition until all LCC work is completed and accepted. Such maintenance shall be performed by the contractor at their own expense.

6.8 Sampling, Testing, and Acceptance

6.8.1 Quality Control Sampling and Testing by the Contractor. The contractor shall sample and test the LCC as follows:

6.8.1.1 As-Cast Density. The first batch placed each day and every hour thereafter during placement shall be sampled and tested according to ASTM C495. The as-cast density shall be the average of at least two tests.

6.8.1.2 If the average as-cast density is outside the specified tolerance shown in Section 6.8.3, the contractor shall reject the batch or make an adjustment to the mix before placement. Adjustments to the mix shall be accomplished by either increasing or decreasing only the preformed foam.

6.8.1.3 Unconfined Compressive Strength. The first batch placed each day and every two hours thereafter shall be sampled according to ASTM C495, noting that samples shall not be oven dried at any time before testing. The minimum number of batches sampled per day shall be two. Eight 3 in. × 6 in. (75 mm × 150 mm) cylindrical test specimens shall be molded for each sample.

6.8.1.4 An unconfined compressive strength test is defined in ASTM C495 as the average of four properly cured, cylinder breaks. For each sample, tests shall be conducted at 28 days.

6.8.2 Quality Assurance Sampling and Testing by the Engineer. The engineer shall sample and test the LCC for quality assurance on independent and split samples. An independent sample is a field sample obtained and tested by only one party. A split sample is one of two equal portions of a field sample, where two parties each receive one portion for testing. The engineer may request the contractor to obtain a split sample. Any failing strength test specimen shall be retained until permission is given by the engineer for disposal. The results of all quality assurance tests by the engineer shall be made available to the contractor; however, the contractor's split sample test results shall be provided to the engineer first. The engineer's independent quality assurance sample and split sample testing for placement or acceptance shall be as follows:

6.8.2.1 As-Cast Density. One independent or split sample test for the first batch placed each day and as determined by the engineer thereafter.

6.8.2.2 Unconfined Compressive Strength. One independent or split sample test for the first batch placed each day and as determined by the engineer thereafter.

6.8.3 Comparison of Test Results. Differences between the engineer's and the contractor's split sample test results shall be considered reasonable if within the limits shown in the following table:

Test parameter	Acceptable limits of precision
28-day unconfined compressive strength	±80 lb/in^2 (0.55 MPa)
As-cast density	±1 lb/ft^3 (16 kg/m^3)

6.8.3.1 Action shall be taken when either the engineer's or the contractor's test results are not within specification limits for strength or density. Action may include but is not limited to the contractor being required to replace or repair equipment as determined by the engineer.

6.8.3.2 Placed material that fails in unconfined compressive strength shall be considered unacceptable.

6.8.4 Acceptance by the Engineer. Final acceptance shall be based on these specifications and the following:

6.8.4.1 Validation of contractor quality control test results using split samples. Any quality control or quality assurance test determined to be flawed may be declared invalid only when reviewed and approved by the engineer. The engineer shall declare a test result invalid only if it is proven that improper sampling or testing occurred. The test result is to be recorded and the reason for declaring the test invalid shall be provided by the engineer.

6.8.4.2 Comparison of the engineer's quality assurance test results with specification limits using samples independently obtained by the engineer.

6.8.4.3 The engineer may suspend mixture production, reject materials, or take other appropriate action if the contractor does not control the quality of the LCC. The decision shall be determined according to Section 6.8.4.1 or 6.8.4.2.

7. Measurement and Payment

7.1 Measurement

This work shall be measured in cubic yards (cubic meters) of completed and accepted LCC fill as determined by the Daily Reports submitted in accordance with Section 6.3.4.

7.2 Payment

7.2.1 This work shall be paid for at the contract unit price per cubic yard (cubic meter) of LCC fill. Such payment shall constitute full reimbursement for all work necessary to complete the LCC fill, including proportioning, mixing, placing, and all other incidental operations.

7.2.2 Trial Batch. If a trial batch is prepared, it shall be paid for on a lump sum basis. Such payment shall constitute full reimbursement for all materials, labor, equipment, mobilization, demobilization, and all other incidentals necessary to produce the Trial Batch in accordance with Section 6.2.

National Concrete Pavement Technology Center

Tech Center

2711 South Loop Drive, Suite 4700 | Ames, IA 50010-8664 | Phone: 515-294-5798 | cptechcenter.org

SR1008P