Alternative Backfills for Highway Applications: State of the Practice

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FOREWORD

Alternative backfill materials are increasingly used in applications such as retaining walls, bridge abutments, pipes/culverts, embankments, ground improvements, and slopes. This report summarizes the current state of practice for nine alternative backfills. The advantages and disadvantages, material characterization, design requirements, design guidelines, placement and construction specifications, cost information, environmental considerations, lifecycle assessment, and case studies/performance records are presented for each material.

The report presents the maturity level of each technology, barriers to the advancement and widespread use of each material, and recommendations for moving forward. The information presented in this report could interest practitioners, designers, and researchers working in roadway geotechnical applications.

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16. Abstract

Using alternative materials (e.g., lightweight, recycled) in geotechnical applications may be advantageous compared to conventional structural backfills. This report summarizes current knowledge and the state of practice for using alternative backfill materials in applications, including backfills for retaining walls, bridge abutments, and pipes/culverts, and for embankments, ground improvements, and slope stability. The researchers evaluated nine alternative and lightweight fill materials as follows: controlled low-strength materials (CLSM); expanded shale, clay, and slate (ESCS); foamed glass aggregates (FGA); lightweight cellular concrete (LCC); polystyrene geofoams; reclaimed asphalt pavement (RAP); recycled concrete aggregates (RCA); recycled glass aggregates; and tire-derived aggregates (TDA). For each material, the researchers gathered information on the advantages and disadvantages of using backfill in applications, available literature on material characterization, design requirements, design guidelines, placement and construction specifications, cost information, environmental considerations, lifecycle assessment studies, case studies, and performance records. Further, the researchers present the maturity level of each technology, the suitability of using the various geotechnical applications, barriers to the advancement and widespread use of each material in backfill applications, and recommendations for moving forward. Some alternative materials (e.g., RAP, RCA, ESCS, CLSM, and TDA) are more widely used in the United States for geotechnical applications, while others are still emerging. Further, some materials (e.g., LCC, TDA, and geofoams) have well-developed design guidelines, while others (e.g., CLSM and FGA) could require more research. Lastly, the researchers concluded that most of these recycled/alternative materials, while marketed as "green" materials, lacked quantifiable environmental impacts obtained from lifecycle assessments and environmental product declarations for products manufactured in the United States.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

AC	asphalt content
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
AMD	acid mine drainage
ASCE	American Society of Civil Engineers
ASR	alkali-silica reactions
$CaCO_3$	calcium carbonate
Caltrans	California Department of Transportation
CBR	California Bearing Ratio
CD	consolidated drained
CDF	controlled density fill
CFC	chlorofluorocarbon
CLSM	controlled low-strength material
CO_2	carbon dioxide
CP Tech Center	National Concrete Pavement Technology Center
CRG	coarse recycled glass
CU	consolidated undrained
C/W	cement-to-water
CWC	Clean Washington Center
DOT	department of transportation
DOTD	department of transportation and development
DST	direct shear test
EN	European Norm
EPA	Environmental Protection Authority
EPD	environmental product declaration
EPS	expanded polystyrene
ESCS	expanded shale, clay, and slate
ESCSI	Expanded Shale, Clay and Slate Institute
FGA	foamed glass aggregate
FGD	flue gas desulfurization
FHWA	Federal Highway Administration
FRG	fine recycled glass
GRG	gasoline-resistant geomembrane
HCFC	hydrochlorofluorocarbon
HMA	hot-mix asphalt
IBU	Institut Bauen und Umwelt
IDOT	Illinois Department of Transportation
ISO	International Organization for Standardization
LA	Los Angeles
LCA	lifecycle assessment
LCC	lightweight cellular concrete
LCCA	lifecycle cost analysis
LWA	lightweight aggregate
MRF	material recycling facilities

MRG	medium recycled glass
MSE	mechanically stabilized earth
NRMCA	National Ready Mixed Concrete Association
ODOT	Ohio Department of Transportation
ODP	ozone depletion potential
OI	oxygen index
OSHA	Occupational Safety and Health Administration
PAH	polycyclic aromatic hydrocarbon
PCA	Portland Cement Association
PCC	portland cement concrete
PCR	product category rule
PI	plasticity index
QA	quality assurance
QC	quality control
RAP	reclaimed asphalt pavement
RCA	recycled concrete aggregate
RCC	recycled crushed concrete
RCM	recycled concrete material
RGA	recycled glass aggregate
RPM	recycled pavement material
RS	reservoir siltation
TCLP	toxicity characteristic leaching procedure
TDA	tire-derived aggregates
TRL	Technology Readiness Level
TxDOT	Texas Department of Transportation
UCS	unconfined compressive strength
USCS	Unified Soil Classification System
UV	ultraviolet
VA	virgin aggregate
W/C	water-to-cement ratio
W/S	water-to-solid
XPS	extruded polystyrene

EXECUTIVE SUMMARY

A variety of alternative backfill materials are currently processed, reclaimed, or manufactured and widely used in various highway applications. These alternative backfill materials may include controlled low-strength material (CLSM); expanded shale, clay, and slate (ESCS); polystyrene geofoam; foamed glass aggregates (FGAs); lightweight cellular concrete; reclaimed asphalt pavement; recycled concrete aggregates (RCAs); recycled glass aggregates (RGAs); tire-derived aggregates (TDAs); or blends of one or more of these materials with or without conventional aggregates. Some alternative backfills have a long performance history, while others are emerging and are at different stages of testing, trials, demonstration, and implementation, depending on the application. For example, RCAs have been used in highway construction for more than 70 yr, usually as pavement base and subbase layers and as embankment and shoulder materials. On the other hand, FGA is a recycled aggregate with limited history but excellent potential. This report provides information on nine known alternative backfill materials for use in highway fill applications and information and literature on their usage, popularity, and suitability for highway geotechnical applications.

This study aimed to assess the current knowledge and state of the practice of alternative backfill materials, particularly emerging materials on the market, for their application as backfill in highway applications such as retaining walls, embankments, bridge abutments, and pipe/culvert covers. The researchers performed a comprehensive review of domestic and international literature. The literature review presents the current knowledge base, knowledge gaps, technology maturity level, barriers to technology advancement and implementation, needs for future research, and a general framework for conducting future laboratory studies and field demonstrations.

Ultimately, the researchers concluded that all the recycled and lightweight materials investigated in this study have been used (or can be successfully used) for the target highway geotechnical applications (i.e., bridge abutments, embankments, retaining wall fills, pipe backfills, and ground improvements) without major issues reported or early failures. For any design alternative, the design engineer should pay special attention to the design requirements of each material, required design aspects, and changes in properties due to the use of a prospective material, such as the improvement/changes in shear strength properties, including the angle of internal friction, and the weight/density of the fill. Further, using the appropriate construction equipment and closely following lift thickness requirements and proper construction guidelines/practices to achieve the desired performance are of the utmost importance.

The researchers identified technology-ready aspects for each alternative lightweight and recycled material based on the comprehensive literature reviewed and synthesized in this report. Overall, these materials have been used in full-scale field construction projects and as alternative designs to conventional backfills, which places all the materials at a Technology Readiness Level (TRL) of 8 according to the guidelines of the Federal Highway Administration's *Technology Readiness Level Guidebook* (Towery, Machek, and Thomas 2017). Despite all the materials being at a TRL of 8, the literature search clarified that some materials have higher market penetration and are more commonly used in the United States for geotechnical applications. For example, comprehensive field application data exist for TDA, expanded polystyrene, and CLSM for most of the aspects of interest in this report, while some materials, such as RGAs, lack comprehensive information, with only a few case studies. One major area in which information is missing for most of the materials (except ESCS and FGA) is the presence of environmental product declarations (EPDs) to summarize the environmental impacts and energy demands for commercial products. In fact, the only product category rule available in the United States is for ESCS, but no publicly available EPD or comprehensive lifecycle assessment studies exist for any of the materials used in geotechnical applications.

Based on the information provided in this report, the researchers identified several knowledge gaps about using recycled or lightweight alternative backfill materials for highway geotechnical applications. Therefore, the researchers provide a list of research need statements to promote more commonplace uses of lightweight and recycled alternative backfill materials to take advantage of these technologies and associated benefits. These research need statements are based on the knowledge gaps identified from the comprehensive literature search and primarily aim to eliminate technology barriers and promote more sustainable construction practices that do not jeopardize performance.

CHAPTER 1. INTRODUCTION

PROJECT OVERVIEW

In certain project conditions, using alternative materials (e.g., lightweight, recycled) in geotechnical applications may be advantageous compared to more conventional structural backfills (e.g., open- and well-graded granular aggregates). Alternative backfills can be either recycled or modified materials engineered to obtain certain physical and mechanical properties (e.g., unit weight, shear strength). Of the currently available alternative backfills on the market, lightweight backfills are becoming a more common solution to address settlement concerns, reduce lateral earth pressures, improve thermal properties, reduce carbon emissions, and accelerate project construction. The engineering properties of these lightweight backfills, whether composed of virgin or recycled materials, are not well established, particularly regarding how they relate to each other and the resulting lifecycle and lifecycle cost analyses (LCCA) impact on their geotechnical applications.

The Federal Highway Administration (FHWA) has a long-standing materials selection policy to consider recycled materials first because recycling and reusing can offer engineering, economic, and environmental benefits. However, FHWA's Recycled Materials Policy cautions that "material used in highway or bridge construction, be it virgin or recycled, shall not adversely affect the performance, safety or the environment of the highway system" (FHWA 2015). This policy requires research, field trials, and project demonstrations on the performance of virgin and recycled materials before the materials can be reliably used. Table 1 lists available lightweight civil engineering materials and their density ranges.

Table 1. Typical unit weight ranges for alternative lightweight materials (Tafreshi, Siabil, and Dawson 2020; Loux 2022).

Lightweight Fill Type	Density Range	
	kg/m^3	lb/ft^3
Air-cooled slag	1,100–1,500	68.7–93.6
Boiler slag	1,000–1,750	62.4–109.3
Controlled low-strength materials	1,442–1,602	90–100
Expanded shale and clay	600–1,040	37.5–65
Foamed concrete	320–961	20–60
Foamed glass aggregates	160–400	10–25
Fly ash	1,120–1,440	70–90
Geofoams	11–48	0.7–3
Lightweight cellular concrete	320–961	20–60
Recycled glass aggregates	1,762–1,922	110–120
Shredded/waste tires	384–900	24–56.2
Wood chips	320–560	20–35
Mineral soils and aggregates (reference)	1,522–2403	95–150

A variety of alternative backfill materials are currently processed, reclaimed, or manufactured and widely used in various highway applications. Alternative backfill materials may include the following:

- Controlled low-strength material (CLSM).
- Expanded shale, clay, and slate (ESCS).
- Polystyrene geofoam.
- Foamed glass aggregates (FGAs).
- Lightweight cellular concrete (LCC).
- Reclaimed asphalt pavement (RAP).
- Recycled concrete aggregates (RCAs).
- Recycled glass aggregates (RGAs).
- Tire-derived aggregates (TDAs).
- Blends of one or more of these materials with or without conventional aggregates.

Some alternative backfills have a long performance history, while others are emerging and are at different stages of testing, trials, demonstration, and implementation, depending on the application. For example, RCAs have been used in highway construction for more than 70 yr (Abukersh and Fairfield 2011). RCAs have been commonly used as pavement base and subbase layers and as embankment and shoulder materials. On the other hand, FGA is a recycled aggregate with a limited history. Though the technology was introduced in Europe more than 25 yr ago, it did not receive much attention in the United States until 2017 (Hibbert 2016; Gibson 2019). This report will provide information on these nine alternative backfill materials for highway fill applications and provide information and literature on their use and suitability.

OBJECTIVES

The primary objective of this study is to assess the state of the practice of alternative backfill materials, particularly emerging materials on the market, for their application as backfill in highway applications, such as retaining walls, embankments, bridge abutments, and pipe/culvert covers, through a comprehensive review of domestic and international literature. The literature review will present the current knowledge base, knowledge gaps, technology maturity level, barriers to technology advancement and implementation, needs for future research, and a general framework for conducting future laboratory experimental studies and field demonstrations.

TARGET APPLICATIONS

The report will mainly target the following applications for lightweight and recycled alternative backfill materials:

- Retaining walls.
- Embankments.
- Bridge abutments.
- Pipe/culvert covers and backfills.
- Ground improvements.

The report will also cover other geotechnical applications for highways for any respective material found in the literature. In addition, the researchers investigated literature on alternative backfill materials as a constituent in hot-mix asphalt (HMA) or portland cement concrete (PCC). While HMA and PCC are not geotechnically focused, any testing of the studied lightweight fill materials conducted for such applications may potentially be applicable to the target geotechnical applications of interest in this study.

PROJECT TASKS

The researchers undertook the following specific tasks for this study:

- Identify and describe various alternative backfills currently produced and used in highway applications.
- Delineate emerging technologies that need future research and add details that facilitate the development of future laboratory experimental studies and field demonstrations.
- Describe the advantages and disadvantages of each type of alternative backfill material.
- Describe the primary highway transportation applications for the various types of alternative materials.
- Identify and describe case studies.
- Identify barriers and impediments to the advancement and widespread application of various alternative backfill technologies.
- Describe any available data on alternative backfills that are important from the standpoint of geotechnical designs, such as gradation, unit weight, friction angle, permeability, etc.
- Describe any needs or special provisions for testing alternative backfills compared to conventional aggregates that researchers and practitioners may have proposed.
- Describe the environmental and economic lifecycle impacts of alternative backfills.
- Identify and describe any available construction specifications and quality assurance (QA)/quality control (QC) procedures for placing alternative backfills in the field.
- Identify future research needed for emerging alternative backfill technologies and develop a research need statement for each topic.
- Develop a general framework for experimental laboratory studies and field demonstrations for emerging alternative backfill technologies.
- Recommend eliminating or minimizing the barriers and impediments to the advancement and widespread application of alternative backfills.
- Recommend any specialized testing needs for alternative backfills.

RESEARCH MATRIX

The researchers conducted a comprehensive literature search and assessment for each lightweight and alternative material included in the study scope to determine the current knowledge base on each material. The literature search encompassed the following topics:

- Broad topics on the geotechnical applications covered in the literature.
- Advantages and disadvantages of using each material in backfill applications.
- Data on material characterization, including physical and mechanical properties, design requirements, and guidelines.
- Placement and construction specifications.
- Cost information.
- Environmental considerations.
- Lifecycle assessment (LCA) studies.
- Case studies and performance records.

After collecting all the available information for the individual materials, the researchers reflected on the maturity level of each technology, suitability for the various geotechnical applications, barriers to the advancement and widespread use of the materials in backfill applications, knowledge gaps, and recommendations for moving forward and overcoming any barriers to widespread and effective use.

REPORT ORGANIZATION

This report is divided into 11 chapters and a references section, including this introductory chapter. Chapters 2–10 provide available information on each alternative/lightweight backfill material, such as applications, advantages, laboratory characterization, environmental studies, case studies, and construction and design requirements. Chapter 11 provides a summary of the findings, conclusions, and recommendations. Chapter 11 also includes a section on the suitability of the lightweight/alternative materials for the geotechnical applications being considered and a section on the gaps in knowledge and barriers to widespread use. Finally, the last section presents an extended list of references compiled through an exhaustive literature search of the available publications for each lightweight/alternative backfill material discussed in the report.

CHAPTER 2. CLSM

INTRODUCTION AND BACKGROUND

CLSMs are self-leveling and self-consolidating cementitious fills that are typically used as an alternative to conventionally compacted aggregate backfills. Other common names for CLSM include flowable fill, unshrinkable fill, liquid dirt, controlled density fill (CDF), and various trademark names. CLSMs have traditionally been used in the construction industry since the 1960s for pipeline backfill, but more recently, their applications have expanded (Wagstaff 2016). CLSMs are now used for a wide selection of geotechnical backfill applications. Figure 1 presents photos illustrating field applications of CLSM.

© 2014 Metropolitan Transit Authority.

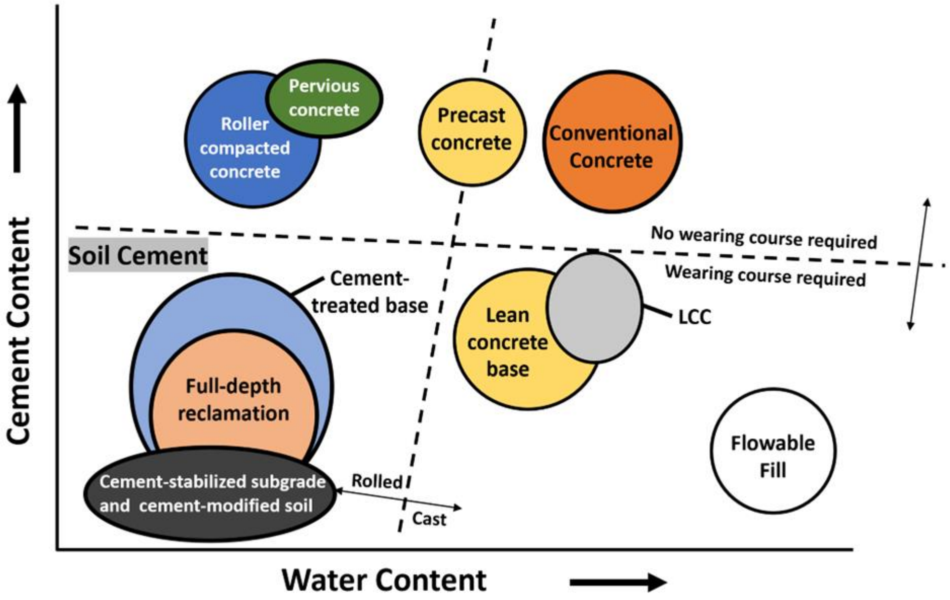
A. Backfilling a trench with CLSM (Creative Commons n.d.a).

Source: Commander, U.S. Naval Forces Europe-Africa.

B. Using a concrete vibe to spread CLSM evenly.

Figure 1. Photos. CLSM in field applications.

CLSMs are made by mixing various amounts of portland cement, fine aggregates, coarse aggregates (mostly sand), and water. Some mix designs include byproduct materials to replace cement or aggregates such as fly ash and other industrial byproducts and admixtures to reduce cement content. ASTM International (ASTM) D5971 and American Concrete Institute® (ACI) 229R define CLSM as a mixture of soil, fly ash, cement, water, and sometimes admixtures that hardens into a material with a higher strength than soil but less than 1,200 psi (ASTM 2010; ACI 2013). In many applications, even lower strengths are often required to ensure the fill can be excavated without excessive effort, e.g., typical unconfined compressive strength (UCS) values of 300 psi or lower. Figure 2 presents different cement-based concrete materials and how they differ in terms of cement and water content. Flowable fill materials (i.e., CLSM) tend to have higher water contents and lower cement contents compared to other cement-based concrete materials.



© 2020 Portland Cement Association. Modifications to colors by FHWA.

Figure 2. Illustration. Comparison between CLSM and other cement-based materials for water and cement contents (Halsted 2020).

ADVANTAGES AND DISADVANTAGES

Reported advantages of CLSM include the following (ACI 229R 2013; Wagstaff 2016):

- Low shrinkage and compressibility characteristics.
- Excavation of the fill is easy using hand equipment at any age.
- Fast construction and strength gain: fill hardens within a short time (i.e., a few hours).
- Compaction or tamping not required.
- Strength and other properties not widely affected by changing moisture conditions.
- Land utilization for dumping coal ash (fly ash) and other industrial byproducts reduced.

ACI 229R (2013) and Wagstaff (2016) also reported the following advantages for CLSM materials: readily available, easy to deliver, easy to place, versatile and adjustable mixes, reduced excavation costs, all-weather construction, no onsite storage required, and less inspection needed.

Disadvantages of CLSM materials include the following:

- Designed to be low strength (thus, generally not considered a disadvantage for the target applications).

- Could incur additional material costs.

- Requires additional training and familiarity by contractors with its purposes, mixture design, testing, and installation to help ensure a quality project.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

The researchers found the following applications for CLSM in the literature (Ling, Kaliyavaradhan, and Poon 2018):

- Lightweight road bases and fills.
- Backfill behind retaining walls.
- Bridge-approach embankments.
- Void and cavity filling (tunnel shafts and sewers).
- Pipe backfilling.
- Structural fills.
- Insulation and isolation fills.
- Erosion control.

MATERIAL CHARACTERIZATION

Physical Properties

The physical properties of CLSM materials are expected to vary greatly based on the constituents used. Flowability is one of the major physical properties specified for CLSM in most design procedures. Flowability measures the average diameter of a disk-shaped spread when the mix is poured from a standard-sized cylinder as per ASTM D6103 (ASTM 2017a). According to ACI 229R and ASTM D6103 guidelines, mix flowability should range between 200 and 300 mm (7.9 and 11.8 inches) to ensure the mix flows easily without segregation while pumping (ACI 2013). Further, water-to-solid (W/S) and cement-to-water (C/W) ratios are the control parameters to achieve a proper mix design that satisfies flowability and strength.

Mechanical Properties

As a consensus, flowability and UCS are the two main properties to check for CLSM mixes. Strength requirements vary depending on the application. Generally, a minimum strength of 345 kPa (50 psi) is specified (ACI 2013). The maximum strength is often limited to

1.4 megapascal (MPa) (200 psi), especially for applications that require excavability; however, the ultimate maximum strength for CLSM is 82.7 MPa (1,200 psi), as required by ACI 229R (ACI 2013; Pierce and Blackwell 2003).

Other mechanical properties reported for CLSM include compressibility from a one-dimensional consolidation test, undrained shear strength using shear box test apparatus, and California Bearing Ratio (CBR) for up to 7 d (Wu and Tsai 2008; Wu and Lin 2011). The angle of shearing resistance (friction angle) varies from 25 to 55 degrees for CLSM mixes cured for 28 d. Lower friction angle values are rarely reported in the literature, e.g., 11.2–12.6 degrees after 7-d curing (Lee and Kim 2013). The cohesion or cohesion intercept typically ranges from 8.3 to 60.0 kPa (1.2 to 8.7 psi). The variation in shear strength properties depends on the type of aggregates and the mix design adopted (McGrath and Hoopes 1998; Langton, Rajendran, and Smith 1998; Masada and Sargand 2007; Türkel 2007). Examples of the mixture properties and mechanical properties of fly ash-based CLSM mixes are given in table 2 and table 3 from a study by Türkel (2007). The researchers measured shear strength properties using a shear box apparatus with tests conducted at a loading strain rate of 0.300 mm/min and having a dial gauge reading of 0.12 mm/division.

Table 2. Example CLSM mix properties and the corresponding compressive strengths (Türkel 2007).

Mixture	Mixture Properties		W/S Ratio	Spread (mm)	UCS (MPa)			
	F/(C + FA)	W/(C + FA)			7 d	14 d	21 d	28 d
M1	3:1	1.00	0.25	220	0.28	0.58	0.84	1.15
M2	3.5:1	1.00	0.22	210	0.24	0.38	0.65	1.06
M3	4:1	1.10	0.22	207	0.22	0.37	0.63	1.02
M4	5:1	1.25	0.21	210	0.19	0.39	0.72	0.92
M5	5.5:1	1.30	0.20	210	0.17	0.34	0.64	0.88
M6	6:1	1.40	0.20	205	0.16	0.31	0.61	0.85

F = filler (crushed limestone powder); C = cement; FA = fly ash; W = water.

Table 3. Direct shear test (DST) results for CLSM mixtures at 7 d (Türkel 2007).

Mixture	M1	M2	M3	M4	M5	M6
Cohesion intercept (MPa)	0.047	0.045	0.044	0.041	0.040	0.038
Angle of shearing resistance (degrees)	54	52	51	47	45	43

Use of Recycled and Byproduct Materials for CLSM

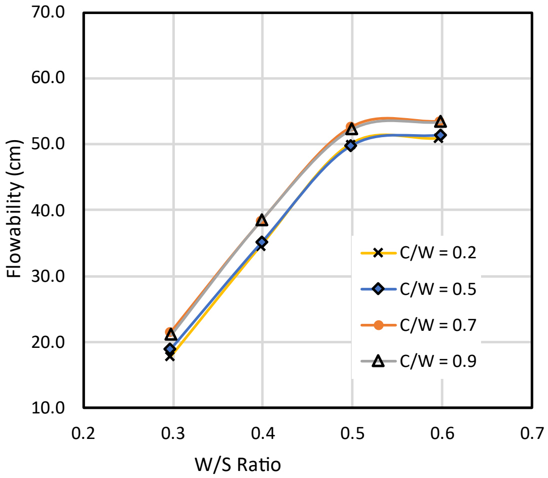
A major disadvantage of CLSM is the high cost of materials. However, CLSM's relatively low mechanical property requirements compared to those for concrete or other cementitious materials enable CLSM production to use industrial wastes, which is a common practice to reduce cost and for environmental considerations. ACI 229R recommends that any available recycled granulated material be considered an alternative aggregate for CLSM as long as it has been tested before use (ACI 1999, 2013). The byproduct materials used to replace cement and aggregates include fly ash, bottom ash as a fine aggregate, cement kiln dust, byproduct foundry sand, flue gas desulfurization (FGD), oyster shells, scrap tire rubber, recycled glass, acid mine drainage (AMD) sludge, blast furnace slag, recycled concrete, and clean coal ash.

According to Do and Kim (2016), the advantages of using fly ash as a replacement for cement include improving flowability, reducing segregation, and reducing material costs. Examples of studies that investigated the use of fly ash in CLSM include those by Dockter (1998); Gabr and Bowders (2000); Katz and Kovler (2004); Lee et al. (2013); Nataraja and Nalanda (2008); Pierce, Gassman, and Richards (2002); and Siddique (2009). Examples of studies that investigated the use of bottom ash as a fine aggregate include those by Katz and Kovler (2004); Naganathan, Razak, and Hamid (2010); Naganathan, Razak, and Hamid (2012); Razak, Naganathan, and Hamid (2009); and Razak, Naganathan, and Hamid (2010). Cement kiln dust is ideal for producing CLSM at a lower cost because it contains smaller amounts of active lime and silica, so it can be effectively added to produce a very low-strength material. Several past research efforts investigated the use of cement kiln dust in CLSM, for example, Pierce, Tripathi, and Brown (2003); Lachemi et al. (2008); and Lachemi et al. (2010). Byproduct foundry sand was also used at lower cost and is abundantly available. Studies investigating the use of foundry sand in CLSM include those by Bhat and Lovell (1997); Siddique and Noumowe (2008); Tikalsky, Gaffney, and Regan (2000); and Trejo, Folliard, and Du (2004). Several research studies also investigated the other byproduct materials:

- Butalia, Wolfe, and Lee (2001) studied FGD.
- Kuo et al. (2013) investigated oyster shells.
- Pierce and Blackwell (2003) and Wu and Tsai (2008) used scrap tire rubber in their studies.
- Lachemi et al. (2010) and Muhmood, Vitta, and Venkateswaran (2009) studied blast furnace slag.
- Ohlheiser (1998), Gabr and Bowders (2000), Achtemichuk et al. (2009), and Naik et al. (1998) studied recycled glass, AMD sludge, recycled concrete, and clean coal ash.

Nehdi and Khan (2001) suggested benefits of using worn-out tire rubber mixed with portland cement include lower density, better toughness and ductility, and higher impact resistance. Wu and Tsai (2008) investigated using recycled crumb rubber (from scrap tires) in a CLSM for bridge approach backfill. Rubber fine particle sizes ranged from 0.9 to 4.76 mm (passing No. 4 sieve), with the rubber fines classified as poorly graded sand according to the Unified Soil Classification System (USCS) and with an average specific gravity of 1.18. The researchers tested 44 rubberized CLSM mixtures. CLSM mixes with rubber fines alone were not flowable in the trial mixes, and reasonable strength values could not be achieved. Rubberized CLSM without the addition of sand exhibited heavy bleeding, and a standard flowability of 200 mm was not achievable. The researchers found that including 40 percent sand in rubberized CLSM resulted in an increase in flowability and strength. The researchers tested flowability immediately after mixing and compressive strength for samples cured at 1, 7, and 28 d.

For the rubberized CLSM with 40 percent sand, Wu and Tsai (2008) found flowability increased with an increase in the W/S ratio (figure 3). The rate of increase became insignificant when the W/S ratio was greater than 0.5. A W/S ratio of 0.3 can be used as the minimum criterion for flowability, while a W/S ratio of 0.5 appears to be the maximum threshold. Further, samples with C/W ratios of 1.0 or less had a maximum 28-d UCS of only 165.5 kPa (24 psi). The use of sand in rubberized CLSM increased the strength considerably. Ultimately, a W/S ratio of 0.3 and a C/W ratio of 0.7 could satisfy both strength and flowability requirements (figure 3).



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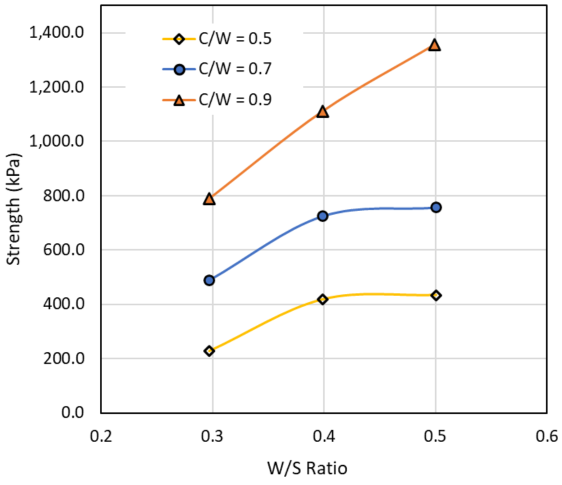
A. Effects of C/W and W/S ratios on the flowability of rubberized CLSM with 40 percent sand.



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B. Effects of C/W and W/S ratios on the UCS of rubberized CLSM with 40 percent sand.

Figure 3. Graphs. Effects of C/W and W/S ratios on the flowability and UCS of rubberized CLSM with 40 percent sand (Wu and Tsai 2008).

According to Wu and Tsai (2008), "Based on the promising performance, rubberized CLSM was used to rehabilitate a bridge approach damaged by significant differential settlement …. The final mix design for the trial construction was 0.7 for C/W and 0.35 for W/S to ensure a design 28-day strength of 600 kPa (87 psi). The flowability observed was about 250 mm (9.8 in.). Testing and monitoring for this project provided evidence that, from a geotechnical standpoint, rubberized CLSM can be successfully used as an alternative to mitigate the settlement under a bridge approach. Field trial details and construction monitoring for this project will be presented elsewhere." However, no followup publications on the topic were found to include in this report.

Wu and Lin (2011) investigated the use of CLSM with reservoir siltation (RS—silty materials collected from settling ponds as an aggregate material). This study used gray silty clay with a plasticity index (PI) of approximately 11 percent and a liquid limit of 35 percent. While using RS is not conventional, the mix design selection methodology can be broadly applied to any byproduct material and CLSM design for geotechnical highway applications, so the researchers evaluated the study further. Series I testing consisted of evaluating proper design mixes for CLSM. Tests included physical properties, flowability, and UCS. A W/S ratio of 0.8–0.9 and a C/W ratio of 0.4–0.5 was proposed for the passing design. Flowability increased with the increase of C/W ratios. For the same C/W ratio, flowability increased with the increase of the W/S ratio because of the presence of clayey fines in the RS material. The UCS of each trial mix varied as a function of W/S, C/W, and curing time. Thus, the values of UCS (i.e., Q_u) increased with the increase of C/W and curing time but did not show a regular behavior trend for the W/S ratios. Further, strength improvements with curing time were more pronounced for W/S ratios between 0.7 and 0.8. Figure 4 summarizes the results for flowability requirements and figure 5 for strength requirements.

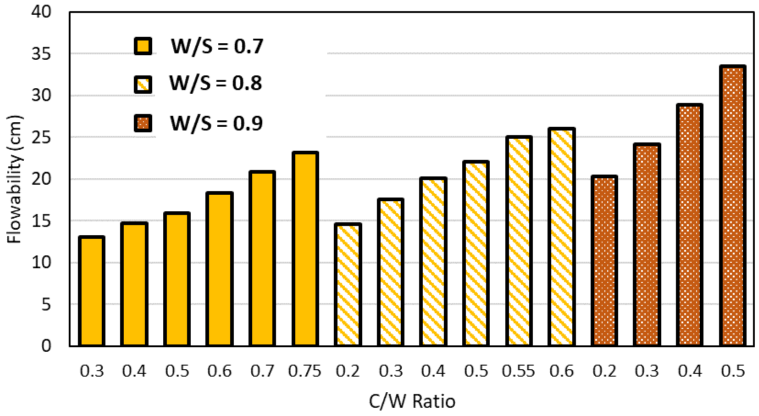

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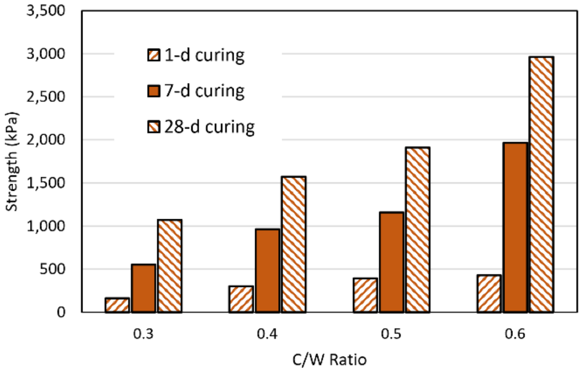
Figure 4. Graph. Effects of C/W and W/S ratios on the flowability of CLSM mixes with RS (Wu and Lin 2011).



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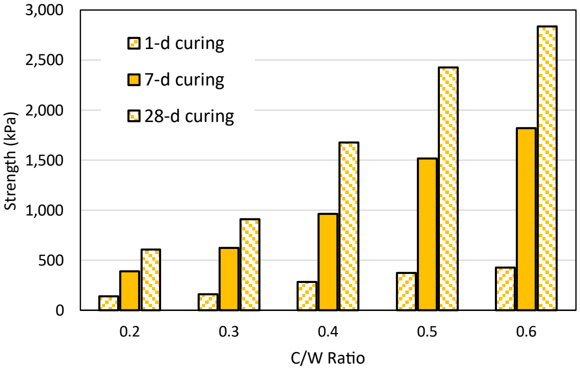
A. W/S = 0.7.



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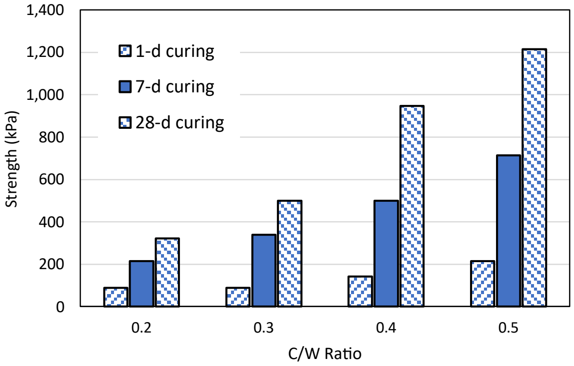
B. W/S = 0.8.



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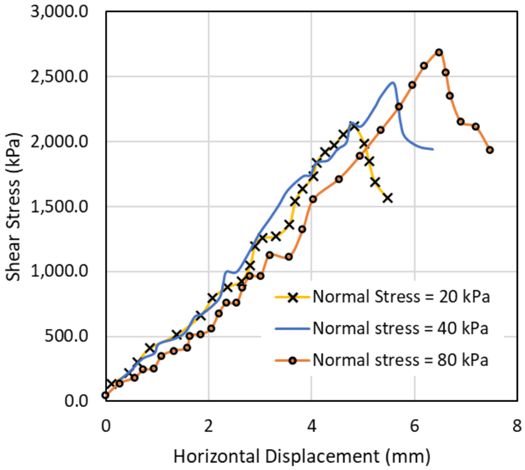
C. W/S = 0.9.

Figure 5. Graphs. Effects of C/W and W/S ratios and curing time on the strength of CLSM mixes with RS (Wu and Lin 2011).

Wu and Lin's (2011) series II testing involved selecting an optimum design mix formula (flowability and strength) for compressibility and undrained shear strength testing with two different C/W and W/S ratios. For compressibility testing, samples with smaller C/W ratios showed a slightly greater vertical strain for similar vertical stress. For the shear box testing, the measured friction angles were quite low (7.1 and 9.9 degrees only). However, the values for cohesion were on the high end, i.e., 2 MPa (288 psi) and 3.75 MPa (544 psi), indicating an overall high shear strength. Figure 6 presents the stress-displacement curves for the shear box testing. Overall, hardened RS-based CLSM behaved as heavily overconsolidated clay due to the strong cementation action of cement, leading to a sound shearing resistance and negligible compressibility.



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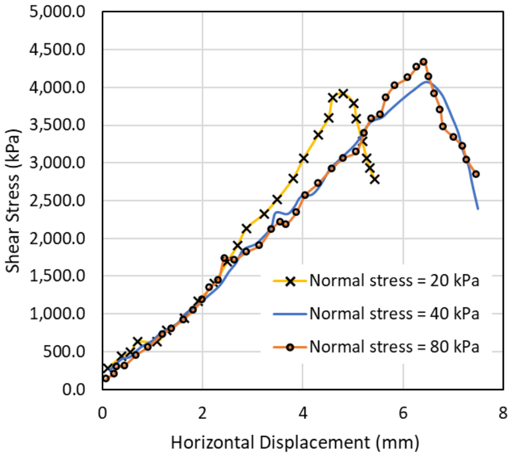
A. C/W = 0.4, W/S = 0.8.



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B. C/W = 0.5, W/S = 0.8.

Figure 6. Graphs. Shear box testing results for RS-based CLSM tested at two different C/W ratios (Wu and Lin 2011).

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

As a general consensus on the control parameters for mix design, W/S ratio and C/W ratio are reported and controlled to achieve a proper mix.

In-place properties and design requirements for CLSM include the following (Graniterock® 2023):

- Strength: A CLSM UCS of 345 kPa to 690 kPa (50 to 100 psi) is equivalent to the bearing capacity of a well-compacted soil. Maintaining CLSM strengths at low levels is critical in projects requiring future excavation.

- Density: Wet density of most CLSM ranges from 1,842 to 2,323 kg/m^3 (115 to 145 lb/ft^3). A CLSM mixture with only fly ash, cement, and water might have a density range of 1,142 to 1,602 kg/m^3 (90 to 100 lb/ft^3).

- Flowability: According to ACI 229R and ASTM D6103 guidelines, mix flowability should range between 200 and 300 mm (7.9 and 11.8 inches), which ensures the mix flows easily without segregation while pumping (ACI 2013; ASTM 2017a).

- Settlement: CLSM does not settle after it hardens.

- Shrinkage: The ultimate shrinkage of CLSM is typically in the range of 0.02-0.05 percent.

- Excavatability: CLSM with compressive strengths of 690–2,068 kPa (100–300 psi) can generally be excavated with mechanical equipment, such as backhoes.

- Corrosivity: Electrical resistivity tests can be performed on CLSM on corrugated metal culvert pipe (e.g., California Department of Transportation (Caltrans) test method 643 (Caltrans 2020)). CLSM uniformity reduces the chance of corrosion.

ASTM Standards for CLSM

The following ASTM standards apply to CLSM:

- ASTM D4832: *Standard Test Method for Preparation and Testing of Controlled Low Strength Testing Materials (CLSM) Test Cylinders* (ASTM 2018).

- ASTM D5971/D5971M: *Standard Practice for Sampling Freshly Mixed Controlled Low-Strength Material* (ASTM 210a).

- ASTM D6023: *Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material (CLSM)* (ASTM 2106a).

- ASTM D6103: *Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)* (ASTM 2017a). For flowable fill mixtures placed on a slope, or when a stiffer mix is required, the slump cone test becomes a more useful indicator of consistency, according to ASTM C143/C143M *Standard Test Method for Slump of Hydraulic-Cement Concrete* (ASTM 2015a).

- ASTM D6024/D6024M: *Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application* (ASTM 2017b).

Table 4 provides examples of the specifications and design requirements for CLSM, as specified by different agencies in the United States for many applications. Reported specifications include strength, aggregate size requirements, cement content, and placement time.

Table 4. Examples of CLSM specifications by different agencies (Kaneshiro et al. 2001).

Agency/Date	Strength (kPa)	Max. Aggregate/ Percent Fines	Aggregate	Cement	Fly Ash	Placement Time (h)	Remarks
ACI Committee 229R Guideline, 1999 (ACI 1999)	<8,300	19 mm	1,540–1,780 kg/m^3	30–119 kg/m^3	Type F <1,200 kg/m^3; Type C <208 kg/m^3	3	Report/ guideline, fly ash, quarry waste, native soil
Greenbook Committee of Public Works Standards, Inc. "Greenbook," (APWA 1997)	—	9.5 mm/ SE = 20, <12 percent, nonplastic	<30% for hand excavation	11.3 kg min	<20 percent, Type C not allowed	2.5.	1998 regional supplement allows >20 percent fly ash
Caltrans Section 19-3.062, (Caltrans 1999)	345–690	—	—	—	—	3	Minimum pH, chloride, and sulfide content specified; >60 kPa for >6 m of cover
Building Technology Research, (BTI HUD 1981)	480–2,400	—	>74 kg/m^3 for trial batches	—	—	—	Types F, C, and N fly ash allowed
City of Orange Environment Management Agency (California), 1993[a]	690–2,400	SE >60	—	<160 kg/m^3	Type F	>1.5	—
Denver International Airport, 1994[a]	345–690	18 percent	—	77 kg/m^3	—	—	Onsite SM material, cement increased from 25 kg/m^3; slump reduced to 127 mm

Agency/Date	Strength (kPa)	Max. Aggregate/ Percent Fines	Aggregate	Cement	Fly Ash	Placement Time (h)	Remarks
ISG Resources, 2000[a]	520–1,040	9.5 mm; 10-12 percent, nonplastic	<30–40 percent	—	—	—	>2,070 kPa specified where higher strength desirable
Southern Nevada Water Authority, 2000[a]	690–2,070	25–76 mm; nonplastic	25–76 mm	Type V	Type C	—	Conflict to use Type C fly ash with Type V cement; Type F specified
City of San Diego Capital Improvement Program Guideline[a]	<8,300	9.5–76 mm; nonplastic	As required	As required	Type F or any suitable fillers	3	All verified by lab and field tests, strength as required

—No data.

[a] For more information about the specifications and design requirements of these agencies, see Kaneshiro et al. 2001.

Max. = maximum; SE = sand equivalent; BTI = Building Technology Inc.; HUD = U.S. Department of Housing and Urban Development; ISG = Industrial Services Group; SM = silty sands, sand-silt mixtures.

According to ACI 229R and ASTM D6103 guidelines, mix flowability should range between 200 and 300 mm, which ensures the mix flows easily without segregation while pumping (ACI 199, 2013; ASTM 2017a). Table 5 provides a design example (for determining required water content given other variables are predetermined) based on the work of Dev and Robinson (2020) for pond ash-based CLSM. The pond ash is classified as a poorly graded silty sand per the USCS and consists of 94 percent sand-sized particles and 6 percent fine (silt and clay) particles. The researchers reported the specific gravity of the pond ash as 2.21 and the pH as 7.5. The optimum moisture contents were 23 and 19 percent, and the maximum dry densities were 1,246 and 1,358 kg/m^3 (77.8 and 84.8 pounds per cubic ft (pcf)) for the standard and modified Proctor compaction methods, respectively (ASTM 2021a, 2021b).

Table 5. Design example of a pond ash-based CLSM passing both strength and flowability requirements (Dev and Robinson 2020).

Cement (percent)	Flowability (mm)	Water Content (percent)	UCS (MPa)
2	200	41.5	0.244
	300	45.5	0.175
3	200	42	0.444
	300	46.5	0.359
4	200	42.5	1.048
	300	47	0.722

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

CLSM can be transferred to the jobsite using ready-mix trucks, pumps, volumetric measuring, and continuous-mixing concrete equipment for jobsite mixing; dump trucks are discouraged (Ragan 2023). The material can be placed with a chute, conveyor, pump, or bucket. CLSM consolidates under its own weight and requires little spreading or compacting when at the appropriate slump. Thus, CLSM is typically cured in the ambient environment (ACI 1999). Further, CLSM does not require a cover or moisturizing equipment to properly cure it to the design strength, but the material might require protection from freezing.

Typical and common field-testing requirements for CLSM include visual checks, consistency checks (flowability and in-place density), and strength checks. The following ASTM standards are commonly used for the QA/QC of in-place CLSM:

- ASTM D6024: *Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application* (ASTM 2017b).
- ASTM C403/C403M: *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance* (ASTM 2017c).
- ASTM D4832: *Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders* (ASTM 2018).

Most of the specifications allowed 2 to 2.5 h of placement time for CLSM. Some specifications allowed up to 3 h (Kaneshiro et al. 2001). Some specifications also indicate at least two vibrators should be used (if needed) according to jobsite conditions.

Unstable soil from trench walls and floors should be removed before placing CLSM (Kaneshiro et al. 2001). Backfilling above CLSM is restricted until after the initial set of 8 h, or 138 kPa strength, is achieved. Alternatively, the results of an indentation of the standard test for the ball drop on CLSM can be used to estimate the setting (ASTM 2017b). Pavement, or other backfill layers, may be placed directly over the CLSM after setting.

Kaneshiro et al. (2001) presented specific construction specifications for when CLSM is used for pipeline fills to ensure proper placement and quality checks. As a start, the placement of material needs to be continuous. Operators should check the wet density to ensure the proper placement density is achieved to prevent segregation. Further, pipe flotation can be prevented by anchorage or backfill sequencing or ballasting, etc. Pours/lifts should be bulkheaded to prevent floatation or separate pours when required. Pipes should also be properly "choked" and supported with sandbags (or an equivalent) to allow free flow of CLSM around the pipes.

COST INFORMATION

The materials cost of CLSM poses a major disadvantage. CLSM's cost comes close to that of ready-mix concrete from several suppliers around the country, as highlighted in the following three examples:

- From Louisville Water Company Bid 16-175/Ready-Mix Concrete, the contractor priced 1 yd^3 of ready-mix concrete at \$127.20–\$148.40 during regular hours and \$190.80-\$212.00 after hours. In comparison, flowable fill was priced at \$100.70–\$148.40 (Louisville Water Company 2017).

- From GSI Concrete in Pennsylvania, 1 yd^3 of ready-mix concrete is priced at \$113 for the 3,000-psi mix and \$133 for the 5,000-psi mix. In comparison, 1 yd^3 of flowable fill is priced at \$120 (GSI Concrete 2022).

- For a competitive sealed bid in Frisco, TX, the letting for bid No. 1911-023 opened in April 2018 and had flowable fill (CLSM) priced between \$88 and \$157 per cubic yard, depending on the delivery option (Frisco n.d.).

Note that although the price per cubic yard of flowable fill is more expensive than other backfill materials (e.g., crushed stone backfill material typically costs \$16–\$23 per ton), flowable fill reduces in-place costs across the board (Charleston Stone Company 2023). For example, on a small pipe backfill job for the City of Houston Department of Public Works, more than \$12,000 was saved by using flowable fill (CLSM) (National Ready Mixed Concrete Association (NRMCA) 2011). The properties of CLSM, being nonsettling, self-leveling, quick drying, nonsegregating, and easy to excavate, makes it cost effective overall. An NRMCA presentation on the use of CLSM in transportation projects compared the labor cost for placing and compacting a traditional granular backfill to a flowable fill (Killingsworth 2021). The costs were

$226.18 versus $35.09, respectively, indicating that the higher material cost was offset during placement.

ENVIRONMENTAL CONSIDERATIONS

Folliard (2008) reported that CLSM is a consumer of various byproduct materials that are not typically allowed in conventional concrete, such as fly ash not meeting ASTM C618 (ASTM 2019a). Therefore, some concern could exist about the potential for leaching of constituents in byproduct materials (e.g., heavy metals, organics) from CLSM and the environmental impacts. Folliard (2008) studied the leachate potential of three fly ashes, one bottom ash, and one foundry sand. Tested heavy metal concentrations included arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. All the byproduct materials tested easily passed the toxicity characteristic leaching procedure (TCLP), meaning the heavy metal concentrations were very low and not of concern.

LCA STUDIES

The comprehensive literature review found no environmental product declarations (EPDs) or product category rules (PCRs) for CLSM materials in the United States or worldwide. Further, no comprehensive LCA studies were conducted in the United States or elsewhere. Most LCA studies examine traditional concrete mixes. Further, many research papers and reports focus on making the CLSM more “sustainable” by using recycled materials to replace cement (e.g., fly ash) and aggregates. Many of these studies have been reported earlier in this chapter. Thus, the lack of LCA studies on CLSM and the lack of PCRs that regulate the publication of EPDs for CLSM are major gaps in research and sustainability assessment that need to be addressed.

CASE STUDIES

Case studies reported for CLSM include its use in bridge approaches, utility fills, void fills, and other backfills:

- Du et al. (2006) reported on using CLSM for bridge approaches in many U.S. case studies. According to Du et al., the Ohio Department of Transportation (ODOT) pioneered this application, and the Delaware DOT favors using CLSM for many of its bridge approaches. Further, the Oklahoma DOT constructed three new bridges on U.S. 177 north of Stillwater, OK, out of five approaches constructed using different structural fill materials. One of the designs had an approximately 2.5-m (8-ft)-deep CLSM bed. No differential settlement at the end of the bridges with CLSM was reported after paving, but data collected before paving indicated the CLSM settled 44 mm/m (1.6 inches/yd), and the settlement increased incrementally until approximately 10 mo after placement. The Iowa DOT had experience with backfilling four bridge approaches using flowable mortar (CLSM), and no appreciable settlement was observed between the bridges and the bridge approaches.

- Seattle Public Utilities in the State of Washington used quick-setting CLSM fill to replace an old water main in downtown Seattle (Vanga 2013). Using CLSM greatly expedited the construction activity, which resulted in reducing the project duration and advancing construction activities. In a similar case study, CLSM was chosen to fill an abandoned pipeline under a segment of I–70 near Officers Gulch, Copper Mountain, CO (Vanga 2013).

- Several agencies and institutions have also experimented with using CLSM for various highway backfill applications. Table 6 provides a comprehensive summary from Folliard (2008) on the technical issues and applications addressed by the case studies and full-scale test sections by the different agencies. More information can be found in the original study.

Table 6. Matrix of field-testing issues and applications (Folliard 2008).

Issue/Application	**Agency or Organization**[a]					
	UT Austin	**NRMCA**	**Hamilton County (OH)**	**EBMUD**	**Texas DOT**	**TAMU**
Technical Issue Long-term strength gain/excavatability	x	x	—	x	—	x
Short-term strength gain/constructability	x	—	x	x	x	x
Corrosion of metals in CLSM	—	—	x	—	—	x
Productivity and cost	—	—	x	—	—	x
Resistance to freezing and thawing	—	—	x	—	—	—
Construction issues (i.e., pipe floating)	—	—	—	—	—	x
Settlement	x	—	—	x	—	—
Use of byproduct materials	x	x	x		x	x
Environmental issues	—	—	x	—	—	—
CLSM Application Backfill	x	x	x	x		x
Utility bedding	—	—	x	—	—	—
Void fill	—	—	—	x	—	—
Bridge approach	—	—	—	—	x	—

—No data.

[a] A field test was planned with Florida DOT, but permitting issues prevented the field test.

UT Austin = University of Texas at Austin; EBMUD = East Bay Municipal Utility District; TAMU = Texas A&M University.

CHAPTER 3. ESCS

INTRODUCTION AND BACKGROUND

ESCS are lightweight ceramic aggregates that are prepared by expanding and vitrifying select minerals, specifically select shales, clays, or slates, in a rotary kiln at temperatures exceeding 982 °C (1,800 °F) (ESCS Institute (ESCSI) 2023). If shale is used, the product is called expanded shale. If clay or slate are used, the products are called expanded clay and expanded slate, respectively. The production and raw material selection processes are strictly controlled to ensure a uniform, high-quality, lightweight aggregate (LWA). Figure 7 shows a typical structure of expanded clay aggregates. Figure 8 presents a map of the sources and manufacturers of ESCS in the United States, as reported on the ESCSI website.

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Figure 7. Photo. Lightweight expanded clay aggregate (Creative Commons n.d.a).

Original map © 2022 Google® Maps™. Modifications by FHWA to show locations (see acknowledgments section).

Figure 8. Map. ESCS sources and manufacturers in the United States (Google 2022).

ESCS have low relative density due to the cellular pore system that forms during the manufacturing process (ESCSI 2023). Heating certain raw materials to incipient fusion form the cellular structure. At the incipient fusion temperature, gases evolve within the pyroplastic mass, causing expansion, which is retained upon cooling. ESCS thus have uniformly distributed pores that range in size from 5 to 300 μm. The system with pores is continuous, relatively crack free, and produces high-strength ESCS. When exposed to moisture, the permeable pores closest to the surface typically fill with water within a few hours to a few days. Interior pores fill up with water extremely slowly and may take months of submersion to approach saturation.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using ESCS in highway backfill applications include the following (ESCSI 2023):

- Cost effective.
- Water and acid insoluble.
- Chemically inert.
- Highly durable.
- Increased stability.
- Free draining.
- Thermal insulation.
- Reduced overturning and lateral forces.
- High internal friction angle and high strength.
- Lightweight.
- Controlled gradations.
- Controlled settlement.

Disadvantages of ESCS are the initial cost of plants and manufacturing facilities and the energy-intensive manufacturing process.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

ESCS can be used in the following geotechnical applications for highways (ESCSI 2023):

- Retaining wall backfill.
- Bridge abutment fills.
- Slope stabilizer.
- Lightweight embankment fill.
- Insulating backfill.
- Underground conduits and pipelines.
- Various landfill applications.

MATERIAL CHARACTERIZATION

Physical Properties

ESCS produced by the rotary kiln process should meet the requirements of ASTM C330, *Standard Specification for Lightweight Aggregates for Structural Concrete* (ASTM 2017d). The following presents some of the common physical and mechanical properties of ESCS that should be met for highway geotechnical applications, with more detailed information provided in table 7 (ESCSI 2008):

- Soundness loss: A maximum of 30 percent with four cycles of magnesium sulfate is recommended according to AASHTO T 104, *Standard Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate* (AASHTO 2022a).

- Abrasion resistance: A maximum of 40 percent is recommended according to ASTM C131, *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine* (ASTM 2010b).

- Chloride content: A maximum of 100 ppm is recommended according to AASHTO T 291, *Standard Method of Test for Determining Water-Soluble Chloride Ion Content in Soil* (AASHTO 2022b).

- Grading: A wide variety of grain size distributions could be made available, specified based on performance needs, in accordance with ASTM C136, *Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates* (ASTM 2015b). Commercially available gradings include the following categories: 19.5–4.75 mm (3/4 inch to No. 4), 12.7-4.75 mm (1/2 inch to No. 4), 9.5–2.38 mm (3/8 inch to No. 8), 9.5–0 mm (3/8 inch to 0 inches), 51–19.5 mm (2 to 3/4 inch), and 51–0 mm (2–0 inches). Blends of the aforementioned categories can also be produced on request.

Table 7. Recommended physical and mechanical properties for ESCS.

Aggregate Property	Measuring Method	Test Method	Commonly Used Specifications for ESCS	Typical Values for ESCS	Typical Design Values for Ordinary Fills
Soundness loss	Magnesium sulfate	AASHTO T 104 (2022a)	<30 percent	<6 percent	<6 percent
Abrasion resistance	Los Angeles abrasion	ASTM C131 (2010b)	<40 percent	20–40 percent	10–45 percent
Chloride content	Chloride content of soils	AASHTO T 291 (2022b)	<100 ppm	10–70 ppm	—
Grading	Sieve analysis	ASTM C136 (2015b)	Wide variety	Wide variety	—
Compacted in-place bulk density (unit weight)	Density test	Contact ESCS producer for local practices	<1120 kg/m^3	640–1,040 kg/m^3 moist	1,600–2,080 kg/m^3
Stability (Φ angle, *f*)	DST consolidated drained triaxial-consolidated drained	ASTM D3080 (2012) (>0.75 inches removed) U.S. Army Corps of Engineers (USACE) EM 1110-2-1906 appendix X (USACE 1970)	Depending on procedure, grading, particle angularity, amount of compaction, and consolidating stress	35–45 degrees	30–38 degrees (fine sand—sand and gravel)
Loose bulk density (unit weight)	Loose	ASTM C29 (2017e)	Dry <50 lb/ft^3 saturated <65 lb/ft^3	Dry 480–800 kg/m^3	1,425–1,680 kg/m^3
pH	pH meter	AASHTO T 289 (2022c)	5–10	7.0–10	5–10

EM = engineer manual.

Further, Zukri et al. (2018) reported the physical and chemical properties of commercially available ESCS materials (table 8).

Table 8. Physical and chemical properties for commercially available ESCS materials (Zukri et al. 2018).

LWA	pH	Density (kg/m^3)		Specific Gravity	Permeability (cm/s)	Water Absorption (percent)	Chloride Content	Sulphate Content
		Loose	Compacted					
Normal aggregate	4–6.5	1,426	2,339	2.6–3.0	1–100	<2	<100 ppm	—
Argex®	No info.	450–635		0.62–1.30	—	7–35	<0.02%	<0.80%
ESCS	5–10	720	960	1.25–1.40	>1	8	10–70 ppm	—
GBC® India	6–7	380–710		—	—	18	—	—
Geo Leca	No info.	424–520		2.37	—	—	5–46	—
Leca®	8.05	220–325		0.41	0.1	36	0.50 percent	<450 mg/L
Optiroc	8–11	280–335		0.45–0.635	0.1–5	14–45	38 mg/kg	1,700 mg/kg
LEXCA Leca	9	266	283	0.771	2.53	30	6.8 mg/L	95 mg/L
Norlite	7.4	644	729	1.25–1.55	13.4–15	—	5–46 ppm	146 ppm
Stalite®	7–9	769	881	1.45	5–15	9–12	0.60–7.0 ppm	32 ppm
Techniclay	—	321–360		—	—	—	—	—

—No information.
info = information.

Mechanical Properties

Zukri et al. (2018) reported on the mechanical properties of commercially available ESCS materials. Researchers measured angles of internal friction by DSTs, consolidated drained (CD) triaxial tests, or large-scale triaxial tests. The angles of internal friction ranged between 35 and 53 degrees for the various products, indicating relatively high shear strength. Table 9 summarizes the full suite of results, and the maximum sizes of the tested particles are reported when available.

Table 9. Mechanical properties for commercially available ESCS materials (Zukri et al. 2018).

LWA	Gradation/Size Information (mm)	Internal Friction Angle	
		Measuring Method	**Value (degrees)**
Normal aggregate	—	Triaxial (CD)	3,642
Argex	—	—	35–42
ESCS	10–20	Direct shear; triaxial (CD)	35–45
GBC India	—	Triaxial (CD)	53
Leca	10–20	—	37
LEXCA Leca	—	Triaxial (CD)	35
Minto	—	Large-scale triaxial test	40.5
Norlite	10–20	Triaxial (CD)	42–53
Optiroc	10–20	Static triaxial	37
	0–32	Static triaxial	45
Solite	—	Large-scale triaxial test	40
Stalite	10–20	Direct shear; triaxial (CD)	4,346
Techniclay	—	Direct shear; triaxial (CD)	53

—No information.

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

ESCSI recommends consulting with the producers for precise information on aggregate grading, bulk density, in-place compacted density, friction angle, thermal conductivity, and placement method(s) (ESCSI 2018). ESCS fills are approximately half the weight of conventional fill materials. Design with ESCS should thus take advantage of the load reduction, coupled with the high internal friction angles commonly reported for the ESCS. Generally, ESCS can reduce vertical and lateral forces by more than one-half and thus be used to solve numerous geotechnical engineering problems and convert soft and unstable soil into usable property.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

No special equipment is needed on the jobsite for compacting ESCS (ESCSI 2008). The material can be placed in any weather with no waiting time between placing lifts. ESCS should be placed in uniform layers. Lift thickness and the number of passes by the compaction equipment are determined by the engineer, depending on project requirements (i.e., specified levels of stability, compaction, and density). A common practice is to limit the thickness of each uniform layer to 300 mm (12 inches) or less in a loose state before compaction. Layers are also commonly compacted using vibratory compaction equipment weighing no more than 12 tons static weight. Vibratory plate compaction equipment should be used in confined areas (3.7-14.9 kW (5-20 hp)). A minimum of two passes should be applied in the case of 150-mm (6-inch) lifts with a 5-hp plate power, and 300-mm (12-inch) lifts with a 20-hp plate (ESCSI 2008, 2018).

Further, the contractor or site engineer should take all necessary precautions to ensure the ESCS material is not over-compacted in the field. Construction equipment, other than for placement and compaction, should not be operated on exposed ESCS lightweight fill (ESCSI 2008, 2018).

AVAILABLE COST INFORMATION

The cost of shale in the United States ranges from \$20 to \$60 per ton, while slate ships between \$27 and \$64 per ton (Homeguide 2022a). The production of ESCS involves using a rotary kiln, which is an energy-intensive production process. Thus, the expansive shales and slates are at the higher end of the cost range (i.e., \$60 and \$64 per ton for shale and slate, respectively). This cost is equivalent to approximately \$85 per cubic yard when the lightweight density of these expanded aggregates is taken into consideration.

ENVIRONMENTAL CONSIDERATIONS

No health or safety issues related to using ESCS materials were cited in the literature. No study reported issues of toxicity with the leachate from these aggregates. The materials are known to be water and acid insoluble, chemically inert, and highly durable (ESCSI 2008).

LCA STUDIES

A PCR document for preparing an EPD for ESCS LWAs is available and geared toward U.S. production methods and applications (ASTM 2015c). The PCR is operated by ASTM, primarily for ESCSI. The targeted applications for ESCS in this PCR include all applications but primarily focus on masonry, concrete, asphalt pavement, lightweight geotechnical fills, horticulture, soil amendment, and water treatment applications. In the United States, the PCR expired in 2020, and no new amendments or newer versions were found online at the time this report was drafted.

Despite having a PCR for ESCS in the United States, the researchers found no publicly available EPDs for any commercially available ESCS material or supplier in the United States. However, the researchers also found very few EPDs for ESCS products manufactured in Europe. All these EPDs were for expanded clay products and included Leca expanded clay (Norway), Argex expanded clay (Portugal), and Laterlite S.p.A. expanded clay (Italy) (Leca 2017; Argex 2015; Laterlite S.p.A. 2018). Note that many of the manufacturers had multiple EPDs for their different products, but the researchers chose to present one as an example for each manufacturer in this report for brevity. The functional unit of all EPDs is 1.0 m^3 of materials produced. The results from the three EPDs are summarized for emissions and environmental impacts (table 10) and energy and resource consumption (table 11). For the environmental impacts, all three products had the same order of magnitude impacts in all categories, except for the Leca product from Norway, which had one order of magnitude lower ozone depletion potential (ODP). Similarly, for energy and resource consumption, Argex expanded clay from Norway had zero reported use of renewable secondary fuels, much lower than the other two products, but used significantly higher net fresh water to produce.

Table 10. Emissions and environmental impacts for three European expanded clay products.

Parameter	Unit	Laterite	Leca	Argex
GWP	kg CO_2-eq	5.44E+01	6.15E+01	4.56E+01
ODP	kg CFC-11-eq	7.55E-06	7.47E-07	4.27E-06
AP	kg SO_2-eq	2.20E-01	1.98E-01	1.03E-01
EP	kg $(PO_4)3$-eq	3.22E-02	4.93E-02	1.21E-02
POCP	kg ethene-eq	1.08E-02	1.19E-02	1.02E-02
ADPM	kg Sb-eq	1.32E-05	1.86E-05	7.70E-05
ADPE	MJ	7.21E+02	5.21E+02	3.80E+02

GWP = global warming potential; AP = acidification potential of land and water; EP = eutrophication potential; POCP = photochemical ozone creation potential; ADPM = abiotic depletion potential of materials; ADPE = abiotic depletion potential for fossil resources; CO_2 = carbon dioxide; eq. = equivalent; CFC-11 = trichlorofluoromethane; SO_2 = sulfur dioxide; PO_4 = phosphate; Sb = antimony; MJ = megajoule.

Table 11. Energy and resource utilization for three European expanded clay products.

Parameter	Unit	Laterite	Leca	Argex
RPEE	MJ	3.93E+01	8.28E+01	5.14E+01
RPEM	MJ	0.00E+00	3.44E-02	0.00E+00
TPE	MJ	3.93E+01	8.28E+01	5.14E+01
NRPE	MJ	7.69E+02	5.41E+02	3.88E+02
NRPM	MJ	0.00E+00	0.00E+00	0.00E+00
TRPE	MJ	7.69E+02	5.41E+02	3.88E+02
SM	kg	0.00E+00	0.00E+00	9.86E+00
RSF	MJ	0.00E+00	0.00E+00	0.00E+00
NRSF	MJ	6.22E+02	3.42E+02	0.00E+00
FW	m^3	4.32E-01	2.46E-01	6.26E+00

RPEE = renewable primary energy resources used as energy carrier; RPEM = renewable primary energy resources used as raw materials; TPE = total use of renewable primary energy resources; NRPE = nonrenewable primary energy resources used as energy carrier; NRPM = nonrenewable primary energy resources used as materials; TRPE= total use of nonrenewable primary energy resources; SM = use of secondary materials; RSF = use of renewable secondary fuels; NRSF = use of nonrenewable secondary fuels; FW = use of net fresh water.

CASE STUDIES

ESCSI (2018) reported a multitude of case studies using ESCS to solve challenging highway geotechnical problems. The following case studies have been reported in the United States using ESCS in real-world applications:

- Fill behind bridge abutment: I–90, Everett Road, Exit 5A (bridge over CSX Spur), Albany, NY. This project used 6,500 m^3 (8,500 yd^3) of ESCS materials. Construction was performed in phases to avoid interrupting traffic flow. ESCS was placed in 300-mm (12-inch) lifts on top of a geosynthetic fabric, which held the lifts in place. The ESCS backfill reduced loads on the existing poor subsoils and minimized settlements at the bridge approach. The lateral pressures acting on the abutments were significantly reduced compared to conventional sand, stone, or clay backfill due to the high angle of internal friction of the ESCS material.

- Slope stability: New York Route 32 at Kenwood Avenue, Delmar, NY. This project was originally constructed in 1963, but after decades of use, the fill on soft soils started to slip, causing movement in the highway. ESCS fill was specified as a solution for this problem due to its lightweight nature and high friction angle. ESCS of 3,975 m^3 (5,200 yd^3) of 19.5 mm (3/4 inch) to 4.75 mm (No. 4)-sized aggregates were used. The sloped portion of the fill was covered with normal-weight riprap to prevent erosion of the lightweight fill.

- Backfill behind mechanically stabilized earth (MSE) walls: Indiana "Major Moves" Project, U.S. 31 and 156th Street Intersection, Carmel/Westfield, IN. A new bridge and bridge approach design used MSE wall construction to eliminate the at-grade crossing with 156th Street. ESCS was used as the backfill material, and 26,000 m^3 (34,000 yd^3) were used between April and October 2013. Buried gas pipelines running under the intersection required the use of a lightweight fill to mitigate a vertical loading issue, and ESCS was chosen for this purpose. An excavator and a small rubber track dozer were used to place and compact 300-mm (12-inch) lifts of the LWA. A 20-hp vibratory plate compactor was used where the excavator could not manage.

- Bridge approaches: Tranters Creek bridge approach, Washington, NC (ESCSI 2018; Wall and Castrodale n.d.). Approximately 2,750 m^3 (3,600 yd^3) of ESCS material were used as the lightweight embankment material for widening and raising the existing bridge embankment as part of the bridge replacement. The embankment elevation was raised by 0.3 m (1 ft), and the bridge was lengthened by 36.6 m (120 ft). The roadway embankment fill was underlain by clayey alluvial muck (2.7–4.9 m (9–16 ft) thick). The older embankment consisted of very loose to loose, silty, fine to coarse sand and was showing poor performance.

- Road base: North Carolina Route 133, repairs to approaches at Lilliput Creek bridge, Brunswick County, NC. Originally, the bridge approach portion of the road had settlement problems that required an unusual amount of maintenance. The road approaches were excavated to 610 mm (24 inches) below the subgrade, and a geofabric was installed. The subgrade was then returned to elevation using 2,390 m^3 (3,125 yd^3) of lightweight ESCS aggregate fill. The construction was completed in August 2005. The repaired approaches have been in service for many years without showing any further issues.

- Pipeline fill: Calgary Pipeline, Calgary, Canada. This project was initiated by the City of Calgary. The reasoning behind using ESCS was to substantially reduce ground movement-induced stresses on buried pipes and structures and as an insulation layer to counteract frost heaving and resist adverse effects caused by freeze-thaw cycles. Using ESCS as a lightweight fill allowed the engineers to reduce the trench depth from 3.3 to 2.1 m (10.8 to 7.0 ft), resulting in cost savings. The design with ESCS also reduced the disruption of water supply by decreasing construction time.

- Embankment fill: Louisiana Department of Transportation and Development (DOTD) Test Project, Morgan City, LA. The Louisiana DOTD constructed test sections with sand fill, 2.9 m (9.5 ft) in depth. In one section, 0.76 m (2.5 ft) of ESCS LWA fill was used. The reduction in weight, coupled with the increase in long-term stability, provided the LWA's reduced settlement by 40 to 60 percent compared to the all-sand fill. Considerable savings in highway maintenance, repairs, and replacement can be realized if differential settlement is reduced.

Other case studies have also been reported by Wall and Castrodale (n.d.) in a webinar entitled "Expanded Shale Clay and Slate Lightweight Aggregate Geotechnical Fill":

- Design-build project: 11th Street Bridge replacement, Washington, DC, 2012. The 11th Street Bridge is a historic structure, and ESCS was used as a lightweight material to minimize weight on top of the stormwater drainage outfalls constructed in the 1850s. ESCS was also used as a backfill material for the MSE walls on the project.

- Emergency bridge replacement: Blackburn Road over Neabsco Creek, Woodbridge, VA, 2012. Tropical Storm Lee in 2011 and heavy rainfalls led to scouring of the bridge abutments. ESCS was used behind the bridge abutments to reduce lateral pressure on the drilled shafts.

- Rapid embankment construction: U.S. 17 bypass interchange, Myrtle Beach, SC. A 3- to 12.8-m (10- to 42-ft)-height embankment was constructed over soft compressible soil. ESCS was used to reduce lateral and vertical pressures due to the thick embankment design.

CHAPTER 4. FGA

FGA (figure 9) is a lightweight fill alternative frequently used in transportation projects. Beneficial properties of FGA include a low unit weight (<2.4 kN/m^3 (15 pcf) bulk dry unit weight), good insulating value, high friction angle, nonreactive and nonleaching behavior, volume stability, and high porosity (Loux 2022; AeroAggregates® n.d.). Additionally, the material is made from 100 percent recycled glass (primarily glass cullet and a foaming agent). Dry processing and closed-cell manufacturing are appropriate for transportation infrastructure applications.

According to a U.S. manufacturer of FGA, the U.S. manufacturing process uses 100 percent curbside recycled glass powder and mixes it with a foaming agent. The mixed powder is softened by heating in a kiln. During the process, FGAs are formed as the foaming agent creates bubbles in the mix (Loux 2022).

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A. One FGA product (Creative Commons n.d.a).

© 2012 Hagmag.

B. Another FGA product (Creative Commons n.d.a).

Figure 9. Photos. FGA.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using FGA in geotechnical highway applications include the following (Loux 2022; AeroAggregates n.d.):

- Lightweight material with a low net surcharge due to the low unit weight.
- High friction angle (high shear strength).
- Excellent insulation and drainage.
- Not flammable.
- No rot or decay.
- Easy to place, especially in difficult-to-reach areas or confined spaces.
- No special equipment required to construct, place, or compact.
- Ultraviolet (UV) stable, volume stable.
- Efficient installation—not weather sensitive.

Disadvantages of FGA include the following:

- Material costs can be relatively high compared to virgin aggregates (VA) and other lightweight materials, though this cost could be offset if hauling, labor, and placement are considered.

- Environmental risks exist because inhaling glass powder can lead to respiratory issues and skin irritation or both.

- Breakage concerns exist because the material is brittle. Construction guidelines need to be strictly followed.

- Concrete strength containing glass aggregates can be 10–20 percent less than conventional aggregates due to bonding issues.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

FGA can be used in the following geotechnical applications for highways (Loux 2022):

- Embankments.
- Retaining wall/MSE wall backfills.
- Bridge abutments backfill.
- Pipeline and utility backfill.
- Backfill material over and around tunnels and culverts.
- Roadway widening and shoulder repair.

MATERIAL CHARACTERIZATION

Physical Properties

Swan et al. (2016) conducted a laboratory study to evaluate the effect of compaction energy on gradation, compression, and direct shear strength of lightweight FGA produced by a U.S. FGA manufacturer. Dry and wet particle-size analyses were conducted before and after testing to evaluate particle breakage due to crushing under vibratory compaction, static compression, or direct shear testing. Vibratory compaction resulted in significant particle breakage, which led to a 1.4 times density increase to 3.2 kN/m^3 (20.3 pcf). Modified Proctor compaction with half the modified Proctor's energy level resulted in significant breakage and 2.4 to 2.7 times density increases (ASTM 2021). The density increased from 227.5 kg/m^3 (14.2 pcf) to a range between 537 kg/m^3 (33.5 pcf) and 612 kg/m^3 (38.2 pcf). The results indicate that uniformly graded FGA (as produced) transforms into an increasingly well-graded material with increasing compactive effort, static loading, and shear conditions. In accordance, using Proctor compaction to prepare samples with FGA might not be an appropriate method due to significant potential changes in gradation and density resulting from particle breakage. Instead, a more controlled and consistent method should be investigated in future research.

Arulrajah et al. (2015) reported the physical and mechanical properties of FGA and how it compares to a typical lightweight material and a conventional fill material. Table 12 provides the comparative data. Compared to a typical lightweight material, the density, water absorption, pH, and Los Angeles (LA) abrasion test results all fall within the limits of other lightweight and conventional fill materials. The CBR (strength) of FGA is higher than that of a typical lightweight material, and the peak friction angles are on the higher end of the range from that typically measured for lightweight materials.

Table 12. Engineering properties of FGAs (Arulrajah et al. 2015).

Engineering properties	Foamed Recycled Glass	Typical Lightweight Material	Typical Conventional Fill Material
D_{10} (mm)	0.13	N/A	0.09
D_{30} (mm)	1.2	N/A	1.30
D_{50} (mm)	18.7	N/A	4.40
D_{60} (mm)	20.6	N/A	6.70
Coefficient of uniformity (C_u)	158	N/A	78.83
Coefficient of curvature (C_c)	0.53	N/A	2.97
Gravel-sized particles: 4.75–40 mm (percent)	66	<70	47.9
Sand-sized particles: 0.075–4.75 mm (percent)	32	<40	42.2
Clay and silt-sized particles: <0.075 mm (percent)	2	<3	9.90
Minimum dry density (kg/m^3)	170	112–204	N/A

Engineering properties	Foamed Recycled Glass	Typical Lightweight Material	Typical Conventional Fill Material
Maximum dry density (kg/m^3)	290	204–306	N/A
Water absorption—coarse fraction (percent)	60	50–60	6.50–6.70
Water absorption—fine fractions (percent)	0.3	<1.0	6.50–7.50
pH	10.48	9–12	10.20–11.40
Organic content (percent)	0	0	1.7–2.1
CBR (percent)	9-12	2–10	172
LA abrasion loss (percent)	94	80–100	29.9–31.7
Peak apparent cohesion, c' (kPa)—DST	23.4	20–100	95
DST: Peak friction angle, ϴ (degrees)	55.7	35–60	65
DST: Critical state apparent cohesion, c' (kPa)	22.1	20–100	80

D_n = sieve size for which n percent of material is passing, n = 10 percent, 30 percent, 50 percent, 60 percent;
N/A = values not provided.

Mechanical Properties

Shear strength properties calculated for FGA using large-scale shear box testing setups (given the large sizes of the particles) are comparatively high. For one FGA material tested by Arulrajah et al. (2015), the measured cohesion and friction angles were 3.4 psi and 54.7 degrees, respectively. Arulrajah et al. (2015) tested geogrid-reinforced recycled foamed glass using a large-scale DST. The researchers found the geogrid-reinforced FGA material to be stress-hardening, and it exhibited smaller vertical displacement and greater dilatancy ratio than the unreinforced FGA material. The researchers also found the geogrid-reinforced FGA exhibited a stress-softening behavior. The failure envelope of the geogrid-reinforced FGA, at peak and critical states, yields a linear trend, likely due to the crushing of FGA particles and the rearrangement of crushed FGA after the peak shearing state. The interface shear strength coefficient, α, was approximately constant at 0.9, indicating that it can be used as the interface parameter for designing a reinforced embankment and MSE wall. In the case of geogrid-reinforced FGA, the geogrid carries the tensile forces, while FGA reduces the bearing stresses imposed on the in-situ soil.

Swan et al. (2016) conducted large-scale shear box testing at different normal stresses. The shear box was 12 inches by 12 inches in plane and had a total depth of 6 inches The researchers conducted tests on an as-received FGA material with no compaction at applied normal stresses of 14.4, 35.9, 57.5, 143.6, 287.3, and 426.1 kPa (300, 750, 1,200, 3,000, 6,000, and 8,900 psf respectively). The test series on a modified FGA material that had undergone modified Proctor compaction using ASTM D1557 with the lower compactive energy were also conducted at applied normal stresses of 143.6, 287.3, and 426.1 kPa (3,000, 6,000, and 8,900 psf respectively) (ASTM 2021a). Table 13 summarizes the results for peak friction angles and cohesion intercepts.

Table 13. Shear strength characteristics of FGA (Swan et al. 2016).

Tested Material	Range of Normal Stress (kPa)	Peak Friction Angle (degrees)	Peak Cohesion (kPa)
As-received FGA	14.5–57.2	56	2.1
As-received FGA	35.9–143.4	29	45.8
As-received FGA	143.3–426.1	27	46.0
Modified FGA	143.4–426.1	31	51.7

The authors of this report conducted triaxial tests on an FGA material (Glasopor®) produced in Norway and intended for use in aircraft energy-arresting system applications at the end of runways.[1] The authors tested both loose and compacted specimens at confining pressures ranging from 35 to 275 kPa (5 to 40 psi). The samples experienced a rapid stress gain at the low-strain levels toward the beginning of the test due to the crushing and densification of the particles. The behavior of the material and the shape of the stress-strain curves were found to be similar at the different confining pressures and compaction states. Figure 10 presents the stress-strain results for the loose and compacted specimens.

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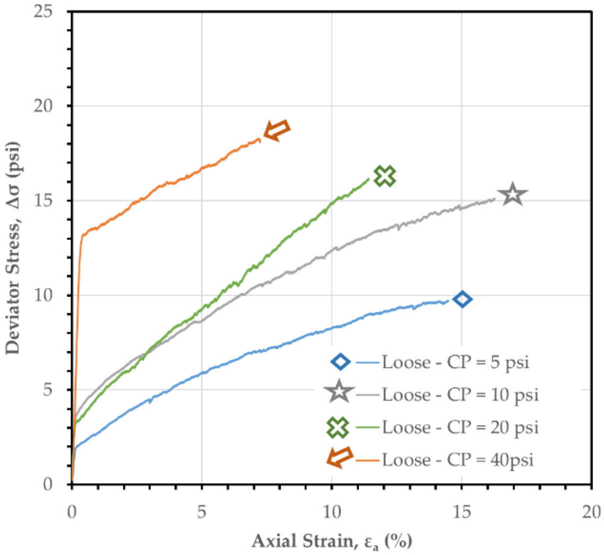
[1] Work performed under a small technical testing agreement for a company.



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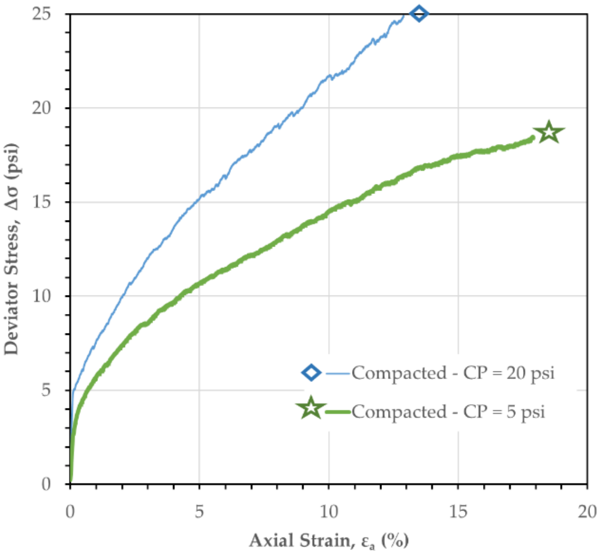
1.0 psi =6.895 kPa, 1 pcf = 16.0 kg/m^3.

A. Loose specimens, density = 9.1–10.3 pcf.



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1.0 psi =6.895 kPa, 1 pcf = 16.0 kg/m^3.

B. Compacted specimens, density = 11.1–11.4 pcf.

Figure 10. Graphs. Stress-strain relationships for loose and compacted FGA material tested at different confining pressures.

The researchers found no specific design guidelines or requirements for FGA used in highway geotechnical applications. Therefore, the researchers recommend consulting with producers for precise information on aggregate grading, bulk density, in-place compacted density, friction angle, and proper placement method(s). FGA design should thus take advantage of the load reduction, coupled with the high internal friction angles commonly reported for FGA, which can reduce the vertical and lateral forces by more than one-half. Surcharge and buoyancy calculations should be conducted to ensure that the aggregates do not float under submerged conditions. A thin cover material (e.g., conventional backfill) could be placed over the FGA to add any weight necessary to prevent buoyancy if that is a concern.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

Compaction of foamed glass layers is commonly performed with a tracked excavator or dozer exerting loads ranging from 28.7 to 47.9 kPa (600 to 1,000 psf) (Loux 2018). A maximum lift thickness of 24 inches is recommended, but a 300-mm (12-inch) maximum lift is specified if a plate compactor is used for the compaction. The FGA layers are normally compacted with two to four passes of the tracked excavator or dozer. Operating construction equipment on the FGA, other than for placement and compaction, should be avoided. Excessive compaction should also be avoided to minimize crushing of the LWA.

The guidelines listed in the previous paragraph, which are recommended by a U.S. manufacturer, are primarily obtained and modified from the following three Scandinavian installation guides that are available to provide direction on the proper installation of FGA (Loux 2022):

- The Swedish Geotechnical Institute handbook recommends using tracked equipment for installation. According to the handbook, the pressure exerted by the equipment should be less than 50 kPa (1,044 psf), the lift thickness should not exceed 0.8 m (2.6 ft), and two passes at a minimum are needed. If a plate compactor is used, the weight should be between 100 kg (220 lb) and 200 kg (440 lb), the lift thickness should not exceed 0.5 m (1.6 ft), and a minimum of four passes are required.

- The Norwegian Roadway Authority also recommends using tracked equipment exerting a force of 50 kPa (1,044 psf). The maximum lift thickness is 1 m (3.3 ft) and only 0.6 m (2 ft) for retaining wall backfills.

- The National Roadway Guideline from Finland recommends using tracked equipment with 30–50 kPa (627–1,044 psf) force, a minimum of two passes, and a maximum of 0.6 m (2 ft) lift thickness. For vibratory plate compactors, the weight should be between 45 and 200 kg (100 and 440 lbs.), the maximum lift thickness should be 0.4 m (1.3 ft), and the minimum number of passes is two.

McGuire, Loux, and VandenBerge (2021) conducted eight field-scale tests on FGA layers to answer two questions regarding the compressibility and volume reduction of FGA compacted in the field. The first is the expected reduction in FGA fill volume using a typical compaction method specification. The second is the increased volume reduction expected for additional passes of the compaction equipment beyond what is required by the specification. During the tests, compaction was performed using a dozer (two tests), two track-mounted excavators (three tests), a vibratory plate compactor (two tests), and a small tandem roller (one test). Each test involved compacting one to three lifts with multiple passes and observing reductions of the fill volume using a light detection and ranging scanner (LiDAR). Table 14 presents the specifications of the compaction equipment. The results of the study showed that a typical method specification results in compacted lifts with a volume that is 7.6 to 16.6 percent lower compared to the uncompacted volume after the placement of the lift. Note that a typical method specification (0.6 m (2-ft) lift compacted using four passes of tracked equipment for area fills) reduces fill volume by 7.6 to 10.7 percent. A typical 0.3-m (1-ft) lift compacted using four passes of a vibratory plate compactor in smaller areas reduces fill volume by 9.9 to 16.6 percent. The researchers found that the volume reduction versus the number of roller compactor passes followed a hyperbolic relationship (McGuire, Loux, and VandenBerge 2021).

Table 14. Compaction equipment specifications (McGuire, Loux, and VandenBerge 2021).

Equipment	Static Ground Pressure (kPa)	Contact Width (mm)	Empirical Compactor Effectiveness Coefficient, *C*
John Deere 700K XLT dozer	46.5	558	0.31
Doosan DX85R-3 excavator	38.3	451	0.79
Komatsu PC138USLC-11 excavator	32.9	710	0.48
Wacker WP 1550 vibratory plate	2.5	509	5.42
Bomag BMP 8500 roller	90.4	851	0.11

AVAILABLE COST INFORMATION

The cost for FGAs runs between \$54–\$61 per cubic meter (\$70–\$80 per cubic yard) (Gibson 2019). Construction does not require any special equipment, and hauling costs are lower than conventional aggregates because of the low density.

ENVIRONMENTAL CONSIDERATIONS

Environmental assessments (pH value, organic content, and leachate concentration) showed all the hazardous concentrations in the leachate are lower than 100 times those of the drinking water standards (Arulrajah et al. 2015; Lenart and Kaynia 2019). Thus, FGA is not considered hazardous for highway geotechnical and pavement applications.

LCA STUDIES

Energy savings assessment demonstrates much lower energy consumption relative to conventional aggregate-cement material in construction projects (Arulrajah et al. 2015). A set of standard references and PCR documents are available for Europe to conduct LCA studies for FGA. These references include European Norm (EN) 15804, the Institut Bauen und Umwelt (IBU) Parts A and B (2012), and the International Organization for Standardization (ISO) 14025 standard (European Committee for Standardization 2019; IBU 2012; ISO 2006). The references have been used for preparing EPDs for FGA in the European markets. The targeted applications for FGA in these PCR and reference documents include highway applications.

Four publicly available EPDs were found for FGA products manufactured in Europe. In particular, two manufacturers (Glasopor in Norway and Hasopor in Sweden) have published EPDs for their products (Glasopor 2014, 2017, 2020; Hasopor 2017). Glasopor had three available EPDs for three different products, while one EPD was found for a Hasopor product. Two similar products, one from Norway and one from Sweden, were selected to summarize the environmental impacts in this report. Table 15 provides a summary of the available information on selected products. The results from the two selected EPDs are summarized for emissions and environmental impacts (table 16) and energy/resource consumption (table 17). The functional unit of all EPDs is 1.0 m^3 of materials produced. For the environmental impacts, the products had varying impacts in most categories, but the difference was at most one order of magnitude except for the depletion of the ozone layer, where the difference is two orders of magnitude. The differences can be attributed to the two countries' different manufacturing processes and energy sources. The impact results for the energy and resource consumption were quite similar for the two manufacturers. The researchers did not find any publicly available EPDs for FGA in the United States.

Table 15. Available EPD information on three European FGAs.

Product	Producer	Country	EPD Validity	System Boundary	Functional Unit	Reference Standard(s) and PCR(s)
Glasopor 10–60 mm	Glasopor AS	Norway	01/16/2025	A1-A5	1 m^3 of Glasopor 10–60 mm	EN 15804[a] IBU—Parts A and B[b]
Glasopor 10–60 mm	Glasopor AS	Norway	01/31/2022	A1-A4	1 m^3 of Glasopor, to factory gate	EN 15804[a] IBU (Parts A and B)[b]
Glasopor 10–60 mm	Glasopor AS	Norway	10/27/2019	A1-A3 (Cradle-to-gate)	1 m^3 of Glasopor 10–60 mm	EN 15804[a] IBU (Part B)[b] ISO 14025[c]
Hasopor foam glass 10–60 mm	Hasopor AB	Sweden	12/13/2022	A1-A3 (Cradle-to-gate)	1 m^3 of Hasopor ready for transport	EN 15804[a] ISO 14025[c]

[a] European Commission for Standardization 2019.
[b] IBU 2012.
[c] ISO 2006.

Table 16. Emissions and environmental impacts for three European FGAs.

Parameter	Unit	Hasopor	Glasopor
GWP	kg CO_2-eq	7.77E+00	6.96E+00
ODP	kg CFC11-eq	7.23E-08	1.01E-06
AP	kg SO_2-eq	2.05E-02	3.01E-03
EP	kg $(PO_4)3$-eq	2.66E-03	2.22E-02
POCP	kg ethene-eq	8.33E-04	1.19E-03
ADPM	kg Sb-eq	1.70E-05	1.96E-05
ADPE	MJ	7.99E+01	1.07E+02

Table 17. Energy and resource utilization for three European FGAs.

Parameter	Unit	Hasopor	Glasopor
RPEE	MJ	5.41E+02	4.38E+02
RPEM	MJ	0.00E+00	4.50E-01
TPE	MJ	5.41E+02	4.38E+02
NRPE	MJ	8.13E+01	1.08E+02
NRPM	MJ	0.00E+00	4.00E-02
TRPE	MJ	8.13E+01	1.08E+02
SM	kg	1.53E+02	1.80E+02
RSF	MJ	0.00E+00	1.97E-04
NRSF	MJ	0.00E+00	−7.22E-06
FW	m^3	1.40E+00	0.00E+00

CASE STUDIES

Case studies for all the target geotechnical applications of interest in this report, except slope stability, were mentioned in the literature. FGA has been used as a lightweight material for embankments, backfills behind retaining walls, bridge abutment fills, and backfill for pipes with no reported failures or adverse effects. No extensive details were found on the performance of the FGA in these applications. A concise list of case studies follows:

- Case studies in Europe include New Metro Line from Jar to Kolsås, Halden Rail Yard, New E18 Motorway—Retvet-Knapstad, Norwegian Public Roads Administration, Hämeenlinna, and Highway E12 (Loux 2022).

- Case studies in the United States include Philadelphia Navy Yard, Pennsylvania DOT; I-95 Cottman-Princeton Ramp F, Pennsylvania DOT; Route 7/Hackensack, New Jersey DOT; and Southeastern Pennsylvania Transportation Authority Media Line (Loux 2022).

- FGA was approved (as of 2018) for use in the United States by the Maryland DOT State Highway Administration, Virginia DOT, New York State DOT, Massachusetts DOT's READi (Review, Evaluate, Accelerate, Deploy, innovation) Committee, Connecticut DOT, New Hampshire DOT, Pennsylvania Turnpike Innovation Council. Two projects were conducted with Pennsylvania DOT, and the first project was conducted with New Jersey DOT (Loux 2022).

CHAPTER 5. LCC

INTRODUCTION AND BACKGROUND

LCC is a mixture of portland cement, water, and air created through a preformed foaming agent, as shown in figure 11 (American Society of Civil Engineers (ASCE) Texas Section 2022). Other ingredients may be incorporated into the mix if they do not adversely affect the quality, size, and distribution of the air bubbles in the cellular concrete. Some common examples include fly ash, slag, silica fume, fibers, gums, accelerators, and retarders. Having low viscosity, LCC allows for long-distance placements and nearly self-leveling installations. As shown previously in figure 2, LCC typically has higher cement content and lower water content than CLSM in the original mix, but LCC tends to be more economical due to foaming and the inclusion of air bubbles (Halsted 2020). LCC is typically placed into its final location using a pump and hose. The LCC is fluid enough to self-consolidate, and no vibration is required. If placed in moderate temperatures (15 to 27 °C), LCC will set and harden within approximately 10 to 14 h.

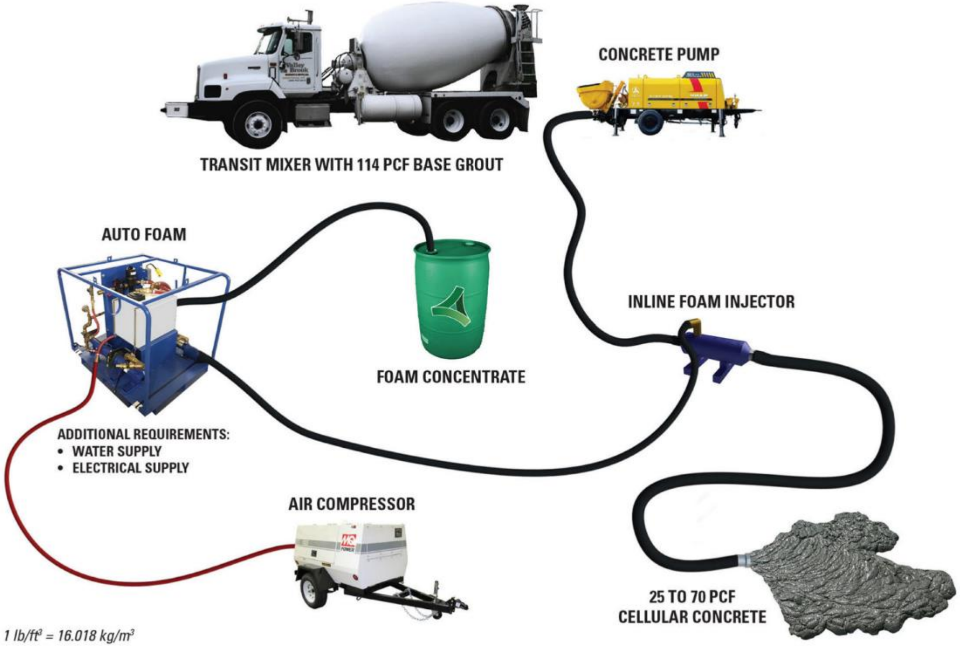

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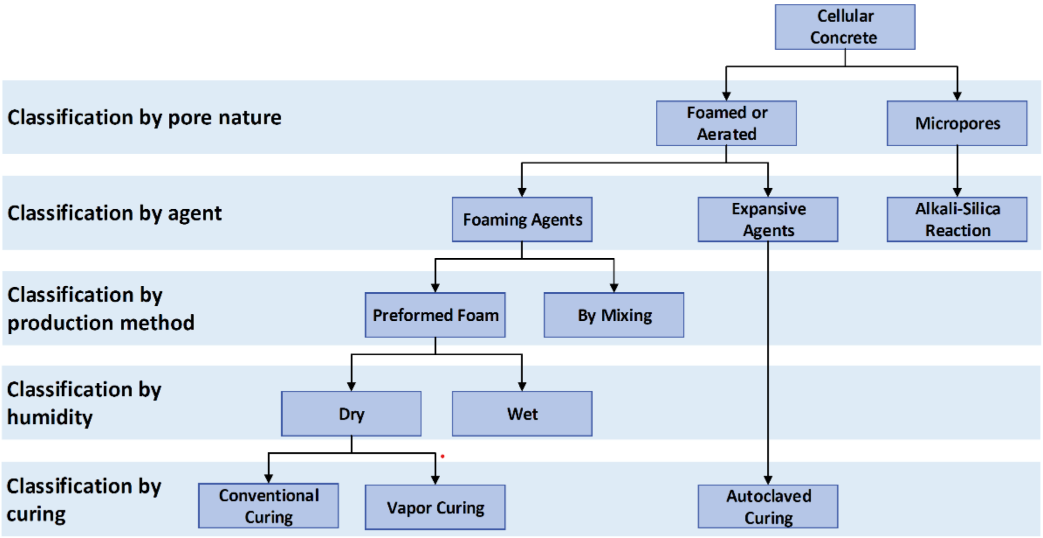
Figure 11. Illustration. Preparation of ready-mixed LCC (Taylor and Halsted 2021).

After placing and hardening, the LCC material should be protected with a wearing course or a surface layer such as concrete, soil, subbase material, drainage mat, etc. No recommended maintenance exists for in-place LCC; once buried and protected, no additional maintenance would be necessary (ASCE Texas Section 2022). Thus, LCC can save construction time, money, and natural resources by replacing aggregates with air bubbles in numerous project applications (Halsted 2020). According to Chica and Alzate (2019), LCC can be classified based on different metrics, including pore nature, agent, production method, and curing method. Figure 12 presents the metrics for classification. This chapter focuses on the pores with a foamed or aerated nature.



© 2019 Chica and Alzate. Modifications by FHWA to colors, shapes, and classification labels.

Figure 12. Illustration. LCC flow chart (Chica and Alzate 2019).

ADVANTAGES AND DISADVANTAGES

Reported advantages of using LCC in highway backfill applications include the following (Taylor and Halsted 2021):

- LCC is a lightweight, strong, durable, and inexpensive soil or fill replacement for geotechnical applications.
- LCC is self-compacting and highly fluid, with water-to-cement ratios (W/C) ranging from 0.35 to 0.80.
- LCC is very strong compared to the material it replaces in the geotechnical environment (typically soil and compacted aggregates).
- The surface of a hose-placed LCC is relatively flat with a slight splatter pattern and normally does not require any additional finishing or curing compounds.

Disadvantages of LCC include the following (Taylor and Halsted 2021):

- Water content significantly affects many properties of LCC, especially its strength and viscosity.
- Small variations in mix designs can cause great differences in the final product, possibly leading to unacceptable materials, failures, and unexpected expenses.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

LCC can be used in the following geotechnical applications for highways (Portland Cement Association (PCA) 2023):

- Lightweight road bases and fills.
- Bridge approach embankments.
- Void and cavity fills.
- Pipe and culvert abandonment fills.
- Annular space tunnel grout fills.
- Foundation fills and energy-arresting systems.
- Retaining wall backfills.
- Landslide repair and slope stabilization fill.
- CDF.

MATERIAL CHARACTERIZATION

Physical Properties

Measured physical properties for LCC include autogenous (drying) shrinkage, permeability, sorption, heat of hydration, and thermal conductivity. Physical properties of interest depend on the state of LCC. Ramamurthy, Nambiar, and Ranjani (2009) broadly classified LCC properties into fresh and hardened state properties. Ni, Oyeyi, and Tighe (2020), on the other hand, reported that LCC properties could be divided into the fresh state, early state, and hardened state.

In the fresh state, LCC is generally free-flowing, self-leveling, and self-compacting (highly workable). Stability (volumetric stability) is crucial because the separation of solids and air phases might cause segregation during fresh state if the LCC is unstable. Consistency (flow behavior), on the other hand, depends on its spreadability and flowability. Spreadability can be measured using the Brewer spread test and slump flow test (British Standards Institution 1998). Flowability is determined by measuring the time taken for the paste to flow through a Marsh cone (Ni, Oyeyi, and Tighe 2020).

In LCC's early state, two main physical characteristics are of interest: heat of hydration and rate of hardening. The volume of pour, cement content, and concrete density influence the heat of hydration. The peak temperature can decrease by 40 percent when the amount of cement is decreased from 600 to 300 kg/m^3. The peak temperature also decreases when more than 30 percent of the cement is replaced with fly ash. For the rate of hardening, there is no standard test method for determining the setting time of LCC. However, the ASTM C266 test method for cement may be a suitable procedure to test the setting time of LCC (ASTM 2021c; Ni, Oyeyi, and Tighe 2020).

LCC is quite thixotropic, making restarting the construction difficult once the concrete starts to harden. In the hardened state, the crucial physical and functional properties include drying shrinkage, density, thermal insulation/conductivity, durability properties, water absorption, permeability, porosity, and freeze-thaw resistance.

Mechanical Properties

UCS is the most commonly measured and reported property for hardened LCC. Other reported mechanical properties in the hardened state include flexural strength, indirect tensile strength, modulus of elasticity, and Poisson's ratio. ACI provides a table of industry-accepted values for maximum cast density and range of UCS properties for various LCC mixes, as shown in table 18 (Halsted 2020).

Table 18. Typical density and compressive strength of LCC mixes (Halsted 2020).

Oven-Dry Density		Usual Range of UCS at 28 d	
lb/ft^3	kg/m^3	psi	MPa
20–25	320–400	70–125	0.48–0.86
25–30	400–480	125–225	0.86–1.55
30–35	480–560	225–350	1.55–2.41
35–40	560–640	350–450	2.41–3.10
40–50	640–800	450–750	3.10–5.17

Ni, Oyeyi, and Tighe (2020) reviewed the potential use of LCC in pavement applications and reported the mechanical properties of LCC mixes and how they vary with compressive strength. Table 19 presents the results of that review. In general, as the compressive strength increases, the average drying shrinkage decreases, the modulus of elasticity increases, and thermal conductivity increases.

Table 19. Mechanical and thermal properties of LCC mixes (Ni, Oyeyi, and Tighe 2020).

Maximum Compressive Strength (ksi)	Average Drying Shrinkage (percent)	Maximum Modulus of Elasticity (ksi)	Minimum Thermal Conductivity (W/mK)
1.0	0.30–0.35	1,000	0.10
1.5	0.22–0.25	1,500	0.11
2.0	0.20–0.22	2,500	0.17
3.0	0.15–0.18	3,000	0.23
5.5	0.09–0.11	4,000	0.38
8.0	0.07–0.09	6,000	0.50
10.0	0.06–0.07	12,000	0.62

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

LCC's properties depend on the microstructure and composition, which are a function of the binder (cement and additives), method of pore formation, and curing (Narayanan and Ramamurthy 2000; Ni, Oyeyi, and Tighe 2020). According to Brady, Watts, and Jones (2001), no standard method exists to calculate LCC's mix proportions. Densities for LCC mixes typically range from 320 to 800 kg/m^3 (20 to 50 pcf), with 28-d UCSs ranging from 483 kPa to 5170 kPa (70 to 750 psi). The high desorption (50 to 200 kg/m^3) of LCCs makes designing LCCs for a target dry density challenging (Jones and McCarthy 2006). Therefore, a target plastic density is used as the design criterion. The target plastic density is assumed to be the sum of solids and water mix as presented in the following equation (Brady, Watts, and Jones 2001; Dhir, Jones, and Nicol 1999; Ni, Oyeyi, and Tighe 2020).

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

Where:

D = target plastic density (kg/m^3).
C = cement content (kg/m^3).
W = water content (kg/m^3).
F = fine aggregate content (kg/m^3).

Other design concerns for LCC include bearing capacity, hydrostatic pressure, buoyancy, punching, design life, seismic considerations, temperature during hydration, drainage, structural number, angle of friction, and pavement support design. Chica and Alzate (2019) presented the physical and mechanical properties of LCC mixes for mixes using fly ash and other additives for cement replacement. Part of their data is presented in table 20. Recycled and byproduct materials are allowed in LCC mixes as long as the minimum required physical and mechanical properties (primarily the UCS) are met.

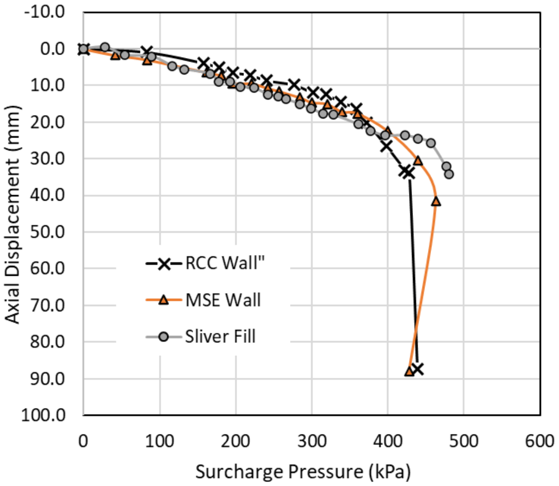
Table 20. Physical and mechanical properties of LCC mixes with partial cement replacement (Chica and Alzate 2019).

		Physical Properties		**Mechanical Properties 28 d**		
Type of Additive	**POC: Binder**	**Dry Density (kg/m^3)**	**Porosity/ Sorptivity (%, mm)**	**Shrinkage (%)**	**Thermal Conductivity (W/mk)**	**Compressive Strength (MPa)**
Fly ash-class F	1:3	—	2.5 mm	0.37	—	5.5
Fly ash-class F	1:1	1,150	29%	—	—	19
Fly ash—class F	—	1,000	31%	—	—	9
Fly ash-class F	—	650	34%	—	—	4
Fly ash	1:0.25	1,000	—	—	—	1.4
Fly ash	1:1.5	1,000–1,200	<10%	0.06–0.10	—	3.7–6.7
Fly ash	—	1,300–1,500	—	—	—	10–18.8
Fly ash	0.3	800	56%	—	—	3.92
Fly ash	1:0.3	1,590		150–550	—	12.1–32.1
Class F fly ash + peroxide	1:0.4	100–300	80.3–70.9%	—	0.043–0.078	0.12–1.0
Fly ash Class F + blast furnace slag + hydrogen peroxide	0:5	1,889–2,106	12–25.4%	—	—	38.3–47.8
Fly ash + blast furnace slag + silica fume	1:20	1,020–1,550	—	—	0.24–0.75	4.2–44.1

		Physical Properties		Mechanical Properties 28 d		
Type of Additive	POC: Binder	Dry Density (kg/m^3)	Porosity/ Sorptivity (%, mm)	Shrinkage (%)	Thermal Conductivity (W/mk)	Compressive Strength (MPa)
Fly ash + silica fume	1:1.5	1,280–1,870	—	—	0.498–0.962	19–47
Blast furnace slag	0.3–0.7	1,300	—	—	—	2.2–0.5
Blast furnace slag	1:6	153–303	6.6–8.3%	—	0.05–0.071	0.57–1.1

—No data.

In a full-scale laboratory study, Wilkinson (2021) and Rollins (2020) investigated using a reinforced LCC backfill behind an MSE wall. The reinforcement included ribbed strips measuring 51 mm (2 inches) wide and 5 mm (0.2 inches) thick. The experiment was conducted in a large-scale box, 3 m (10 ft) tall by 3.8 m (12.5 ft) long by 3 m (10 ft) wide. The MSE wall panels were nominally 1.5 m (5 ft) tall by 3 m (10 ft) wide and 0.15 m (0.5 ft) thick. The study involved a 1:1 slope of silty sand with a sliver fill of reinforced LCC behind the MSE wall panels. The researchers concluded that MSE walls with LCC sliver fills adjacent to soil slopes can withstand significant surcharge loadings with limited axial and lateral deformations (figure 13). Failures and excessive displacements or both can occur when the surcharge pressures are increased to about half of the UCS of LCC. The researchers found the surcharge pressure versus axial settlement for the sliver LCC fill test to be consistent with curves from previous tests conducted by the researchers with a recycled crushed concrete (RCC) cantilever wall and an MSE wall prior to failure. The failure load in the LCC case was also somewhat higher due to the higher UCS for the LCC. In addition, the researchers previously tested a full-scale MSE wall with an unreinforced LCC backfill and concluded that the failure of the reinforced MSE wall in this study was more ductile compared to the brittle failure of the unreinforced LCC, which indicates an improved performance produced by the MSE reinforcements.



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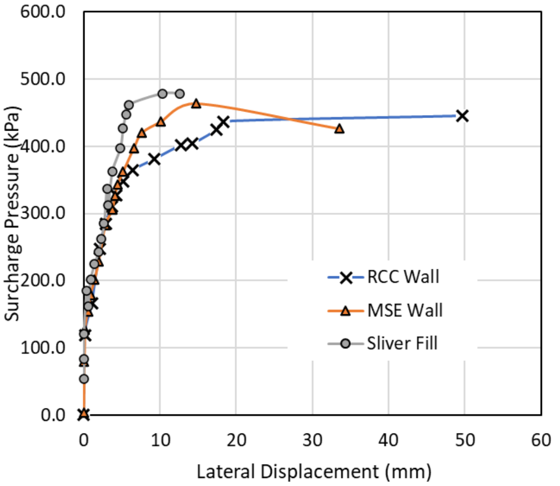
A. Load-axial displacement behavior.



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B. Load-lateral displacement behavior.

Figure 13. Graphs. Load-displacement behavior of full-scale MSE walls backfilled with various materials, including LCC (Rollins 2020).

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

In 2021, the PCA and the National Concrete Pavement Technology Center (CP Tech Center) at Iowa State University published a comprehensive report on the use of LCC in geotechnical applications (Taylor and Halsted 2021). The report primarily focused on the proper construction and QA and QC methods used to produce high-quality mixes with LCC. Most of the information in this section comes from that report. Overall, LCC should be carefully observed, inspected, and regulated with the highest QC available. Field measurements of unit weight, along with the known C/W ratio of the fresh LCC mixture, are the primary QC mechanisms. Wet density (cast density, or target plastic density, as defined in equation 1) is the density used in the specification and design of LCC projects.

LCC should not be allowed to set and then be remixed (Taylor and Halsted 2021). Instead, it should be kept plastic until allowed to set in its final location. Weather conditions should be monitored before starting LCC placement. If heavy rain is imminent, placement should be delayed; however, LCC mixes can still be placed in conditions of light rain. LCC placement is not recommended if the ambient temperature is below 32 °F (0 °C) or above 100 °F (38 °C). High heat can evaporate the water, causing excessive shrinkage. Cold weather, on the other hand, can inhibit the curing time and the quality of placed LCC.

Transportation

Cement and water slurry mix are routinely delivered to jobsites for LCC (Taylor and Halsted 2021). Transportation of premixed LCC should always be avoided because vibrations from movement may displace the entrained air and alter the density of the final product. Prolonged periods in a ready-mixed concrete truck may also cause the properties of LCC to change.

Mixing and Construction Equipment

Mixing energy (shearing) imparted to the mixture affects the final properties and is the primary factor affecting production equipment selection. Taylor and Halsted (2021) reported that batch mixing and auger mixing (mobile volumetric mixers) are the two types of production systems generally used to mix cement and water in LCC.

Batch mixing is the simplest system. It provides an excellent mix quality at low production rates and can produce 23 to 38 m^3 (30 to 50 yd^3) of LCC per hour (Taylor and Halsted 2021). Batch mixers are typically mounted on a trailer for easy mobility. The mixing action must be aggressive enough to thoroughly disperse the cement, water, and foaming agent. When a batch mixer is used, operators should ensure enough mixing time to provide a uniform product with no cement lumps. High-shear batching mixers result in higher strength LCC due to faster mixing and can produce 38 to 115 m^3 (50 to 150 yd^3) of LCC per hour.

Auger mixers (mobile volumetric mixers), on the other hand, use a rotating shaft and flange (auger) to blend ingredients. An operator must pay attention to the first amounts of material exiting the machine and make flow and rate adjustments to ingredients. Auger mixers are a convenient and fast method for making large volumes of LCC. Production rates vary from 23 to 382 m^3 (30 to 500 yd^3) per hour for the largest equipment (Taylor and Halsted 2021). The prepared LCC may be placed directly into the final location. For other types of mixers, LCC is typically pumped first.

Pumping LCC can be challenging. The challenge can occur a little later during placement when the cement paste starts to collect on the interior walls of the pump and pumping hoses and begins to solidify. Operators should closely control pumping pressures with LCC, given that pressure makes a difference with preformed foam. Preformed foam must conform to the properties listed in ASTM C869 when tested following the procedures in ASTM C796 (ASTM 2016b; ASTM 2019b). Field monitors should check density in accordance with ASTM D6023 before and after pumping, observing any increase or change in density (ASTM 2016a).

The three pumping systems most used for LCC are progressive cavity pumps, peristaltic pumps, and piston pumps (Taylor and Halsted 2021). Less commonly used pump types are ball valve pumps, centrifugal pumps, and diaphragm pumps. Progressive cavity pumps are the most common for LCC. Progressive cavity pumps are extremely steady, with no pulsing required, and they keep themselves clean on the inside during operation. These pumps operate at relatively low pressures ranging between 690 and 2,070 kPa (100 and 300 psi). On the other hand, peristaltic pumps are squeeze pumps that can easily transport LCC. The benefit of using peristaltic pumps for LCC is that they separate the cementitious materials from the pumping mechanism, which makes them beneficial for sticky and solidifying LCC mixtures. Peristaltic pumps have lower repair costs and can obtain higher pressures than progressive cavity pumps. Lastly, piston pumps are reliable and provide sufficient power for moving fluids. Piston pumps are the third most common pumps for LCC and should be used with caution since a line blockage can lead to extremely high pressures. Piston pumps commonly use a check valve and a piston retracting system.

Placement and Handling

Most LCC placing equipment uses a progressive cavity pump because it is extremely steady and self-cleaning. Peristaltic pumps can also be used to transport LCC easily. Factors to consider during placement include the following (Taylor and Halsted 2021):

- Metered cement content or flow rate.
- Metered water content or flow rate, density of cement, and water slurry.
- Density of preformed foam.
- Density of the 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.
- Temperatures that are excessively hot or cold.
- Lumps of cement in the mix.
- Leakage in the formwork (if present).
- Excessively high cure heat.
- Location of any bleed water after curing.
- Buoyancy on LCC layers placed below grade.
- Weather (i.e., avoid placement in heavy rain).

QA/QC Measures—Inspection, Testing, and Maintenance

ASTM testing necessary for LCC includes ASTM C495, ASTM C796, and ASTM C869 (ASTM 2019c; ASTM 2019b; ASTM 2016b). An experienced quality engineer should be employed for verification of LCC’s quality. The two main QC parameters are the material density and the UCS of the hardened material. Slurry density checks should be performed regularly to ensure that the flow meters for the cement and water are operating properly. The wet density and temperature of the mix should be monitored during production and placement, with necessary adjustments made to density if and when required. Table 21 presents the density and compressive strength sampling requirements and acceptance criteria.

Table 21. Sampling requirements for LCC mixes for density and compressive strength testing (Taylor and Halsted 2021; Ni, Oyeyi, and Tighe 2020).

Material Property	Frequency	Acceptance Criteria	Comments/Additional Requirements
Density	One per batch or every 10 m^3 Every 50 m^3 or once per 20 min during continuous production	10 percent of the design density	No additional comments or requirements
Compressive strength	One sample per 100 m^3	Meets or surpasses design strength	75 × 150 mm cylinders Store in an unobstructed condition within 13.7 m of the molding area Curing temperature of 77–86 °F for 24-96 h Cure in an 80–100-percent humidity chamber at 64–81 °F

Further, LCC construction and placement have some special considerations. Excessive walking and driving directly on the LCC surface can cause damage and should be avoided (Taylor and Halsted 2021). As a rule of thumb, construction may proceed as soon as the LCC layer can be walked on without excessive surface penetration (up to 1.0-inch penetration is acceptable).

According to ACI Committee 523, special precautions should be taken if the ambient temperature is below 32 °F or above 100 °F (ACI 2013). LCC placed in moderate temperatures (60-80 °F) will set and harden within 10–14 h. Moisture should not evaporate off the placed LCC too quickly to avoid excessive shrinkage. In most applications, shrinkage cracks are only superficial and do not detrimentally impact service life. Excessive evaporation of water from the LCC can be reduced by covering the surface with a layer of plastic sheeting or insulated blankets. Due to the insulative properties of LCC, a relatively high thermal differential is possible, causing surface cracking and accelerated wear if left exposed.

Postconstruction inspection is also crucial for LCC. The LCC should be inspected the day after placement, and the mix should be stable enough to walk on with limited surface impressions of no more than 1.0 inch (Taylor and Halsted 2021). Postconstruction testing primarily involves testing for UCS since no strict standards have been developed for other properties. The procedure provided by ASTM C495 provides the most accurate laboratory results for UCS testing (ASTM 2019c; Siebold and Tootle 2016). Variations (e.g., oven drying or improper curing) can have dramatic effects on UCS test results.

AVAILABLE COST INFORMATION

The cost of LCC depends on several factors, primarily the mix composition and properties, including water concentration ratio, foam density, and cost per gallon of foam concentrate. For example, a 30 pcf wet-density material starting with 1 yd of neat cement and having a 0.50 W/C ratio would require 2,060 lb of cement, 467 kg (1,030 lb) of water, and 2.27 m^3 (80 ft^3) of foam. The total yield of LCC material would be 2.9 m^3 (3.75 yd^3). With these calculations, the base slurry cost is \$175 per cubic yard (delivered as a local ready mix). The cost of foam is \$36 (based on \$13.2 per L (\$50 per gal), 48 kg/m^3 (3 pcf) foam density, and 40:1 water concentrate ratio). Thus, the total material cost is \$211 per yield. This cost divided by 2.9 m^3 (3.75 yd^3) equals \$56.26 per cubic yard of cellular concrete (Richway Industries 2022). This cost is still significantly less than CLSM and ready-mix concrete if comparing only material costs.

ENVIRONMENTAL CONSIDERATIONS

Similar to CLSM, the major environmental concern with LCC is the leaching of toxic levels of minerals from a byproduct material used in the mix. However, as indicated by Folliard (2008) for CLSM, leachate potential from three tested byproduct materials, namely three fly ashes, one bottom ash, and one foundry sand, was lower than tolerable levels. Heavy metal concentrations, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, passed the TCLP, meaning the heavy metal concentrations were very low and not of concern.

LCA STUDIES

In the comprehensive literature review, the researchers found no EPDs or PCRs to date for LCC materials in the United States or worldwide. Further, no comprehensive LCA studies were conducted in the United States or elsewhere. Some research papers and reports focused on making the LCC more “sustainable” by using recycled materials to replace cement (e.g., fly ash). However, with normal cement-water mixes, the only concern for leachate and safety from LCC would be the type and chemical composition of the foaming agent. The lack of LCA studies on LCC and the lack of PCRs that regulate the publication of EPDs for LCC is a research gap that needs to be addressed.

CASE STUDIES

There have been numerous installations of LCC for geotechnical applications with excellent performance records across the United States. LCC is extremely stable long term and has no known flaws once properly designed and installed. Case study examples in the United States include the following:

- Bridge approaches and retaining wall backfills (Sutmoller 2020). The Illinois DOT (IDOT) installed LCC in a segmental wall configuration on the Lake Shore Drive and I-55 Interchange. In this project, 16,820 m^3 (22,000 yd^3) of LCC (384–480 kg/m^3 (24-30 pcf)) were placed to drastically reduce lateral and vertical loads and enable the construction of three new ramps. In another IDOT project for the Circle Interchange, 13,762 m^3 (18,000 yd^3) of LCC (384–480 kg/m^3 (24–30 pcf)) were placed at a circle interchange for the reduction of lateral loads.

- Fill for underground tanks, pipelines, abandoned mines, and conduits (Sutmoller 2020). LCC was used in a water main abandonment fill application as part of an Illinois Tollway project. High fluidity, lightweight, and elevated compressive strength made LCC an ideal choice for this project. A total of 9,940 m^3 (13,000 yd^3) of LCC (384–480 kg/m^3 (24-30 pcf)) was installed into 3,962 m (13,400 LF) of abandoned water mains along three Illinois tollways.

- Rapid Design and Construction of an Integral Abutment Bridge with MSE Walls and Cellular Concrete Backfill—Manitoba, Canada. LCC was used for the Chief Peguis Trail Extension at the Rothesay Street Overpass. Loewen, Baril, and Eric (2012) published a comprehensive paper on the design and construction challenges of this project. Traditional structures could not achieve the project goals, so LCC was used as the fill behind MSE walls, abutment piles, and some embankments. The project used LCC backfill up to a depth of 5 m (16.5 ft) to compensate for poor soils and high anticipated settlement. Operators poured LCC with a unit weight of 476 kg/m^3 (29.7 pcf). The benefits of LCC included low weight, cost savings, and rapid construction. As Loewen, Baril, and Eric reported, the components of the structure performed well, and the expansion and contraction of the structure performed as anticipated.

- Slope stability. Reported case studies include the following:
  - Mount Hamilton Road: Caltrans emergency road repair, San Jose, CA, 2017 (Cell-Crete Corporation n.d.).
  - Highway 128 (west of Winters, CA), 2015 (Cell-Crete Corporation 2023).

- Bridge abutment fills. Reported case studies include the following:
  - Tahoe Echo Summit Bridge, 2019 (Caltrans 2019).
  - Michigan DOT bridge replacement to modernize 7 mi of I–94 in the City of Detroit, with an estimated completion date in 2023 (Cell-Crete Corporation 2022).

CHAPTER 6. POLYSTYRENE GEOFOAMS

INTRODUCTION AND BACKGROUND

Polystyrene geofoams are extremely lightweight blocks that have been widely used in highway applications to mitigate issues related to low bearing capacity; freeze-thaw and soil heaving issues, particularly in areas with harsh winters; and construction of pavements/structures over pipes and utilities. Geotechnical highway applications for polystyrene geofoams include use as a lightweight fill, thermal insulator, and vibration dampener, as well as for the protection of underground services (Mohajerani et al. 2017). Depending on the manufacturing methods, geofoams can be either expanded polystyrene (EPS) or extruded polystyrene (XPS). EPS geofoams are more common for highway applications due to their consistent properties, sufficient strength, and more sustainable and energy-efficient production technologies (Walimbe 2020). Figure 14 shows some images of EPS installations.

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A. Polystyrene geofoam block (Creative Commons n.d.b).

© 2018 Washington State DOT.

B. Polystyrene geofoam blocks for a backfill application (Creative Commons n.d.b).

Figure 14. Photos. Placement of geofoam blocks for various applications.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using EPS geofoams in geotechnical highway applications include the following (XR Geomembranes 2019; Styrene Insulation Industry 2021):

- Accelerates construction.
- Can be constructed in adverse weather conditions.
- Eliminates the need for heavy earthmoving equipment.
- Provides the potential for overall project cost savings.
- Reduces labor needs and labor costs.
- Eliminates the need for environmental permits.

Reported disadvantages of geofoams include the following (Worley 2016; Emergen Research 2022):

- EPS is a plastic material prone to flammability and burning in fire.
- EPS is vulnerable to petroleum solvents.
- EPS is buoyant. For example, an incident was reported for a parking structure in Crayford, UK, on October 9, 2016. Cars were crushed against the ceiling after floodwaters raised the ESP geofoams below the floor of the parking structure.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

EPS can be used in the following geotechnical applications for highways (EPS Industry Alliance n.d.; Styrene Insulation Industry 2021):

- Insulation layers.
- Lightweight fill for highways.
- Bridge abutment fills.
- Slope stabilizers.
- Retaining wall fills.
- Pipeline and trench fill for weight reductions.
- Temporary road construction.

MATERIAL CHARACTERIZATION

Physical Properties

ASTM D6817 reports the physical property requirements for geofoams, as listed in table 22 and table 23 for EPS and XPS geofoams, respectively (ASTM 2021d). Physical properties commonly reported for geofoams include puncture strength, abrasion resistance, tensile strength, flexibility, toughness, and chemical resistance. EPS and XPS have different grades with different compressive resistances and flexural strengths based primarily on product density. Projects may specify a minimum grade to be used, which will primarily depend on the expected dead weight and live load on top of the geofoam. An oxygen index (OI) is also specified to ensure that the geofoam is not flammable in air. An OI of 24 (as required by ASTM D6817) entails chemically treating the polystyrene material, which is inherently flammable, to provide fire resistance and additional protection.

Table 22. Physical property requirements for EPS geofoams (ASTM 2021d; Geofoam International, LLC, n.d.).

Grade	EPS 12	EPS 15	EPS 19	EPS 22	EPS 29	EPS 39	EPS 46
Density, min. (pcf)	0.70	0.90	1.15	1.35	1.80	2.40	2.40
Compressive resistance, min. (psi at 1 percent)	2.2	3.6	5.8	7.3	10.9	15.0	15.0
Compressive resistance, min. (psi at 5 percent)	5.1	8.0	13.1	16.7	24.7	35.0	35.0
Compressive resistance, min. (psi at 10 percent)	5.8	10.2	16.0	19.6	29.0	40.0	40.0
Flexural strength, min. (psi)	10.0	25.0	30.0	35.0	50.0	60.0	60.0
OI, min. (volume percent)	24.0	24.0	24.0	24.0	24.0	24.0	24.0

1 pcf = 16 kg/m^3; 1.0 psi = 6.895.
min. = minimum
Note: Original table is in U.S. customary units.

Table 23. Physical property requirements for XPS geofoams (ASTM 2021d).

Grade	XPS 20	XPS 21	XPS 26	XPS 29	XPS 36	XPS 48
Density, min. (pcf)	1.15	1.25	1.54	1.73	2.11	2.88
Compressive strength, min. (psi at 1 percent)	2.90	5.08	10.88	15.23	23.21	40.61
Compressive strength, min. (psi at 5 percent)	12.33	15.95	26.83	34.08	48.59	77.60
Compressive strength, min. (psi at 10 percent)	15.08	15.08	25.09	40.03	60.05	100.08
Flexural strength, min. (psi)	40.03	40.03	50.04	60.05	74.98	99.93
OI, min. (volume percent)	1.15	1.25	1.54	1.73	2.11	2.88

ASTM C578 presents detailed information on the physical property requirements for different grades of EPS geofoams (ASTM 2022a). These include density, thermal resistance, compressive strength, flexural strength, and maximum allowed water absorption (table 24).

Table 24. Physical property requirements for EPS geofoams (ASTM 2022a; Geofoam International, LLC, n.d.).

Property	Type XII	Type I	Type VIII	Type II	Type IX
Normal density (pcf)	0.75	1.00	1.25	1.50	2.00
Density, minimum (pcf)	0.70	0.90	1.15	1.35	1.80
Design thermal resistance per 1.0-inch thickness at 75 °F (°F·ft^2·h/Btu)	3.22	3.85	3.92	4.17	4.35
Design thermal resistance per 1.0-inch thickness at 40 °F (°F·ft^2·h/Btu)	3.43	4.17	4.25	4.55	4.76
Thermal resistance, min per 1.0-inch thickness at 75°F (°F·ft2·h/Btu)	3.10	3.60	3.80	4.00	4.20
Thermal resistance, min per 1.0-inch thickness at 40°F (°F·ft2·h/Btu)	3.30	4.00	4.20	4.40	4.60
Compressive strength at 10% deformation, min. (psi)	5.0	10.0	13.0	15.0	25.0
Flexural strength, min. (psi)	10.0	25.0	30.0	40.0	50.0
Water vapor permeance of 1.0-inch thickness, max., permeance	5.0	5.0	3.5	3.5	2.0
Water absorption1 by total immersion, max. (volume %)	4.0	4.0	3.0	3.0	2.0
OI, min. (volume %)	24.0	24.0	24.0	24.0	24.0
Flame spread	20	20	20	20	20
Smoke developed	150–300	150–300	150–300	150–300	150–300

Mechanical Properties

Unlike other alternative lightweight and recycled materials discussed in this report, the selection of geofoams for highway geotechnical applications is based on specifying a material that fits the physical property requirements mentioned in the previous section. However, the researchers found extensive studies in the literature on the mechanical properties of geofoams. Kaké, Temesgen, and Negussey (2018) studied the influence of strain rate on the stress-strain behavior of EPS geofoams. Beju and Mandal (2018) studied the CBR behavior of EPS geofoams through experimental and numerical approaches. Gade and Dasake (2018) investigated the mechanical properties of EPS geofoam under various loading conditions, including cyclic uniaxial compression, accelerated creep, and pseudo-long-term tests. They noted that elastic modulus (E) decreases with an increase in compressive creep.

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

Several thorough guidelines are available for designing highway applications with geofoams. For pavement foundations and embankments, available design guidelines include the Swedish Standard by Gandahl (1988), the Norwegian Standard (Norwegian Road Research Laboratory 1992), and U.S. guidelines for highway embankments by Stark et al. (2004a, 2004b). For highway culverts, Sun, Hopkins, and Beckham (2005) published guidelines for using geofoams to reduce the stresses in highway culvert extensions. Further, Arellano et al. (2010) published guidelines for geofoam applications in slope stability projects. Other general guidelines for using geofoams in ground modification methods were published by Schaefer et al. (2016). In fact, for all lightweight and recycled materials investigated in this report, the guidelines and design requirements for EPS geofoams are the most complete. The resources mentioned in this paragraph are good sources of information for design guidelines and requirements.

Due to the extremely lightweight nature of geofoams, buoyancy can be a major issue. The design guidelines have addressed these issues by calculating the buoyancy forces and requiring counteracting dead loads for any EPS geofoam block fill that may be subjected to submergence. Sufficient dead-load stress on the geofoam or another physical restraint must be applied to counteract uplift forces (Horvath 1999). Additionally, to minimize creep and deflection, manufacturers recommend that EPS geofoam design loads not exceed the compressive resistance at 1 percent capacity. Staying below this load limit will protect the geofoam from excessive long-term deflections from the sustained permanent loads.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

EPS is resistant to alkalis, dilute inorganic acids, gypsum plaster, most alcohols, portland cement, silicone oil, and solvent-free bitumen. Chemical products that may damage EPS include hydrocarbons, chlorinated hydrocarbons, organic solvents, ketones, ethers, esters, diesel and gasoline, concentrated acids, vegetable oils, paraffin, and animal fats and oils (Mohajerani et al. 2017). For this reason, Caltrans specifies that for geofoams used as a structural backfill, a reinforced gasoline-resistant geomembrane (GRG) must be used to protect the geofoam from spilled liquid hydrocarbons, and other fluids (XR Geomembranes 2019). The GRG membrane must cover and conform to the corners of the EPS geofoam.

Any free-standing water should be drained from the site, and a proper drainage system should be installed to keep the water level from rising (Tafreshi, Siabil, and Dawson 2020). Except where the designer has considered the effect of thawing in permafrost regions, the EPS should not be placed directly on frozen ground. Further, any vegetation and debris should be removed. To avoid EPS damage from direct contact with coarse granular soil, operators should place sand in a 0.5–1.0-inch-thick layer. Adding the sand will also help level or slope the ground surface.

AVAILABLE COST INFORMATION

Multiple sources and manufacturers report the cost of geofoam blocks to range between $40-$76 per cubic meter ($52 and $100 per cubic yard) ($40–$76 per cubic meter). XPS geofoams are sold at a higher price and can achieve higher strengths. The material cost is thus comparable to other lightweight fill materials and more expensive than traditional fills. The information available on the cost of installation and handling is conflicting. Some sources and manufacturers claim that using the geofoam blocks reduces labor and transportation costs due to ease of handling and their lighter weight. However, some sources claim that the cost of installing geofoams can be higher than other alternative backfill materials, depending on the specified density (grade) of the geofoam and the total dead and live load applied on top of the geofoam.

ENVIRONMENTAL CONSIDERATIONS

EPS is considered to be nonharmful. EPS has even been used as a material for the manufacture of eating utensils, containers, and beverage cups (Mohajerani et al. 2017). Thus, no issues with leaching of chemicals or toxic metals into groundwater are expected.

EPS and XPS are inherently flammable. Flammability is quantified by the OI, which is the minimum percentage of oxygen required for maintaining the combustion of an ignited material. EPS geofoams naturally have an OI of 18 percent by volume, and since air is 21 percent oxygen, geofoams are deemed flammable. In the United States, however, ASTM D6817 requires a minimum OI of 24 percent by volume for geofoams used in highway applications (table 22 and table 24) (ASTM 2021d). Beads that contain fire-retardant additives are used to manufacture these geofoams. Even by chemically treating the polystyrene material, these flame-retardant EPS geofoams will still completely melt at temperatures exceeding 300 °F. The flame-retardant EPS is more expensive to produce, and some questions exist regarding its environmental safety (Mohajerani et al. 2017; Horvath 2011).

LCA STUDIES

EPS and XPS are both closed-cell foam materials, but the main ingredient, manufacturing process, and resulting emissions are quite different. Thus, the environmental impacts are completely different. Many EPDs for geofoams are available, but the applications are mostly for home and roof insulations. No publicly available EPDs could be found for geofoams rated for use in highway applications.

EPS is more popular than XPS, with similar engineering properties, because the manufacture of EPS has not been linked to the depletion of the earth's ozone (Mohajerani et al. 2017). Unlike XPS, the manufacture of EPS does not involve the use of chlorofluorocarbon (CFC) and hydrochlorofluorocarbon (HCFC) and does not result in the release of formaldehyde.

Table 25 presents data collected from a comparative lifecycle assessment on extruded and expanded geofoams. Though EPD data are only available for home insulation applications, one may infer that the use of geofoams in highway applications should be limited to EPS geofoams due to the huge difference in environmental impacts. XPS geofoams can provide higher strengths than EPS, but the ODP is approximately 42 times higher due to the CFCs and HCFCs (Quad-Lock 2023). Further, the global warming potential is approximately 34 times higher for XPS, indicating that the manufacturing process is more energy intensive. Due to higher costs, XPS geofoams are less common in geotechnical and pavement applications.

Table 25. Emissions and environmental impacts for EPS and XPS (Quad-Lock 2023).

Impact Category	Units	EPS	XPS	Ratio XPS/EPS
ODP	kg CFC-11-eq	0.000014	0.604	41.938
Global warming	kg CO_2-eq	2,511	85,757	34
Eutrophication	kg N-eq	0.324	2.45	7.6
Acidification	mol H+-eq	414	898	2.2
Total energy	MJ	64,250	79,908	1.24
Total solid waste	kg	675	722	1.07
Smog formation	kg O_2-eq	180	178	1
Water consumption	kg = liter	4,904	4,904	0.55

CASE STUDIES

The literature includes extensive case studies using EPS geofoams in highway geotechnical applications. Arellano et al. (2018) published a multitude of case studies as part of the proceedings of the 5th International Conference on Geofoam Blocks. The document covered case studies related to the use of geofoams for lightweight fills (Norway), embankments (Netherlands and Turkey), bridge abutments (Norway), and pipeline and culvert fills (Norway and Turkey). The case studies reported in the United States and Canada include the following:

- Road embankment: Port Mann/Highway 1 Improvement Project, Vancouver to Langley, BC, Canada (Arellano et al. 2018).
- Bridge abutment fill: Norman Kill, Albany, NY (Arellano et al. 2018).
- Utility fill: Two case studies referenced by Tafreshi, Darabi, and Dawson (2020) using EPS geofoam.
- Culvert fill: Layers of rigid geofoam insulation were applied under a culvert in Manitoba, Canada. Moussa et al. (2019) collected the temperature data from the thermistors installed under the culvert and calibrated a numerical model for predicting the freezing and thawing regimes. The geofoam insulation layer was found to reduce the temperature variation under the culvert and prevent freezing so that the frost heave–related pavement distress could be avoided.
- Roadway embankments: In Illinois in 2016, Contract 60W55 used geofoams. No issues have been identified in the project thus far (Arellano et al. 2018). Another project involving geofoams in Cook County, IL, for Project No. NHPP-VQ14(255) used EPS geofoam blocks that conformed to the minimum requirements of the ASTM C578 standard (2022). Sand layers were placed underneath the first level of EPS geofoam blocks and compacted to satisfaction. No issues were raised with this installation.

CHAPTER 7. RAP

INTRODUCTION AND BACKGROUND

RAP materials are created by removing, crushing, and reprocessing existing asphalt layers. RAP materials typically contain aggregate particles that vary in size and are coated partially or fully with asphalt binder (figure 15). Particle size and shape properties, the amount of asphalt coating the RAP particles, and the binder content of the RAP are among the important engineering parameters that control the quality of this material. Since a principal constituent of RAP is its mineral aggregates, the overall chemical composition of RAP is similar to that of the mineral aggregates in the mix. RAP has traditionally been used in the United States and other parts of the world as granular material for fills and pavement layers, in asphalt mixes, and in concrete mixes (Bennert et al. 2000; Copeland 2011; Huang, Shu, and Li 2005). When RAP is used as an unbound aggregate, the volume of asphalt in the RAP reduces the specific gravity. The amount and percent coverage of asphalt binder on the aggregate surface impacts the moisture sealing of the mineral aggregate in RAP, which is an important consideration for the reuse associated with highway geotechnical applications. These characteristics result in RAP having a lower unit weight compared to VAs, and the amount of water needed to achieve the desired compaction level is often less.

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A. RAP material—a closeup (Creative Commons n.d.c).

© 2016 Moondosmile.

B. Another photo of RAP from a different source.

Figure 15. Photos. RAP materials.

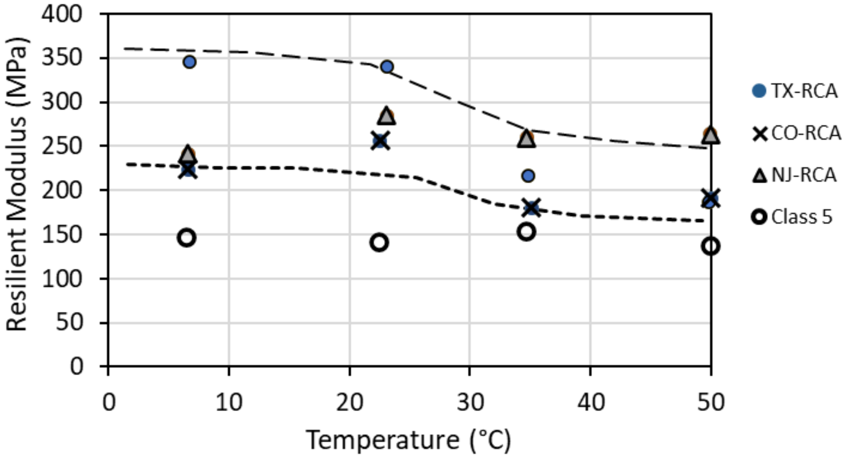
ADVANTAGES AND DISADVANTAGES

Reported advantages of using RAP in geotechnical highway applications include the following (Dager et al. 2023; Edil 2017; FHWA 1997; Richfield Blacktop 2020):

- Cost-effective.
- Environmental impacts (emissions) reduced.
- Energy savings from production anticipated.
- High modulus and layer stiffness characteristics.
- Moderate to high internal friction angle and high strength (debatable in literature).
- Controlled gradations are possible.
- Nonplastic, free draining, and not frost susceptible.

Disadvantages of RAP include the following (Barzegar et al. 2023; Dager et al. 2023; Edil 2017; Gao et al. 2021):

- Not lightweight.
- Temperature sensitivity—mechanical properties vary with temperature (figure 16).
- Poor creep performance—may have excessive settlement under load and compaction.
- Source variability and impurities.



© 2015 Soleimanbeigi. Modifications by FHWA to consolidate information into one graph.

Figure 16. Graph. Resilient modulus properties of RAP materials collected from different States (Soleimanbeigi et al. 2015).

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

RAP can be used in the following geotechnical applications for highways (Al-Shujairi, Al-Taie, and Al-Mosawe 2021):

- Road shoulders as embankments.
- Back-filling material.

- Retaining walls as a backfill material.
- Slope protection/slope stability.
- Landfill capping systems.
- Pothole filler material.
- Drainage works.
- Aggregates in bituminous and concrete mixes.
- Base and subbase materials for roadways.
- Soil stabilization—mixed with naturally weak soils.

Based on the literature review, some States allow RAP in embankments or as structural backfills (table 26 provides a nonexhaustive list). Texas successfully used RAP for embankments, MSE wall backfills, and erosion control (Ncube and Bobet 2021). According to the National Asphalt Pavement Association, "RAP must not be considered a hazardous waste and can be used as a clean fill" (Ncube and Bobet 2021).

Table 26. Select States allowing RAP usage in highway geotechnical applications (Ncube and Bobet 2021).

State	RAP in HMA Mixes	RAP for Embankments and Fills	Structural Fills	Subgrade	Max. % RAP Allowed in Subgrade	RAP for Base or Subbase	Max. % RAP Allowed in Base or Subbase
California	✓	—	—	—	—	✓	40
Colorado	✓	✓	—	✓	—	✓	—
Florida	✓	✓	—	✓	—	✓	—
Illinois	✓	✓	—	✓	40	✓	50
Minnesota	✓	—	—	—	—	✓	25
Texas	✓	✓	✓	—	—	✓	20
Wisconsin	✓	—	—	—	—	✓	—

—No data.

According to FHWA, at least nine States reported using RAP in embankments (Chesner et al. 1997). Connecticut, Indiana, Kansas, Montana, New York, and Tennessee used RAP as an additive in embankment construction, while California, Connecticut, Illinois, Louisiana, and Tennessee used RAP directly as an embankment fill material. RAP performance in these applications was generally considered satisfactory to good. However, some States (e.g., Illinois) experienced excessive settlements in some locations where RAP was used for embankments. A request for proposal by the Illinois Tollway (2019) stated, "In isolated instances, excessive settlement has occurred, which may be attributed to the use of RAP. The excessive settlement is typically identified months after placement, primarily in situations where construction was performed late in the season (late fall/winter).” No report or further information detailing the explanations of these excessive settlements has been published or provided to date.

MATERIAL CHARACTERIZATION

Physical Properties

Based on samples obtained from eight States, including California, Colorado, Michigan, Minnesota, New Jersey, Ohio, Texas, and Wisconsin, the RAP and recycled pavement materials (RPMs) had reasonably consistent properties (Edil 2017). Note that RAP and RPM are used interchangeably for the context of this report to indicate materials recycled from asphalt content (AC) layers. Table 27 shows the range of properties for gradation (e.g., fines content), absorption, AC, and soil classification.

Table 27. Physical properties of RAP—average values and typical ranges (Edil 2017).

Properties	RAP/RPM Average (range)
Fines (percent)	0.92 (0.4–1.8)
Gravel (percent)	38.38 (32–51)
Coefficient of uniformity, C_u	9.80 (7–17)
Specific gravity	2.38 (2.34–2.57)
Absorption (percent)	1.84 (0.6–3.0)
AC (percent)	5.9 (4.7–7.1)
Classification	SP, SW, GW
	A-1-a, A-1-b

SP = poorly graded sands, gravelly sands, little or no fines; SW = well-graded sands, gravelly sands, little or no fines; GW = well-graded gravels, gravel-sand mixtures, little or no fines.

Mechanical Properties

Stroup-Gardiner and Wattenberg-Komas (2013) reported average friction angles for RAP materials comparable to those of the virgin crushed stone and RCAs (table 28). Among all three, the friction angle of RAP was significantly lower, but the effective cohesion due to the presence of the binder adds to the shear strength. Edil (2017) reported the typical resilient modulus values of RAP materials collected from four different sources and States, as previously shown in figure 16. The resilient modulus values were quite similar and showed a temperature-dependent behavior, with lower modulus reported for higher testing temperatures. Domitrović, Rukavina, and Lenart (2019) conducted repeated load triaxial testing for resilient modulus and permanent deformation on RAP and crushed limestone mixtures, with RAP contents varying between 0 percent, 20 percent, 35 percent, and 50 percent of dry mass. Samples exposed to 14 freeze-thaw cycles were also tested in addition to standard samples. Freeze-thaw conditioning resulted in a decrease in resilient modulus values and an increase in permanent deformation. This result was most pronounced for the crushed limestone with 0 percent RAP. Mixtures with 35 percent RAP exhibited stable, resilient behavior and the lowest change in permanent deformation accumulation after freeze-thaw conditioning.

Table 28. Shear strength properties of RAP, RCA, and VAs (Stroup-Gardiner and Wattenberg-Komas 2013).

Measurements	Control	RCA	RAP
Effective confining pressure range (kPa)	83–276	83–255	83–310
Effective stress friction angle (degrees)	55	54	39
Effective cohesion, *c* (kPa)	0	0	55.2

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

The literature does not contain extensive guidelines for using RAP as an embankment construction material. The undersized portion of crushed and screened RAP (<2 inches) may be blended with soil or finely graded aggregates or both (Chesner et al. 1997). The uncrushed or coarsely graded RAP may be used as the embankment base. The RAP utilized in embankment construction does not take advantage of the asphalt cement component, so it is typically not used for embankments unless abundant quantities are available or if the RAP quality is not suitable for other uses.

The design requirements for RAP used in embankments are the same as the requirements for similar-sized soil-aggregate blends or conventional aggregates. The design should take into consideration slope stability, settlement, consolidation, and bearing capacity concerns (Chesner et al. 1997). Representative samples of RAP or blended materials should be tested for triaxial compression. The maximum particle size for the CBR test is 3/4 inch. When used for embankment applications, the engineering properties of interest for RAP include the following (Chesner et al. 1997):

- Particle size: Maximum allowed in embankments is 610 mm (24 inches).
- Compacted density: Typically is between 1,600 and 2,000 kg/m^3 (100 and 125 pcf).
- Moisture content: Typically is higher than that for conventional/virgin embankment materials.
- Shear strength, bearing strength, and consolidation characteristics: Consolidation is negligible for coarsely graded RAP.
- Permeability: Typically is satisfactory.

- Durability: Is not a concern because the quality of aggregates used in HMA is better than those specified for fill materials.
- Drainage characteristics and corrosivity: RAP is considered noncorrosive for steel and other metals (limited testing results).

For MSE walls, critical material properties for using RAP as a backfill material include hydraulic conductivity (i.e., permeability), shear strength properties, interface friction, compaction characteristics, compressibility of compacted materials, time-dependent effects (i.e., creep), and corrosivity (Stroup-Gardiner and Wattenberg-Komas 2013). Corrosivity is checked for RAP in the proximity of steel or other metals. Rathje et al. (2001) evaluated RAP and RCA for MSE applications; their research concentrated primarily on the durability aspects of geosynthetic and metallic reinforcements. The researchers recommended polymeric reinforcement be designed to resist most forms of degradation and provide adequate performance with RAP and RCA backfills. RAP from mixes with a tendency to strip should be avoided. A pH typically around 8 is satisfactory for MSE wall backfill applications. Further, the researchers found limited deicing chemical salt contents on the RAP/RCA surfaces to be a minor issue for long-term durability.

Rathje et al. (2002) continued to evaluate RAP and RCA for MSE backfill applications. The researchers conducted triaxial testing to determine the cohesion and the angle of internal friction for RAP, RCA, and a control VA material. RAP generated a small cohesive value because of the asphalt particles adhering together in the compacted specimens. The internal friction angle of RAP was also the lowest among all three materials. Rathje et al also evaluated the corrosive potential of RAP by soaking materials in water, decanting the water, and using it as an electrolyte in a corrosion cell. No statistically different corrosive potentials were determined after 64 d of testing. Carley (2002) also evaluated RAP as backfill for MSE walls compared with crushed limestone. RAP provided adequate strength and hydraulic conductivity as a backfill material. Table 29 presents general guidelines and design parameters for RAP and other backfill materials used in MSE wall backfill applications (Stroup-Gardiner and Wattenberg-Komas 2013).

Table 29. General guidelines for using RAP and other backfill materials in MSE wall backfill applications (Stroup-Gardiner and Wattenberg-Komas 2013).

Requirement	TxDOT (Type A)	TxDOT (Type B)*	FHWA
Gradation: maximum size	76 mm (3 inches)	152 mm (6 inches)	102 mm (4 inches)
Gradation: percent passing sieve 76 mm (3 inches)	—	75–100	—
Gradation: percent passing sieve No. 40	0–60	—	0–60
Gradation: percent passing sieve No. 200	0–15	0–15	0–15
PI	—	—	<6

Requirement	TxDOT (Type A)	TxDOT (Type B)*	FHWA
Compaction: dry density	95 percent (Tex-114-E (TxDOT 2011))	Not specified	95 percent (AASHTO T-99 (2022e))
Compaction: moisture content	±2% of W_{opt}	Not specified	Within 2% dry of W_{opt}
pH	5.5–10	Not specified	5–10
Resistivity (ohm-cm)	>3,000	Not specified	>3000

TxDOT = Texas DOT.
*Type B backfill that does not meet the sieve No. 200 requirement may be used if less than 25 percent passes sieve No. 200, PI < 6 percent, friction angle is at 95 percent dry density (Tex-114-E), and OMC > 34 degrees.

In addition, a survey of transportation agency guidelines and practices in the United States and Canada by Tutumluer, Moaveni, and Qamhia (2018) has demonstrated that some agencies limit the use of RAP in highway applications. Table 30 summarizes the agency responses. Note that the study focused primarily on traditional highway applications (i.e., mostly in pavement layers).

Table 30. Survey of transportation agency responses related to restricting use of RAP in highway applications (Tutumluer, Moaveni, and Qamhia 2018).

Transportation Agency	Restriction for Using RAP, Considering Quality Concerns
British Columbia	Only for asphalt pavement
Florida	Minimum 4-percent AC and mix must meet Florida DOT specifications. Minimum 2.5-percent AC for coarse portion above No. 4 sieve
Illinois	Not allowed in concrete pavement
Kentucky	Only allowed as part of the aggregate blend for asphalt layers
New Hampshire	Dust-to-asphalt ratio as identified in AASHTO M 323 (2022d); stockpiles must be tested for gradation and AC every 1,000 tons

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

To minimize/avoid agglomeration, crushed RAP should be blended as soon as possible with conventional aggregate (using a cold feed system) to obtain a homogeneous mixture. If the blended material was stockpiled for a considerable period, particularly in warm weather, the stockpile might harden and require recrushing and rescreening before use (Chesner et al. 1997). Blended RAP-aggregate stockpiles should not be allowed to remain in place for extended periods because the stockpiled material is likely to become overly wet.

The same equipment and procedures used to handle and place conventional aggregates are applicable for RAP. RAP blended with VAs can be placed as a conventional granular material. Blending at a central plant provides better material consistency. Additional care is required during stockpiling and handling of RAP and RAP blends to avoid segregation or reagglomeration (Chesner et al. 1997). Conventional granular aggregates generally do not bond well with RAP. Consequently, raveling may occur if thin layers of conventional aggregates are placed over constructed layers containing RAP. During placement of RAP or blends with RAP, finish grading can be difficult because of the adhesion of asphalt in the RAP. Particular attention should be paid to avoid postconstruction densification. Compaction improves if little or no water is used.

The same field test procedures and QC measures used for conventional aggregates are also recommended for RAP. However, QC testing needs additional sampling and testing of the recycled stockpiles to account for the increased material variability (Stroup-Gardiner and Wattenberg-Komas 2013). Testing moisture content and compaction using nuclear gauges are affected by the presence of binder in RAP. Both parameters are overestimated because of the presence of hydrogen ions in the binder. In particular, the nuclear gauge showed higher readings for moisture content than measurements obtained with oven drying (Rathje et al. 2002). Compaction may be carried out using a control strip to avoid such measurement issues in the field. Laboratory moisture checks should be completed to calibrate nuclear density gauge readings and create correction multipliers. Table 31 presents the ratios of moisture contents obtained using a nuclear gauge to those calculated from oven-drying measurements.

Table 31. Ratios of nuclear moisture contents to oven-dried measurements for RAP (Rathje et al. 2002; Stroup-Gardiner and Wattenberg-Komas 2013).

	Ratio of Nuclear Moisture to Oven-Drying Measurement		
Statistics	**Control**	**RCA**	**RAP**
Average	0.99	1.19	3.07
Standard Deviation	0.12	0.10	0.69
Min. and max. values	0.84–1.19	1.03–1.33	2.36–4.51

AVAILABLE COST INFORMATION

The price of RAP in the United States generally ranges from $10 to $20 per ton (Auburn Aggregates 2022; Homeguide 2022b). The price is comparable to that of VAs but is typically on the higher end due to the presence of asphalt binder, a precious and costly material for asphalt mixtures. For this reason, RAP used for fill applications should either be in abundance or not pass the specifications for use in asphalt mixes.

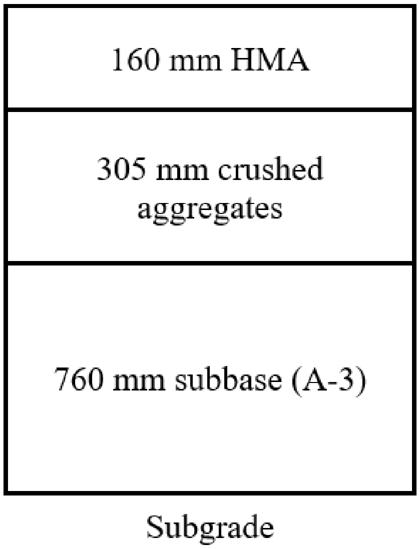
ENVIRONMENTAL CONSIDERATIONS

Asphalt pavement layers consist of aggregates and petroleum-derived asphalt binders containing volatile and semivolatile constituents such as polycyclic aromatic hydrocarbons (PAHs) (Recycled Materials Resource Center n.d.). Additionally, asphalt pavement roadways may contain surface treatments, rubberized materials, or contaminants from vehicles or other emissions (e.g., historically, lead). Since RAP is coming from these materials, such contaminants can be present at various levels and can pose environmental concerns. The environmental issues are different for RAP based on various beneficial uses. For unbound applications, such as use as a backfill material, leachability from the RAP may be a concern (Melton and Kestler 2013).

A project in Florida tested leaching volatile organic compounds, PAHs, and heavy metals in RAP materials (Melton and Kestler 2013). Results showed that the levels of these contaminants were far below the detection limit and the State's regulatory groundwater guidance. Similarly, batch and column leaching tests found constituents leached were low and generally below European drinking water standards. Further, the University of Minnesota completed a review on PAHs in asphalt pavements, and the researchers concluded that PAH concentrations depended on the type of pavement (coal tar versus petroleum-based pavement) (Melton and Kestler 2013). Petroleum-based asphalt pavements contained PAHs at concentrations below Minnesota Pollution Control Agency human health risk clean-up levels. Based on these studies, RAP does not pose environmental considerations when used as an unbound backfill material. When RAP is mixed with soils or other conventional aggregates, the mixture would not likely exceed applicable limits for leaching or other environmental pollutants.

LCA STUDIES

Edil (2017) conducted comparative LCA and LCCA studies for designs using RAP/RPM as a base material. The researchers' analyses concluded a 20-percent reduction in carbon dioxide (CO_2) emissions, 16-percent reduction in energy consumption, and a 21-percent savings in lifecycle costs due to the use of RAP/RPM in lieu of crushed aggregates in base materials. Figure 17 presents the pavement cross sections. The researchers assumed that the service life of conventional and alternative designs could be based on international roughness index predictions made with the AASHTOWare® Pavement ME Design software and that the rehabilitation occurs at the end of the predicted service life for both designs (AASHTO 2015). Thus, these conclusions can apply to using RAP in other geotechnical highway applications, such as fill materials.



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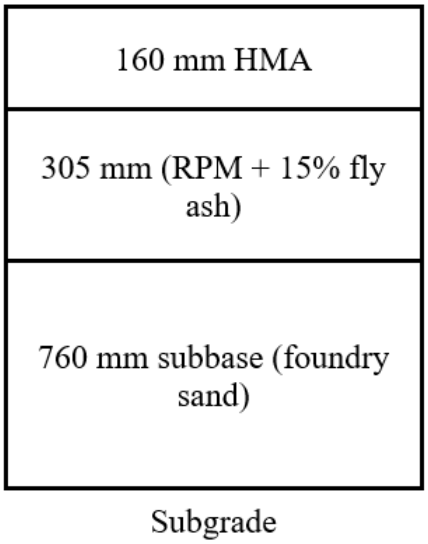
to figure label.

A. Conventional design.



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B. Design with RPM (RAP).

Figure 17. Illustrations. Pavement cross sections with conventional and RPM (RAP) base materials (Edil 2017).

Another study by Aurangzeb et al. (2014) presented an LCA for HMA mixes with varying percentages of RAP ranging between 0 and 50 percent. The study assumed similar construction practices and maintenance activities; therefore, the reductions obtained in all energy and emission footprints due to the use of RAP are primarily attributed to the material phase. Thus, these results can be further extended to different highway applications (e.g., embankments, MSE wall backfills, and bridge abutments) for environmental impacts due to initial material use. Table 32 presents the results of the study.

Table 32. Effects of percent RAP used on LCA results (material phase) (Ncube and Bobet 2021; Aurangzeb et al. 2014).

Parameter	Lifecycle Phase	0% RAP	30% RAP	40% RAP	50% RAP
Energy (Btu millions)	Total	10,897	10,100	9,834	9,569
CO_2 (lb CO_2e)	Total	1,528,780	1,416,499	1,379,072	1,341,645
CH_4 (lb CO_2e)	Total	272,749	251,459	244,362	237,265
N_2O (lb CO_2e)	Total	11,324	10,418	10,115	9,813
GHG (lb CO_2e)	Total	1,821,700	1,686,510	1,641,446	1,596,383

CO_2e = carbon dioxide equivalent; CH_4 = methane; N_2O = nitrous oxide; GHG = greenhouse.

CASE STUDIES

Currently, several States and agencies allow RAP to be used in roadway embankments, structural backfills, and aggregate surfacing. In some cases, such as for the Illinois Tollway, RAP in roadway embankments and as a structural backfill is loosely specified in terms of maximum size, gradation, engineering properties, and acceptance (Illinois Tollway 2019). The literature is rich with case studies related to the use of RAP in asphalt mixes and in base and subbase layers, but the researchers found no well-documented case studies for the use of RAP in embankment, backfill, and other highway geotechnical applications.

CHAPTER 8. RGA

INTRODUCTION AND BACKGROUND

In the United States, 10 million tons of glass are disposed of every year, yet only 33 percent of the waste glass gets recycled (Jacoby 2019). One of the early steps of glass recycling involves crushing the cleaned glass to make glass cullet, as shown in figure 18. The glass is normally collected from municipal and industrial waste streams. The crushing process can be controlled by crushing the glass into cullet of a specific size (Tao 2017). Glass cullet is the main raw material to produce FGAs, discussed in chapter 4. Glass cullet can ultimately be used as RGAs for various highway and pavement applications. In fact, RGA has been used in different construction applications, including cement and aggregate replacement in concrete and asphalt concrete mixtures, a material for roadbeds and pavement, trench fill, and a drainage medium (Chindaprasirt and Cao 2015). Some of the glass that cannot be recycled into new containers may find its way into pavement applications, especially as a substitute for sand or fine aggregates in concrete mixes.

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A. Glass cullet, the main ingredient for RGA (Creative Commons n.d.d).

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B. Glass cullet of different colors, shapes, and sizes.

Figure 18. Photos. RGAs.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using RGA in geotechnical highway applications include the following (Manyara 2019; Afshinnia 2019):

- Comes in a variety of sizes and gradations.
- Has a high friction angle.
- Is inexpensive to produce/crush.
- Has achieved density that is insensitive to moisture content.
- Has favorable compaction characteristics and good workability.
- Can be placed and effectively compacted during wet weather.
- Has improved resistance to freeze-thaw effects.
- Has reduced drying shrinkage and abrasion potential when used in concrete mixes and when blended with other virgin or recycled aggregates or both.

Disadvantages of RGA include the following (Mike's Trucking 2022):

- Health effects are possible from the dust generated from dumping, leveling, and compacting glass aggregates.

- Dust, though the Occupational Safety and Health Administration (OSHA) currently classifies glass dust as "nuisance" dust and not as hazardous dust.

- Skid resistance lower when used in asphalt pavements (use is limited to lower speed roadways, <65 mph).

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

RGAs can be used in the following geotechnical applications for highways (Donlon 2019; Dodge 2015):

- Backfill applications.

- Backfill for pipes and trenches.

- Aggregate replacement: When finely crushed, RGA can replace sand. If less finely crushed, RGA can be used to replace gravel. RGAs are commonly used as aggregate substitutes in asphalt paving or fine aggregate replacement in concrete.

MATERIAL CHARACTERIZATION

Physical Properties

Ooi et al. (2008) provide the physical properties of RGAs from different literature sources, summarized in table 33. The physical properties include soil classification, specific gravity, optimum moisture content, and maximum dry density. The specific gravities reported for sand-sized RGA mostly range between 2.45 and 2.50 for specific gravity. The maximum dry densities, calculated using the modified Proctor compactive energy, typically range between 109 and 120 pcf, which indicates that the sand-sized materials are lighter than conventional aggregates but are not necessarily lightweight compared to the other lightweight materials discussed in this report, such as ESCS (chapter 3), FGAs (chapter 4), and geofoams (chapter 6).

Disfani et al. (2011) investigated the physical properties of RGA using glass cullet ranging in size according to different gradations. The researchers tested coarse, medium, and fine RGAs (termed herein as coarse recycled glass (CRG), medium recycled glass (MRG), and fine recycled glass (FRG), respectively). The maximum particle size for CRG, MRG, and FRG was 0.5 inches, 3/8 inches, and 0.2 inches (i.e., No. 4 sieve), respectively, and all materials were well graded. The study found that CRG can be highly crushable by a standard LA abrasion test. Table 34 presents the physical properties of all three aggregate gradations.

Table 33. Physical properties of RGAs (Ooi et al. 2008).

Description*	USCS Symbol	Specific Gravity	OMC (%)	Maximum Dry Density[a] (kg/m^3)
Stoltzfus—as received	SW	2.48	10.8	1,894
Stoltzfus—coarse fraction	GP	—	7.8	1,750
Heller—as received	SW	2.49	10.8	1,810
Heller—coarse fraction	GP	—	9.9	1,759
Stoltzfus—as received	SW	2.48	9.7	1,882
Heller—as received	SW	2.49	11.2	1,800
City of Philadelphia curbside glass	SP	2.48	8.0	1,924
CA-14 6.4 mm (1/4 inch) minus	SP	2.49	5.6	1,791
WA-09 6.4 mm (1/4 inch) minus	SP	2.52	5.2	1,831
WPBMRF	SW	2.45–2.50	—	—
ASTM No. 8 average	GP	2.45–2.50	—	—
ASTM No. 9 average	SP	2.45–2.50	—	—
ASTM No. 10 average	SP	2.45–2.50	—	—
Uniform—loose	SP	2.50	—	—
Well-graded—loose	SW	2.50	—	—

—Could not determine from literature.

[a]Based on ASTM D1557 (ASTM 2021a).

GP = Poorly graded gravels, gravel-sand mixtures, little or no fines; WPBMRF = West Palm Beach (FL) Material Recycling Facility.

*FGA materials having the same description (name) indicate tests were performed by different agencies or researchers. More information can be found in the original reference by Ooi et al. (2008).

Table 34. Physical and geotechnical properties of RGA samples (Disfani et al. 2011).

Test	FRG	MRG	CRG
Specific gravity	2.48	2.50	2.50
Flakiness index	—	85.4	94.7
Debris level (visual method) (percent)	7	5	3
Debris level (weight method) (percent)	1.23	2.01	2.98
Organic content (percent)	1.3	0.5	0.23
pH value	9.9	10.1	9.6
Standard Proctor max. dry density (kN/m^3)	16.7	18	N/A
w_{opt} from standard Proctor (percent)	12.5	9	N/A
Modified Proctor max. dry density (kN/m^3)	17.5	19.5	N/A
w_{opt} from modified Proctor (percent)	10	8.8	N/A
LA abrasion value (percent)	24.8	25.4	27.7

Mechanical Properties

According to Ooi et al. (2008), appropriate gradations and sufficient compaction densities of RGA can yield significant shear strengths because of the large friction angles observed. Therefore, RGA is a potential candidate for use in geotechnical and highway projects for foundation and ground improvement applications (e.g., compacted aggregate foundations, sand compaction piles, vibro-replacement, vibro-flotation) The researchers compiled data on the mechanical properties of RGAs from different literature sources and manufacturers. The researchers measured shear strength data, primarily peak friction angle, by DSTs and CD and consolidated undrained (CU) triaxial tests. Table 35 shows that the friction angles measured by DSTs were consistently higher than those measured using CD triaxial test experiments. Table 36 summarizes the shear strength properties (friction angles) for RGA of different grain size distributions, i.e., well-graded and poorly graded sands and poorly graded gravel. The friction angles range from 37 to 62 degrees, indicating considerably high shear strength properties. Disfani et al. (2011) reported similar trends and magnitudes for MRG and FRG. The researchers conducted DSTs on RGA samples compacted in three layers. The friction angles ranged from 50 to 53 degrees for FRG and from 40 to 47 degrees for MRG samples.

Table 35. Mechanical properties of RGAs (Ooi et al. 2008).

Description*	Density[a] (kN/m^3)	Maximum Dry Density[b] (kN/m^3)	Relative Compaction (percent)	Test Type	Peak Friction Angle (degrees)
Stoltzfus—as received	106.0	18.4	90.0	Direct shear	61
				CD triaxial	47
Stoltzfus—coarse fraction	98.3	17.0	91.0	Direct shear	54
				CD triaxial	45
Heller—as received	101.5	17.6	92.0	Direct shear	56
				CD triaxial	46

Description*	Density[a] (kN/m^3)	Maximum Dry Density[b] (kN/m^3)	Relative Compaction (percent)	Test Type	Peak Friction Angle (degrees)
Heller—coarse fraction	98.9	17.1	93.0	Direct shear	48
				CD triaxial	44
Stoltzfus—as received	106.0	18.3	90.1	Direct shear	61–63[c] 58–61 53–58
				CD triaxial	48
Heller—as received	101.5	17.5	90.0	Direct shear	59–62[c] 55–59 47–55
				CD triaxial	47
City of Philadelphia curbside glass	114.3	18.7	95.0	CU triaxial	37
CA-14 (1/4 inch) minus	99.6–100.2	17.4	89.1–89.3	Direct shear	51.3
WA-09 (1/4 inch) minus	100.2–100.8	17.8	88.0–88.2	Direct shear	51.2
WPBMRF	91.8	—	—	Direct shear	40
	104.1	—	—		45
ASTM No. 8 average†	88.6	—	—	Direct shear	45
	93.8	—	—		51
ASTM No. 9 average†	91.9	—	—	Direct shear	37
	102.2	—	—		45
ASTM No. 10 average†	95.7	—	—	Direct shear	34
	109.2	—	—		46
Uniform—loose	—	—	—	CD and CU triaxial	31–32
Uniform—medium	—	—	—	—	35
Uniform—dense	—	—	—	—	36
Well-graded—loose	—	—	—	CD and CU triaxial	37–38
Well-graded—medium	—	—	—	—	39
Well-graded—dense	—	—	—	—	42–43

—Could not determine from literature.

[a] As-compacted for shear strength test.

[b] Based on ASTM D1557 (ASTM 2021a).

[c] The three ranges of friction angle correspond to normal stresses of 0 to 60, 60 to 120, and 120 to 200 kPa, respectively.

*FGA materials having the same description (name) indicate tests were performed by different agencies or researchers. More information can be found in the original reference by Ooi et al. (2008).

†Based on ASTM E11 (ASTM 2022b).

Table 36. Summary of shear strength properties of RGAs (Ooi et al. 2008).

USCS Classification	Friction Angle (degrees)		
	Direct Shear	Triaxial	Overall
SW	40–62	37–48	37–62
SP	34–51	31–37	31–51
GP	45–54	44–45	44–54

Further, Ooi et al. (2008) studied the bearing strength characteristics (CBR) of three recycled materials (RGA, RAP, RCA) and a basaltic VA, all having similar gradations. The gradations of the materials were at the finer end of Hawaii DOT fill gradation. The researchers found the CBR (strength) of recycled glass was insensitive to moisture content and comparable to or slightly higher than that of fine RAP (figure 19).

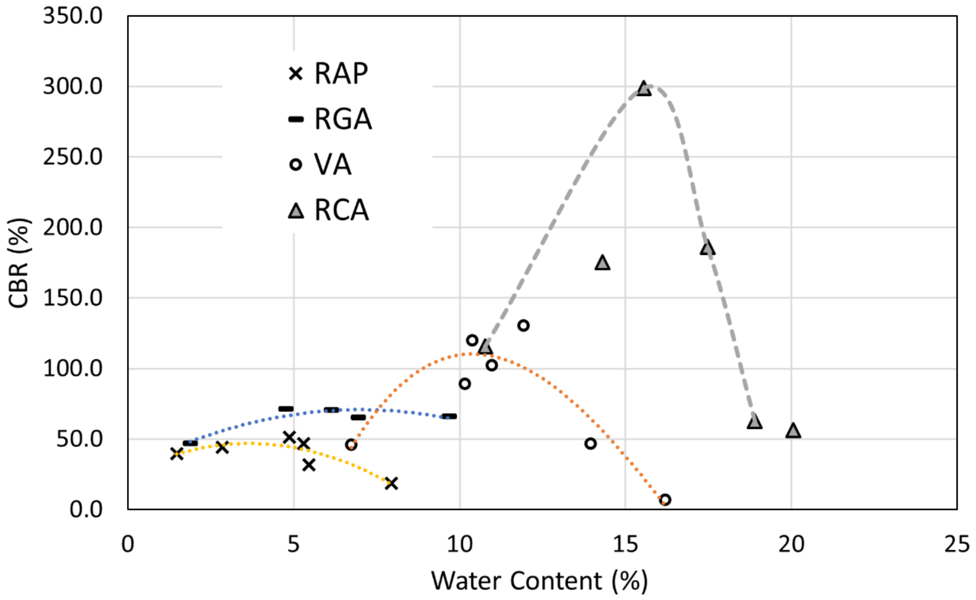

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Figure 19. Graph. CBR versus water content for RGA, RCA, RAP, and VAs tested at the same gradations (Ooi et al. 2017).

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

Several studies investigated and reported recycled glass used as percentage replacements in unbound granular materials for highway applications (i.e., as a percentage replacement of RCA and crushed rock) and for clayey soils. Such studies include the worldwide study by Perera et al. (2021), the study by Arulrajah et al. (2017) for Australia, and the study by Machuca et al. (2020) for Peru. The researchers reported improved performance trends with certain percentage replacements with RGA ranging from 0.75 to 50 percent, depending on the properties that needed to be enhanced, as shown in table 37.

Table 37. Suitable glass content that best enhances respective properties (Perera et al. 2021).

Materials/Blends	UCS (%)	CBR (%)	LA Abrasion (%)	Resilient Modulus (%)	Permanent Deformation (%)	Shear Strength (%)
RG-CR/WR	10	15	50	15	10	15
RG-CR-R	5	5	5	5	5	3
RG-RCA/RCC/CC	20	10	15	10	10	15
RG-RCA-R	5	3	5	5	5	3
RG-soil-cement	10	—	—	—	—	—
RG-clay/soil	10	12	—	30	—	15
GF-clay/soil	0.75	1	—	—	—	0.75
GP-geopolymer	15	20	—	20	—	40

—No data.
RG = recycled glass, GF = glass fiber, CR = crushed rock, WR = waste rock.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

The blending of crushed glass with other aggregates in low percentages (<15 percent) will not noticeably affect the compaction characteristics of the major constituent of the blend (Mike's Trucking 2022). According to FHWA, the recommended percentages of glass cullet in the base and subbase layers (and other applications) are between 15 and 30 percent (Chesner et al. 2002). According to the Clean Washington Center (CWC) (1996), for 100-percent cullet, the apparent cohesion is low, and the material flows relatively freely. Therefore, CWC recommended using hoppers for directing flow, which has been proven efficient and successful. Some cullet particles are sharp and can puncture tires. Experience has indicated that solid rubber tires are a better alternative to compact layers with glass cullet and RGAs. Lift thickness should be between 4 and 6 inches for manually operated equipment and between 8 and 12 inches for automatic compaction equipment. Vibratory compactors are effective for cullet or cullet mixtures; jumping jacks and walk-behind rollers can be used. Plate or slick compactors are ineffective and should be avoided.

AVAILABLE COST INFORMATION

According to Rossetti (2020), recycling glass costs between $70 and $90 per ton, but the cullet sells for only about $10 per ton. A feasibility study conducted in Iowa by Tao (2017), who investigated the feasibility of using RGAs in highway applications, confirmed the costs of recycling glass. The report indicated that a recycled materials facility was shipping glass at a cost as high as $40 per ton, but this cost significantly exceeds the price of RGA/glass cullet, which is $15 per ton. Currently in Iowa, the recycling facilities are receiving subsidies from the State to cover freight and operation costs (Tao 2017). Thus, RGAs are relatively inexpensive compared to other materials discussed in this report since RGAs are being sold at a price ranging from $10 to $15 per ton in the United States.

ENVIRONMENTAL CONSIDERATIONS

OSHA currently classifies glass dust as “nuisance” dust and not as hazardous dust (Mike’s Trucking 2022). Imteaz, Ali, and Arulrajah (2012) found that conductivity, pH values, most heavy metals, and organic and inorganic material (sulfate and chloride) contents were all within acceptable limits for extracts into water, acid, and base. The researchers tested the leachate from water extract that had contact with recycled glass. The pH increased from 7.65 prior to contact to 7.93 after the contact, which indicated insignificant leaching potential from the glass samples. Disfani et al. (2011) obtained a pH value of 9.9 from the leachate of FRG, which is not designated hazardous by the Federal regulatory limits since it falls within the range of 2.0 to 12.5 (inclusive). Thus, RGA leachates are not considered hazardous.

According to the Environmental Protection Authority (EPA) Victoria (Australia)-specified limits, all the metals in the recycled glass samples are well below the threshold limits except iron (EPA Victoria 2007). Iron content in normal water extracts remained well under acceptable limits. The inorganic content (chloride and sulfate) was also within acceptable limits.

LCA STUDIES

The largest market for recycled glass is using glass cullet to produce new glass products and containers. Several studies have focused on the LCA of using glass cullet in the glass manufacturing industry to offset the need to mine new raw materials for making glass. The researchers found no studies in the literature for the lifecycle impacts of using glass cullet in geotechnical highway applications since this application has not yet gained good momentum, especially in the United States. The lack of glass cullet use is also clear from the limited applications and case studies found related to recycled glass use in embankments, slope stability, and backfill applications. If glass cullet is used in such applications, it is normally blended in small quantities with other materials.

The literature review revealed that recycling glass for highway geotechnical applications is more environmentally friendly and sustainable than recycling glass for other applications, particularly recycling glass for making new glass containers (Buczynski 2010; Strategic Materials 2023; Friends of Glass 2023. The main reason is that the glass recycled to make glass cullet for highway geotechnical applications does not need to be sorted into different colors or types, which saves energy. Additionally, some glass types that cannot be recycled for use as raw material in glassmaking can still be recycled into finely ground sand for highway pavement applications. Nevertheless, these impacts have not been quantified through comparative LCA studies. EPDs from recycling facilities in the United States or worldwide are not publicly available. Conducting such environmental studies remains a future need for promoting the use of glass cullet and getting the technology ready as a sustainable and relatively inexpensive material for highway geotechnical applications.

CASE STUDIES

The following case studies included research publications and websites documenting the use of glass cullet/RGAs in various geotechnical highway applications. Other than the stated information, no further details were mentioned on the performance trends related to glass cullet or RGA applications:

- "Glassphalt" was used in the 1970s to pave the streets around Trump Tower in New York City. A combination of asphalt and crushed glass, glassphalt produced pavement that glistened and glowed in the light. The roads are still in good condition. (Mike's Trucking 2022).

- Fairfax County, VA, used RGAs as a utility fill over sewer pipes in 2019, marking the first time Fairfax County used crushed glass in a construction project (American Public Works Association 2022). The pipe is a 175-ft-long sanitary sewer pipe made of ductile iron encased in steel. The conventional approach to stabilize the pipe in place is to put the pipe on a 6-inch-deep bed and cover it with 4 inches of crushed stone before backfilling soil into the trench. In the Fairfax County project, the pipe rested on 525 tons of crushed glass. The Fairfax County Department of Public Works and Environmental Services anticipates that the crushed glass will support the sanitary sewer pipe for decades.

- A feasibility study was conducted in Ohio to use crushed recycled glass in the construction of local roadways (Tao 2017). The study was initiated to assess the feasibility of using RGA in local roadway construction. The study concluded that glass processors and material recycling facilities (MRFs) in Ohio had a strong interest in using recycled glass in roadway construction, but the projected annual supply of recycled glass was not sufficient for wide-scale use, given other competitive applications in the State. The study recommended that leadership from ODOT and other agencies was crucial to encourage better coordination of MRFs, glass suppliers, and end user.

- The City of Devine, TX, used an 80/20 blend of crushed limestone and glass cullet to construct a flexible base (Davio n.d.). A local company supplied 440 tons of waste glass. The glass and limestone were blended in the proper ratio and crushed before construction. The mix conformed to Texas DOT (TxDOT) specifications. Table 38 presents the geotechnical properties of the limestone and glass blends. The project experienced premature cracking due to unusually high and heavy truck traffic, exceeding three to four times the design traffic, due to nearby road closure.

- The TxDOT Abilene District also carried out a project using recycled glass in a flexible base (Davio n.d.). Glass cullet was mixed with conventional crushed limestone at the jobsite. The May 1997 project involved widening a two-lane road to a five-lane road. Construction involved spreading 12 inches of crushed limestone and glass cullet. A recycler mixed the two materials prior to compaction, and then a 1.5-inch-thick HMA was placed on top. The eastern section of the road used a 10-percent glass cullet, while the western section used 15 percent. Dyess Air Force Base crushed the glass for this project at a cost of $9 per ton. The case study reported that the recycled glass in this project performed well, but no detailed test data were available.

Table 38. **Geotechnical properties of the limestone and glass blends for Texas projects (Davio n.d.).**

Test	Limestone	Limestone with 10% Glass	Limestone with 15% Glass
Sieve analysis (percent retained)			
1 3/4 inches	0	0	0
1 inch	12	17	17
7/8 inch	17	21	21
1/2 inch	34	44	44
3/8 inch	39	53	53
No. 4	55	68	68
No. 10	68	74	74
No. 40	81	84	84
Atterberg limits (percent)			
Liquid limit	22.2	30.2	23.5
PI	7.1	12.8	7.0
Standard Proctor			
Max. dry density (pcf)	134.0	136.8	135.4
Optimum moisture content (%)	7.8	7.3	6.3

CHAPTER 9. RCA

INTRODUCTION AND BACKGROUND

RCAs (figure 20), also termed recycled concrete materials (RCMs), have been used in the construction of highways for more than 70 yr (Cackler 2018). RCAs have been commonly used as pavement base and subbase layers and as embankment and shoulder materials. A more rigorous evaluation and assessment by industry experts and researchers determined that RCA can also replace VAs in concrete mixtures. Even with 70 yr of history, RCA's use in highway applications is still limited. Two primary barriers to the widespread use of RCA exist. First, sufficient information and understanding of the properties of RCA are lacking, and second, the existing State specifications on the use of RCA can be rigid. FHWA, working with its stakeholders, has taken a leadership role in overcoming these barriers. FHWA has developed a series of webinars, technical briefs, guides, and reports to fill this knowledge gap. These collaborative efforts and increased technical information can help States revise specifications to allow RCA for compatible highway applications (Van Dam 2018). This chapter presents the current knowledge and state of practice on using RCA in geotechnical highway applications.

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A. RCA pile at a concrete yard.

© 2019 Washington State DOT.

B. Pile of RCA rubbelized to a uniform size (Creative Commons n.d.d).

Figure 20. Photos. Recycled concrete pavements and concrete demolition waste.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using RCA in highway geotechnical applications include the following (Edil 2017; Melton and Kestler 2013; Specify Concrete 2019; Tigard Sand & Gravel 2019; ETM Recycling 2023):

- Cost effective compared to conventional aggregates.
- Environmental impacts (emissions) are less than conventional aggregates.
- Energy savings from production are anticipated.
- High internal friction angle and high strength are characteristic.
- Nonplastic RCM is not susceptible to frost.
- Temperature dependence is less compared to RAP.
- Structurally reliable and safe for use as natural aggregate materials (debatable).

Reported disadvantages include the following:

- Not lightweight.
- Source variability and presence of impurities.
- High moisture absorption.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

FHWA (2004) reported the following highway applications for RCA/RCM:

- Base and subbase materials for roadways (most common use).

- Aggregate base. A common theme from Texas, Minnesota, and California was that RCA performed better than VA as an aggregate base.

- Backfilling material.

- MSE walls as a backfill material.

- Slope protection and slope stability.

- Riprap and erosion control applications (large-sized RCA).

- Replacement of natural aggregates in HMA mixes. Used in Western Michigan but does not seem to be promising due to the high absorption of the RCA increasing binder demand and cost.

- Replacement of natural aggregates in concrete mixes. Allowed in specifications established in Michigan, Minnesota, and Texas. Texas is the most advanced.

MATERIAL CHARACTERIZATION

Physical Properties

RCA is typically highly angular. According to the American Concrete Pavement Association (ACPA) (2008), RCA has the following characteristics compared to conventional construction aggregates: higher water absorption capacity, lower specific gravity, lower strength, and lower abrasion resistance. NCHRP Synthesis 435 by Stroup-Gardiner and Wattenberg-Komas (2013) compared RCA's physical and chemical properties to that of a new VA material. Table 39 presents the range of properties and shows that RCA has a significantly higher water absorption capacity, lower specific gravity, and generally more variable properties due to source variability. Melton and Kestler (2013) reported LA abrasion loss for RCA ranged from 20 to 45 percent for coarse aggregates, while the magnesium sulfate soundness loss was less than 4 percent for coarse RCA and less than 9 percent for fine RCA.

Table 39. Physical and chemical properties of RCA compared to VAs (Stroup-Gardiner and Wattenberg-Komas 2013).

Property	New Aggregate	RCA
Shape and texture	Varies	Angular with rough surface
Water absorption capacity (percent)	0.8–3.7	3.7–8.7
Specific gravity	2.4–2.9	2.1–2.4
LA abrasion (percent loss)	15–30	20–45
Sodium sulfate soundness (percent loss)	7–21	18–59
Magnesium sulfate soundness (percent loss)	4–7	1–9
Chloride content (lb/yd^3)	0–2	1–12

Based on samples obtained from eight States (i.e., California, Colorado, Michigan, Minnesota, New Jersey, Ohio, Texas, and Wisconsin), the RCA materials had more variable properties than RAP materials collected from different sites and States (Edil 2017). Table 40 presents the range of properties for gradation (e.g., percentage fines, referring to passing the No. 200 sieve size or smaller than 0.075 mm), absorption, mortar content, and classification.

Table 40. Physical properties of RCA—average and range values (Edil 2017).

Properties	RCA Average (range)
Fines (percent)	5.05 (2.01–12.8)
Gravel (percent)	46.19 (32–69)
C_u	24.60 (8–45)
Specific gravity	2.31 (2.2–2.4)
Absorption (percent)	5.52 (5.5–6.9)
Mortar content (percent)	50 (37–65)
Classification	SP, GP, GW
	A-1-a, A-1-b

Mechanical Properties

Melton and Kestler (2013) reported the CBR for RCA material ranges from 94 to 148 percent. Soleimanbeigi et al. (2016) reported the range of soil friction angles of RCA material compared to other coarse aggregate materials, including sand, gravel, and crushed stone (table 41). The ranges reported by Soleimanbeigi et al. were collected from multiple sources. Among the different materials, the friction angles of RCA, which range between 41 and 65 degrees, are among the highest and are higher than those for RAP, which is mainly attributed to the higher angularity. Lastly, Edil (2017) reported the resilient modulus of RCA materials collected from three States: Colorado, Texas, and New Jersey. The resilient modulus values were quite similar and temperature-independent (figure 21) and were generally lower than the resilient moduli of RAP presented earlier.

Table 41. Ranges of friction angles for soils and coarse aggregate materials, including RCA and RAP (Soleimanbeigi et al. 2016).

Soil Type	Range of Friction Angles (degrees)
Sand (well graded)	34.7–37.5
Gravel	38.4–45.9
Crushed stone	34.8–55.3
RCA	41.0–65.0
RAP	37.0–45.0
Foundry sand	31.0–44.0

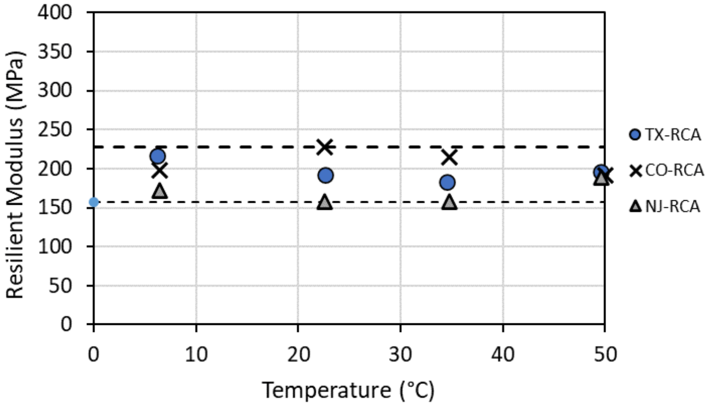

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Figure 21. Graph. Resilient modulus properties of RCA materials collected from different States (Soleimanbeigi et al. 2015).

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

The material properties that are usually of interest when using RCA materials in embankment applications are included in the following list (Chesner et al. 1997). The design requirements for RCA in embankments are the same as those for similar-sized soil-aggregate blends or conventional aggregates. The researchers found no comprehensive specifications covering the use of RCA and RCM as embankment or fill materials in the literature. However, the following information was documented for the properties of RCA:

- Specific gravity is between 2.0 and 2.5, slightly lower than VAs.
- Stability and strength are generally satisfied due to the high friction angles exceeding 40 (table 41). For CBR, a range from 90 to 140 percent is acceptable, which is typically satisfied for the highly angular RCA materials.
- Durability is proven (i.e., resistant to weathering and erosion).
- Drainage characteristics are that the RCA material will be nonplastic and nonsusceptible to frost to maintain drainage. Coarse fractions of RCA are free draining.
- Corrosivity is like those of steel and aluminum, due to RCA’s high alkalinity.

“RCM has demonstrated satisfactory performance as an embankment or backfill material. Its use is covered by special provisions to specifications in a number of jurisdictions” (Chesner et al. 1997). However, RCA materials used in embankments or backfills may not make the best use of the high-quality aggregates associated with RCA because the benefits are not fully taken advantage of in design since RCA is considered by many agencies as conventional aggregate for design purposes. RCA requires minimal processing to satisfy physical requirements for embankment/fill. The relatively lower compacted unit weight of RCA versus VAs results in higher yield (greater volume for the same weight), which makes it economically attractive to contractors. Further, onsite processing and recycling of RCM is likely to result in economic benefits due to reduced hauling costs (Chesner et al. 1997).

In addition, a survey of DOT practices in the United States by Tutumluer, Moaveni, and Qamhia (2018) demonstrated that some States limit the use of RCA in highway applications. While the study focused primarily on traditional highway applications, i.e., mostly in pavement layers, only a few States (e.g., Pennsylvania) specifically mentioned using RCA as embankment or backfill material. Table 42 presents a summary of DOT responses.

Table 42. Survey of DOT responses for the restrictions on using RCA in highway applications (Tutumluer, Moaveni, and Qamhia 2018).

Transportation Agency	Restrictions on Using RCA, Considering Quality Concerns
Arkansas	Only used in unbound base courses.
British Columbia	Only for base and subbase.
Florida	Not permitted in new concrete pavement. RCA is not permitted in new asphalt pavement unless concrete is from a Florida DOT project.
Maryland	TCLP may be required. Specific gravity and LA abrasion tests are performed routinely.
Nebraska	Not used in PCC or AC.
New Jersey	Allowed only in subbase.
North Carolina	Limited to use in base applications. Not allowed to be used in concrete mixes.
Oklahoma	Only as an unbound aggregate base course layer.
Pennsylvania	Only used for subbase and fill.
Utah	Not allowed for concrete use.
Virginia	Not used as subbase or base when any subsurface drainage system is present except when cement stabilized.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

The same methods and equipment are used for RCA handling and storage as for conventional aggregates. Some jurisdictions in Canada (e.g., Ontario) may restrict stockpiling and placement near water courses due to alkaline leachate possibilities (Chesner et al. 1997). To avoid segregations, Chesner et al. recommend stockpiling RCA using radial stackers and remixing using a front-end loader or bulldozer prior to load out.

Due to its high angularity, RCA usually requires the addition of water during the placement and compaction of RCA layers. For QC, the same procedures used for conventional aggregate are appropriate for RCA (Chesner et al. 1997).

AVAILABLE COST INFORMATION

RCAs typically cost around $15 to $55 per ton in the United States, depending on the availability, processing, and added transport cost. Given RCA's typical density, the final cost translates to $18 to $80 per cubic yard. The price also depends on the quality of the RCA (Civiconcepts 2022).

ENVIRONMENTAL CONSIDERATIONS

RCA contains water-soluble calcium hydroxide from the original cement hydration reaction. When water flows through RCA aggregates, some calcium hydroxide will dissolve in water. Eventually, it interacts with atmospheric CO_2 to form calcium carbonate ($CaCO_3$), hence precipitating out of solution and leaving deposits where the water flows. This reaction will result in issues if the precipitate clogs up pavement drainage systems, such as filter fabrics, drainage pipes, and outlets (Van Dam et al. 2011; ACPA 2009). In locations subject to wet conditions, tufa-like precipitates ($CaCO_3$) associated with leachate may develop. Further, environmental considerations have focused on the leaching of high-pH solutions from concrete aggregates. The potential for pH and drainage issues led some States/jurisdictions to require that RCA stockpiles be separated a minimum distance from water sources (Melton and Kestler 2013).

Melton and Kestler (2013) reported several case studies about using RCA aggregates in the United States:

- ODOT research concluded that RCA as an aggregate base in low-lying or wet areas where alkaline runoff likely would occur could adversely affect the environment.
- An Iowa report found that the high pH of the drainage water from RCA use could kill or impede grass growth at a drain outlet.
- Texas completed research on using RCA in MSE berms. The study involved material characterization, pH measurements, and a usage evaluation. The study concluded that the pH and resistivity specifications for MSE wall backfill materials should be waived, and concrete structures that have suffered sulfate attack should not be crushed and used as backfill in MSE walls. Further, the study recommended that MSE walls with crushed concrete backfill include adequate drains and high-permittivity filter fabrics behind the wall to avoid potential drainage issues.

Overall, the most encountered concerns among different agencies are often the high pH values and issues with leaching. Tutumluer, Moaveni, and Qamhia (2018) reported concerns about the number of fines from crushing and the possibility of alkali-silica reactions (ASR) (table 43).

Table 43. Concerns for using RCA in highway applications—agency survey responses (Tutumluer, Moaveni, and Qamhia 2018).

Agency	Description of Environmental and Performance Concerns
Alberta, British Columbia; Kentucky; Maine; Pennsylvania; Tennessee; and Washington State	Concerned with potential leaching with RCA.
Arkansas	Concerned with RCA in rigid or flexible pavement due to the number of fines from crushing.
Delaware	Not allowing RCA in concrete because it may have an ASR.
Florida and Maryland	Higher pH of RCA if used in the same area as metallized pipe.
Michigan, Montana, and South Dakota	RCA cannot be used in ephemeral drainages or high water table conditions.
Ohio	Leaching of high-pH water leaving the right-of-way from the use of RCA. The formation of tufa in underdrains due to the use of RCA.

LCA STUDIES

The vast majority of the LCA studies involving RCA calculate the environmental impacts of RCA used in concrete mixes to justify using the recycled material for lower environmental impact and lower cost concrete mixes. The literature is shy on RCA used for embankments, backfill materials, and slope stability applications. More broadly, the literature lacks LCA studies for RCA used as an unbound fill material either by itself or blended with other VA or recycled aggregates. In the United States, there are no available PCR documents for RCA. EPDs from recycling yards and manufacturers are also not available publicly. This lack of information is expected due to source variability and the low energy required to recycle concrete pavements and produce RCA. However, the lack of PCRs, EPDs, and comprehensive or comparative LCA studies for RCA in backfill applications is a research gap that requires attention and can be easily addressed since this material has been used in the United States for more than 70 yr. A multitude of data should be readily available on the production and fuel consumption rates involved in producing RCA materials and the fuel consumption of construction equipment used to construct layers with RCA.

CASE STUDIES

According to Kim, Shin, and Cha (2013) and Gabr and Cameron (2012), RCA is mostly used in granular bases, embankments, sound barriers, and fills. Further, Van Dam et al. (2011) reported that 65.5 percent of the RCA produced in the United States is used for aggregate bases, 9.7 percent in asphalt concrete, and 6.5 percent in new concrete mixtures, while 7.6 percent is used as a fill material. Abundant case studies can also be found describing the use of RCA as an unbound or bound base/subbase material, which has been the largest application for RCA in the United States to date. RCA has been used in retaining wall backfill, slope stability, embankments, and pipe fill applications. However, the researchers did not find well-documented case studies that monitored and reported the performance trends of RCA in these applications.

CHAPTER 10. TDA

INTRODUCTION AND BACKGROUND

TDAs are made from shredded scrap tires and are used in a wide range of construction projects, such as retaining wall backfill, lightweight embankment fill, landslide stabilization, vibration mitigation, and various landfill applications. More than 500 million scrap tires are discarded in the United States every year (Edinçliler, Baykal, and Saygili 2010), but as little as 22 percent of these tires get recycled. Passenger car and truck tires are composed of synthetic rubber, fibers, and steel cords (El Naggar and Iranikhah 2021). Table 44 presents typical tire composition, and figure 22 illustrates the tire shredding procedure.

Table 44. Typical passenger car and truck tire compositions (El Naggar and Iranikhah 2021).

Material	Passenger Car Tire	Truck Tire
Natural rubber (percent)	14	27
Synthetic rubber (percent)	27	14
Carbon black (percent)	28	28
Steel (percent)	14–15	14–15
Fiber (percent)	16–17	16–17
Average weight (new) (kg)	11	—

—No data.

Figure 22. Illustration. Rubber shredding procedure and outputs (Creative Commons n.d.c).

Between 1994 and 1996, some expensive failures took place related to using TDA in highway applications. By 1996, reports from three projects that experienced catastrophic internal heating reactions stopped the use of TDA in pavement projects in the United States. Two of these projects were in Washington State and one was a retaining wall project in Colorado (Patenaude and Wright 2017). In 1997, a partnership between government and industry formed an ad hoc civil engineering committee to establish new design guidelines for TDA. The committee investigated the failures and established guidelines to minimize TDA internal heating in backfill applications. As a consequence, TDA has been used in highway applications since then.

ADVANTAGES AND DISADVANTAGES

Reported advantages of using TDA in highway applications include the following (Edinçliler, Baykal, and Saygili 2010; Liberty Tire Recycling 2022; CalRecycle 2023):

- Cost effective: Less expensive than other lightweight fill materials.
- Well performing: Lightweight and free-draining characteristics help solve engineering problems effectively.
- Environmentally friendly: TDA reduces the need for mined resources such as pumice and gravel.
- No special equipment needed.
- Easy to transport and handle: Transported by trucks to a project in a 40-ft walking-floor trailer, which makes it easy to unload the TDA material. Once delivered to the site, TDA is spread and compacted by standard earthwork equipment.
- Vibration dampening.
- Viable reuse alternative to the millions of waste tires currently disposed of in landfills.

Reported disadvantages of TDA include that internal heating reactions may cause catastrophic failures (CalRecycle n.d.). New regulations overcome this issue as long as the TDA is constructed according to the guidelines.

REPORTED GEOTECHNICAL APPLICATIONS FOR HIGHWAYS

TDAs can be used in the following geotechnical applications for highways (CalRecycle 2023):

- Retaining wall backfill.
- Lightweight embankment fill.
- Landslide stabilization.
- Vibration mitigation.
- Landfill applications.

MATERIAL CHARACTERIZATION

Physical Properties

ASTM D6270 is the standard specification that regulates the size of TDA and other physical properties based on application (ASTM 2020). ASTM D6270 divides TDA into Types A and B. Type A is suitable for drainage, vibration damping, and insulation applications, while Type B is larger, produced by a shearing process (*not* a hammer mill), and is suitable for embankment fill, wall backfill, and landfill drainage applications. Table 45 and table 46 compare the properties of both types of TDA.

Table 45. Grain size distributions for Type A and B TDAs (Cheng 2016; ASTM 2020).

Sieve Opening (mm)	Sieve Opening (inches)	Type A Specification Requirements (percent passing)	Type B Specification Requirements (percent passing)
450	18	100	100
300	12	100	100
200	8	100	75–100
100	4	100	—
75	3	95–100	0–85
38	1.5	0–70	0–25
4.75	0.187 (No. 4)	0–5	0–1
Pan	Pan	0	0

—No data.

Table 46. Specifications for Type A and B TDAs (Cheng 2016; ASTM 2020).

Property	Type A Specification Requirements (percent passing)	Type B Specification Requirements (percent passing)
Free steel	1 maximum	1 maximum
Longest shred (inches)	10	18
Percent weight of shred > 12 inches	—	16 maximum
Sidewall shreds (each)	0	0
Shreds > 2 inches, wire exposed	10 maximum	10 maximum
Shreds > 1 inch, wire exposed	25 maximum	25 maximum

—No data.

Mechanical Properties

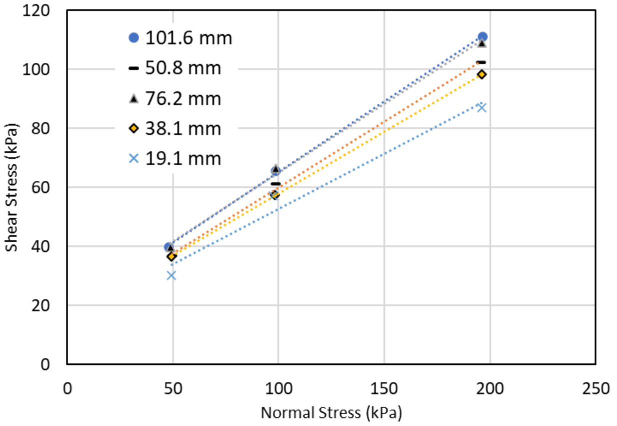
Studies have investigated the mechanical properties of TDAs used in highway geotechnical applications. El Naggar and Iranikhah (2021) looked at the optimum TDA percentage to maximize strength/performance, and El Naggar, Zahran, and Moussa (2021) investigated the effect of TDA particle size on mechanical properties. A third study investigated the effect of shear box size on the calculated shear strength properties (Zahran 2021). This section summarizes some of the essential technical content from these research efforts.

El Naggar and Iranikhah (2021) investigated the effect of the percentage of TDA in aggregate and soil mixes. The researchers mixed TDA with gravelly, sandy, and clayey soils to determine the optimum soil-TDA mixtures for each soil type. The researchers used a large-scale direct shear box (12 inches by 12 inches by 8.7 inches) and examined the mixtures for mechanical behavior trends through a series of DSTs conducted at confining pressures of 7.3, 14.3, and 28.5 psi. Table 47 presents the results. For the gravel-TDA mixes, the optimum TDA percentage that maximizes the shear strength properties is 0–10 percent. On the other hand, the optimum TDA percentage for TDA mixed with sand and clay is 10–25 percent.

Table 47. Optimum TDA percentages in aggregate and soil mixes (El Naggar and Iranikhah 2021).

Mixtures	Mixture ID	TDA by Weight (percent)	Soil by Weight (percent)	Bulk Density, γ_{bulk} (kN/m^3)	Friction Angle (degrees)	Cohesion (kPa)
Gravel—TDA	GT0	0	100	127.4	44.0	3.6
	GT10	10	90	118.1	45.4	2.5
	GT25	25	75	94.9	43.9	2.1
	GT50	50	50	65.6	42.2	2.2
	GT100	100	0	43.7	23.9	2.6
Sand—TDA	ST0	0	100	120.3	37.1	0.7
	ST10	10	90	113.8	38.4	1.9
	ST25	25	75	101.0	38.3	2.1
	ST50	50	50	77.5	31.8	2.3
	ST100	100	0	43.7	23.9	2.6
Clay—TDA	CT0	0	100	131.0	18.8	3.2
	CT10	10	90	121.6	32.3	4.2
	CT25	25	75	98.5	25.6	4.2
	CT50	50	50	70.7	25.0	2.8
	CT100	100	0	43.7	23.9	2.6

El Naggar, Zahran, and Moussa (2021), who conducted shear box tests using a large-scale direct shear machine, studied the effect of TDA particle size on the shear properties. The researchers conducted the tests under three normal stresses: 49.4, 97.6, and 196 kPa (7.3, 14.3, and 28.5 psi) using a constant shearing rate of 0.5 mm/min (0.02 inches/min). The researchers found the angle of internal friction of TDA to increase as the maximum particle size (D_{max}) increased from 19 mm (0.75 inches) to 102 mm (4.0 inches). The cohesion from the interlocking among the TDA particles was not significantly affected by the particle size (the difference was less than 0.5 psi). Further, all Type A TDA samples exhibited contractive behavior. The smaller TDA aggregates were more compressible than the relatively larger TDA aggregates. Figure 23 shows the effect of particle size on shear stress and secant shear modulus.



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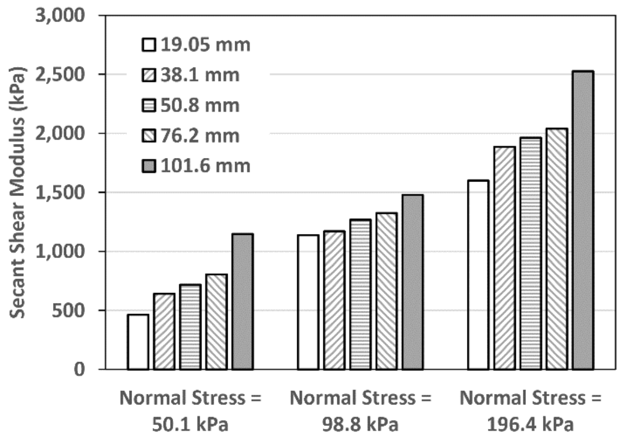
A. Normal stress versus shear stress.



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B. Normal stress versus secant shear modulus.

Figure 23. Graphs. Effect of TDA particle size on shear strength and secant shear modulus (El Naggar, Zahran, and Moussa 2021).

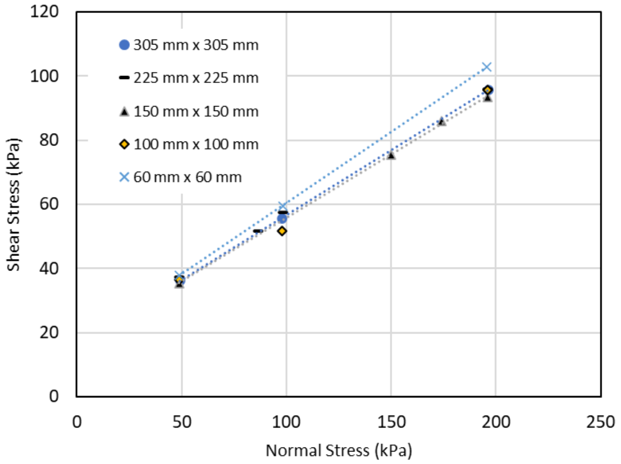
Another recent study conducted by Zahran (2021) investigated the effect of shear box size on the shear strength properties of TDA. The researchers used five shear boxes with different box sizes and aspect ratios, as summarized in table 48. Table 49 presents the properties of the 1.5-inch-mix TDA used for all studies, and the calculated shear strength properties are listed and summarized in figure 24. According to these results, the smaller shear box sizes can measure slightly higher friction angles. However, no clear trend was found for the cohesion/cohesion intercept.

Table 48. Summary of shear box sizes and aspect ratios (Zahran 2021).

Dimensions	Shear Box				
	1	2	3	4	5
Length (mm)	305	225	150	100	60
Width (W) (mm)	305	225	150	100	60
Height (H) (mm)—lower part	80	80	80	18	18
H (mm)—upper part	130	130	130	25	25
W/H aspect ratio	1.45	1.07	0.71	2.33	1.40
W/D_{max} aspect ratio	8	6	4	2.6	1.6

Table 49. Summary of the TDA gradation parameters and grain size distribution (Zahran 2021).

Gradation Parameter	Value
D_{10} (mm (inches))	12 (0.47)
D_{30} (mm (inches))	15.5 (0.61)
D_{50} (mm (inches))	24.5 (0.96)
D_{60} (mm (inches))	27 (1.06)
C_c	2.25
C_u	0.74



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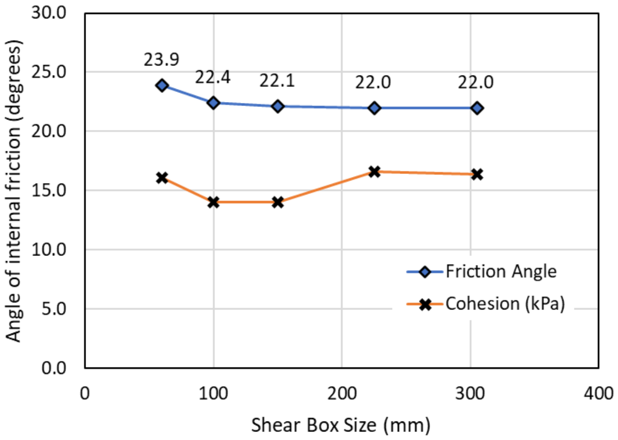
A. Normal stress versus shear stress.



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B. Effect of shear box size on shear properties.

Figure 24. Graphs. Effect of shear box size on the shear strength properties of TDA (Zahran 2021).

DESIGN REQUIREMENTS AND AVAILABLE GUIDELINES

ASTM D6270, entitled *Standard Practice for Use of Scrap Tires in Civil Engineering Applications,* provides general guidelines for using TDA in pavement geotechnical applications (ASTM 2020). Construction requirements and guidelines are fully developed, but, to date, no comprehensive design guidelines or detailed design requirements for TDAs have been published in the United States.

BACKFILL PLACEMENT AND CONSTRUCTION SPECIFICATIONS

ASTM D6270 indicates that TDA should be covered with sufficient soil thickness to limit overlying pavement deflections (ASTM 2020). Soil thicknesses of 2.6 ft or higher are suitable for light traffic scenarios. Further, TDA layers should not be more than 10 ft thick. Multiple TDA layers should have a minimum 3-ft separation layer of nonorganic soil. Lastly, a TDA layer should be wrapped completely in a layer of nonwoven or woven geotextile to minimize the infiltration of soil particles. Including this layer is essential for pavement, drainage, and retaining wall backfill applications.

Certain specifications are recommended to ensure TDAs are placed and compacted properly. Such specifications/guidelines include the following (Patenaude and Wright 2017):

- Tire shreds should not contain any contaminants (e.g., oil, grease, gasoline, or diesel fuel, among other chemical substances).
- Tire shreds should not contain fragments of wood, wood chips, or any other fibrous organic matter and should not contain loose wire or metal fragments.

- TDA material should be spread using track-mounted equipment.
- TDA lifts should be compacted using a minimum of six complete coverage passes by a vibratory smooth drum steel roller imposing a minimum static weight of 10 tons.

AVAILABLE COST INFORMATION

El Naggar and Iranikhah (2021) presented the cost of producing TDA by shredding tires (table 50). According to the data, the cost is lowest for larger shreds exceeding 2 inches in particle size but gets increasingly higher for smaller shred sizes. The process rate is also faster for the larger shred sizes.

Table 50. Cost for shredding tires (El Naggar and Iranikhah 2021).

Particle Size	Cost Per Ton ($)	Process Rate (tons/h)
50 mm	12	10–12
<50 mm	31	7
<12.5 mm	31–68	2–3

Additionally, a third party performed a cost-benefit assessment for California's Department of Resources Recycling and Recovery in 2015 for TDA use in geotechnical highway applications. The study evaluated six civil engineering projects that used TDA in California for four different applications: embankment fill projects, landfill applications, landslide repair projects, and light-rail vibration mitigation projects (Cheng 2016). Table 51 presents the results and lists the costs associated with using TDA, which are by far the least expensive among the alternative backfill materials. The total costs include material and transportation costs but exclude installation costs and the contractor's overhead and profit.

Table 51. Cost comparison between TDA and other fill materials for different applications (Cheng 2016).

Application	Location	Material Option	Material	Total Cost ($)	TDA Cost (%)
Embankment	Hwy 101, Mendocino County, CA	Traditional fill option	Soil	316,358	169
Embankment	Mendocino County, CA	Lightweight fill option	Pumice rock	514,354	274
			EPS	643,539	343
			Expanded shale clay	632,716	337
			Wood chips	307,138	164
			Type B TDA	187,500	100
Embankment	Dixon Road, Milpitas, CA	Traditional fill option	Soil	562,864	169
		Lightweight fill option	Pumice rock	632,726	190
			EPS	1,144,984	343

Application	Location	Material Option	Material	Total Cost ($)	TDA Cost (%)
Embankment	Milpitas, CA		Expanded shale clay	489,829	147
			Wood chips	545,226	163
			Type B TDA	333,600	100
Landfill	Riverside County, CA	Traditional trench	Crushed gravel	19,102	139
Landfill	Riverside County, CA	TDA material	TDA Type A	13,750	100
Landfill	Sacramento County, CA	Traditional trench	Crushed gravel	295,343	141
Landfill	Sacramento County, CA	TDA material	TDA Type A	209,585	100
Slide repair	Mendocino County, CA	Traditional fill option 2	Soil	937,612	492
Slide repair	Mendocino County, CA	TDA material option	Type B TDA with soil layers	190,555	100
Vibration attenuation	Santa Clara VTA, CA	−15 dB for 14–17 Hz	Floating concrete slabs	2,115,000	2951
Vibration attenuation	Santa Clara VTA, CA	−10 dB for >16 Hz	TDA	71,667	100

VTA = Valley Transportation Authority.

ENVIRONMENTAL CONSIDERATIONS

Laboratory and field testing have shown that TDA is not a hazardous waste based on TCLP standards. Low levels of metals and various organic compounds were detected in leachate that contacted the TDA, and these levels were below applicable water quality thresholds (Cheng 2016). Chronic toxicity testing showed no adverse effects from elevated levels of iron and manganese in the leachate from TDA fill above the water table based on leachates collected from two fill sites in Maine after approximately 10 yr in place. A toxicity effect was found in leachate from a TDA fill that was below groundwater level, but the metals quickly formed immobile and insoluble particles in the subsurface soil (Sheehan et al. 2006). Field testing additionally showed that the concentrations of metals within a TDA fill were effectively attenuated within a few feet of soil.

LCA STUDIES

No EPDs or PCRs were found for TDAs in the United States or worldwide. Further, no comprehensive LCA studies exist in the United States. However, a journal paper by Corti and Lombardi (2004) evaluated the emissions at the end of life of tires (i.e., tire shredding and pulverization) for tire waste in Italy. The researchers considered two processes, a mechanical pulverization process and a cryogenic pulverization process. Mechanical pulverization involves three steps (grinding, crushing, and pulverization) of mechanical size reduction up to 0.04-inch shred sizes. Cryogenic pulverization (freeze-milling) produces a higher quantity and quality of recycled rubber. Since highway geotechnical applications require relatively large shred sizes, all pulverization processes (i.e., fine grinding) were omitted from the reported environmental impacts. Thus, for mechanical pulverization, only the first two steps of grinding and crushing were included, and cryogenic pulverization was completely excluded. The assumed size for the tire shreds after the crushing process is 0.63 inches by 0.63 inches (16 mm). Corti and Lombardi (2004) reported that the pulverization process consumes around 50 percent of the energy for tire shredding. The analysis was performed for 1,000 kg of tires (table 52 and table 53 for the inputs and outputs of the process). To reasonably compare the results with the other lightweight materials presented in this report, a density of 45 pcf equals 720 kg/m^3 was assumed for the TDAs, and the environmental impacts were reported with a functional unit of 1.0 m^3 of crushed tire shreds (table 54).

Table 52. Inputs and outputs of the tire grinding process (Corti and Lombardi 2004).

Input	Output	Amount
Tires	—	1,000 kg
Electricity	—	170 MJ
Water	—	150 kg
Steel	—	0.230 kg
Oil	—	0.011 kg
—	Ground tires	966 kg
—	Iron scrap	34 kg

—Not applicable.

Table 53. Inputs and outputs of the tire shredding process (Corti and Lombardi 2004).

Input	Output	Amount
Ground tires	—	1,000 kg
Electricity	—	573 MJ
Steel	—	0.010 kg
—	Crushed tires (16×16 mm)	750 kg
—	Iron scrap	250 kg

—Not applicable.

Table 54. Summary of environmental impacts from grinding and crushing 1.0 m^3 of tires.

Environmental Effect	Units	Impacts from Mechanical Crushing and Grinding
Greenhouse effect	kg CO_2	4.39E+01
Ozone layer depletion	g CFC11	1.51E-02
Acidification	kg SO_2	1.71E-01
Eutrophication	g PO_4	3.60E-01

CASE STUDIES

The following list includes projects that used TDA for various geotechnical highway applications in the United States, as documented by Igwe (2021).

- Riverside, CA, 2007: TDA was used as a lightweight fill material to exert less pressure behind the retaining wall 207 project, which was constructed to aid the widening of the I-215/Route 60/Route 90 freeway interchange (Cheng 2016). TDA served as both the backfill and the drainage material.
- Sonoma County, CA, 2008: TDA was applied as the subgrade layer for Geysers Road, providing a lightweight fill to repair the landslide failure caused by the saturation of soil backfill during periods of heavy rain (Cheng 2016).
- Indiana, 2008: A mixture of TDA and soil was used as lightweight backfill for the widening of SR–110 in Marshall County and SR–19 in Elkhart County, where the grade needed to be raised over peat to minimize soil settlement (Hoppe and Oman 2013).
- Mankato, MN, 2010: TDA was used as a lightweight fill to stabilize the peat under the embankment area of the Blue Earth County Road 12 bridge, which sustained cracks after construction (Hoppe and Oman 2013).

California implemented a long list of successful projects using TDA (Patenaude and Wright, 2017):

- Dixon Landing Interchange, 2001 (first TDA project).
- Highway 215 and Route 91 retaining wall research, 2003–2007. Joint project with Caltrans.
- Valley Transit Authority vibration mitigation, 2004.
- Marina Drive, Mendocino County landslide repair, 2007.
- Riverside County landfill gas collection system pilot projects, 2008.
- Caltrans Confusion Hill lightweight fill embankment, 2008.
- Sonoma County, Geysers Road landslide repair, 2008.
- Sonoma Mountain Road landslide repair, 2009.
- Sacramento County, Keifer Landfill leachate recirculation, 2009.
- Santa Barbara County, Palomino Road slide repair, 2010.

The following list includes projects described by Igwe (2021) that successfully used TDA for various geotechnical highway applications in Canada:

- Winnipeg, Manitoba, 2000: TDA was used to build a 305-m- (1,000-ft)-long embankment above soft ground to act as a subgrade thermal insulator to limit frost penetration and prevent road damage (Hoppe and Oman 2013).

- New Brunswick, 2007: TDA was used as a lightweight fill in the first stage of construction of the Route 1 highway embankment after it collapsed due to underlying soft marine clay (Hoppe and Oman 2013). TDA helped reinforce the holding capacity of the foundation soil.

- Stettler County, Alberta, 2013: The Alberta Recycling Management Authority and the County of Stettler used TDA as a lightweight fill in place of conventional clay fills for a section of Range Road 184 between Township Road 360 and 361 (Igwe 2021). TDA's elasticity resulted in a less rigid fill that still provided the required structural strength.

- Edmonton, Alberta, 2013: TDA was used as a fill to construct an 80-m- (262.5-ft)-long embankment connecting the Anthony Henday Drive ring road to the Edmonton Waste Management Centre (Meles 2014). TDA was chosen because of its light weight and greater permeability.

- Halifax, Nova Scotia, 2016: TDA was used to build a high-traffic off-ramp for the Ragged Lake Transit Centre, saving the municipality up to $140,000 (Moore 2016). TDA was applied because of its effectiveness with high groundwater table and poor soil conditions (Igwe 2021).

CHAPTER 11. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY OF FINDINGS

This report presents findings on the potential use of alternative lightweight and recycled materials in geotechnical highway applications, including retaining walls, MSE walls, embankments, fills behind bridge abutments, pipe/culvert backfills, and ground improvements. Such materials may be advantageous compared to more conventional structural backfills to combat design challenges and reduce costs, construction time, surcharge loads, and environmental impacts.

The researchers studied nine lightweight and alternative backfill materials in detail: CLSM, ESCS, FGA, LCC, polystyrene geofoams, RAP, RCA, RGA, and TDA. The researchers covered the following aspects of each material when information was available:

- Geotechnical highway applications in the literature.
- Advantages and disadvantages of using each material in backfill applications.
- Literature on material characterization.
- Design requirements.
- Design guidelines.
- Placement and construction specifications.
- Cost information.
- Environmental considerations.
- LCA studies.
- Case studies and performance records.

The report summarized the material characteristics in detail. Table 55 summarizes the key aspects of each investigated material that make it a suitable fill material, along with the friction angle and density. Six of the materials are considered lightweight alternatives (CLSM, ESCS, FGA, LCC, geofoams, and TDA), while the other three (RAP, RCA, and RGA) are recycled, low-cost alternatives.

Table 55. Key advantages of using alternative backfill materials in geotechnical applications.

Lightweight/ Alternative Material	Friction Angle (degrees)	Density (kN/m^3)	Key Advantages as a Backfill Material
CLSM	25–55	14.14–15.71	Lightweight, easily excavated, fast strength gain, does not require compaction, suitable for complex geometries
ESCS	35–53	5.88–10.20	Lightweight, chemically inert, high durability, high friction angle, controlled gradation
FGA	27–56	1.57–3.92	Lightweight, high friction angle, inert (nonflammable and UV stable, low decay), requires no special equipment, can be installed in any weather
LCC	—	3.14–9.42	Lightweight, high workability, does not require compaction, suitable for complex geometries
Polystyrene geofoams	—	0.11–0.47	Extremely lightweight, thermal insulator, can be installed in any weather, fast construction, and low labor cost
RAP	39–54	15.69–19.61	Nonplastic, free draining, not susceptible to frost
RCA	41–65	16.67–20.10	High strength and friction angle, nonplastic, not susceptible to frost
RGA	37–62	17.28–18.85	Inexpensive to produce/recycle, high friction angle, can be installed in any weather, easy to compact (good workability), requires no special equipment
TDA	24–45	3.77–8.83	Lightweight, inexpensive to produce, free draining, requires no special equipment, vibration-dampening characteristics

—No data.

ALTERNATIVE LIGHTWEIGHT/BACKFILL MATERIALS USED IN GEOTECHNICAL HIGHWAY APPLICATIONS

The researchers concluded that all the recycled and lightweight materials investigated in this study have already been used (or can be successfully used) for the target geotechnical highway applications (i.e., bridge abutments, embankments, retaining wall fills, pipe backfills, and ground improvements) without major reported issues or early failures. For any design alternative, the design engineer should pay special attention to the design and construction requirement details of each material separately in their prescriptive environment while accounting for the changes in physical properties, such as the improvement/changes in shear strength and angle of internal friction, and the weight/density of the fill. Further, closely following the proper construction guidelines and practices with the correct construction equipment at the specified lift thickness is paramount. Table 56 lists applications for the lightweight/recycled materials that the literature reports have been used successfully. If a material is not listed for a certain application, it might mean that it has not been attempted for that application or that the researchers did not find a documented case study for its use in the perspective application.

Table 56. Alternative backfill materials and reported geotechnical applications.

Material/Application	Retaining Walls	Embankments	Bridge Abutment Fill/Bridge Approach embankment	Pipe/Culvert Covers and Backfills	Slope Stabilization	Ground Improvements
CLSM	X	X	X	X	—	X
ESCS	X	X	X	X	X	X
FGA	X	X	X	X	—	X
LCC	X	X	X	X	X	X
Polystyrene geofoams	X	X	X	X	X	X
RAP	X	X	—	X	X	X
RCA	X	X	—	X	X	X
RGA	—	—	—	X	—	X
TDA	X	X	X	X	X	X

—No data.

CONCLUSIONS

Table 57 identifies and summarizes the technology-ready aspects of each alternative lightweight and recycled material discussed in this report based on the comprehensive literature review. Overall, all these materials have been used in full-scale field construction projects as an alternative to conventional backfills. All of these alternative backfill materials are placed at a TRL of 8, according to FHWA's *Technology Readiness Level Guidebook* (Towery, Machek, and Thomas 2017). A TRL of 8 requires that the following questions be fully answered and the requirements met by each alternative lightweight or recycled material discussed in this report for use in geotechnical highway applications:

- Are all system components form-, fit-, and function-compatible with each other and with the operational environment?
- Is the technology proven in an operational environment (i.e., meets target performance measures)?

- Was a rigorous test and evaluation process completed successfully?
- Does the technology meet its stated purpose and functionality as designed?

Note that despite all the materials having a TRL of 8, the literature search made clear that some materials presently have a higher market penetration and are more commonly used in the United States for geotechnical applications. For example, TDAs and CLSMs have comprehensive field application data for most of the aspects of interest in this report, while some materials, such as RGA, lack comprehensive information with very few case studies. One major area where information is missing for most of the materials (except ESCS and FGAs) is the presence of EPDs to summarize the environmental impacts and energy demands for commercial products. In fact, the only PCR available in the United States is for ESCS, but no publicly available EPDs or comprehensive LCA studies exist for any of the materials used in geotechnical applications.

Table 57. Technology readiness for the studied alternative backfill materials.

Material	**Technology-Ready Aspects**
CLSM	• Extensive studies have been done on laboratory characterization, including using recycled and byproduct materials to reduce cost. • ASTM standards exist for QA/QC and postconstruction practices.
ESCS	• ESCSI published a PCR (expired in 2021). EPDs are available for some products in Europe. • Promising (well-performing) case studies are available, with abundant examples in the literature. • Construction procedures seem to be well developed; no special equipment is needed. • Physical and mechanical properties are well understood and well cited in the literature. • ASTM/AASHTO standards used for conventional aggregates can be extended to ESCS.
FGAs	• PCR and EPDs are available from Europe. • Case studies in the United States and worldwide are available (and promising). • The number of States in the United States using/accepting use is on the rise.
LCC	• Construction procedures seem to be well developed. • ASTM standards are available to control foaming material properties and requirements. • Promising (well-performing) case studies are available.
Polystyrene geofoams	• Design guidelines are available for various geotechnical applications. • Promising case studies, especially using polystyrene geofoams as an insulating material, are available.
RAP	• RAP is heavily used for highway applications. Most DOTs and agencies have had good experience with RAP as a construction material.

Material	Technology-Ready Aspects
RCA	• RCA is heavily used for highway applications. Most DOTs and agencies have had good experience with RCA as a construction material.
RGA	• Laboratory testing techniques have been well developed, and abundant testing results are available. • Special requirements for construction are minimal. RGA does not need special equipment.
TDA	• Documented case studies are abundant. • Laboratory characterization is well documented. • Special equipment for construction and handling is not needed. • Cost saving is well documented from several projects in the United States.

KNOWLEDGE GAPS AND BARRIERS TO WIDESPREAD USE

Table 58 summarizes several knowledge gaps pertaining to the use of recycled and lightweight alternative backfill materials for geotechnical highway applications. For all the alternative backfills, barriers to widespread use are mainly a result of concerns about long-term performance, given a lack of local experience. The following section recommends research needed to adequately address these knowledge gaps and promote more successful use of these alternative backfill materials in the United States.

A clear understanding of the key geotechnical properties and design considerations of each material (compared to conventional fills) needs to be fully studied to promote more use of the investigated materials in the United States. While the researchers found information about geotechnical properties and design considerations, to a large extent, the information was from laboratory studies. Quantitative information from full-scale field testing or actual construction projects was scarce. The researchers found few long-term performance records, especially comparative performance to conventional fill materials. The specifications of most U.S. DOTs and agencies are performance-based rather than material-based. Therefore, a full understanding of the long-term performance and better knowledge about the key design aspects and material properties, including consistent and standardized procedures to characterize these unique materials across different laboratories, will increase understanding of these materials' performance and promote more successful use in highway geotechnical applications. The lack of knowledge about long-term performance and standardized laboratory test procedures are major barriers to implementation and gaps in knowledge that need to be addressed for lightweight backfill materials, particularly for emerging products, in order to disseminate their full potential and promote increased use.

Table 58. Identified barriers to deployment of the studied alternative backfill materials.

Material	Barriers to Implementation and Gaps in Knowledge
CLSM	• The initial cost of the material is relatively high. However, lower labor costs can make it cost effective. • Special construction requirements need special equipment and skilled labor. • Postconstruction testing (e.g., QA/QC) is not fully developed and can be challenging. • Few documented case studies exist for backfill applications. • No PCRs, EPDs, or LCAs are available in the United States or elsewhere. • Little/no data from long-term performance are available.
ESCS	• Production sites in the United States are limited—high hauling costs for some locations. • No EPDs or LCAs are available in the United States. • Little/no data from long-term performance are available.
FGAs	• Few ASTM/AASHTO standards exist for laboratory testing. • Compaction method for laboratory testing is largely based on the Proctor method, methods that significantly alter gradations, or both. • PCR, EPDs, and LCAs are not available in the United States. • Some construction recommendations are available, but no solid construction guidelines are available. • Postconstruction testing is not fully developed. • Little/no data from long-term performance are available.
LCC	• No approved or standard mix design procedure is available. • No approved density check/measurement procedure (except for plastic density) is available. • No PCR, EPD, or LCA was found in the literature. • Postconstruction testing is not fully developed; only UCS (strength) checks are performed. • Little/no data from long-term performance are available.
Polystyrene geofoams	• No published PCRs, EPDs, and LCAs exist for geofoams used in geotechnical applications. • Not suitable for complex geometries.
RGAs	• PCR, EPDs, and LCA studies are not available for geotechnical uses. • Postconstruction testing (e.g., QA/QC) is not fully developed. • Very few documented case studies are available for backfill applications. • Some States conducted feasibility studies and found they don’t have enough resources to mass-produce the material. Little/no data from long-term performance is available.

Material	Barriers to Implementation and Gaps in Knowledge
TDAs	• Material can be used elsewhere as an energy source; market availability is questionable. • No PCRs, EPDs, or LCAs are available, especially in the United States or elsewhere. • Little/no data from long-term performance are available.

RECOMMENDED FUTURE WORK AND INVESTIGATIONS

Based on the findings and conclusions presented in table 58, the following research needs are suggested to promote more commonplace uses of lightweight and recycled alternative backfill materials to take advantage of these technologies and associated benefits in geotechnical highway applications (see table 59). These research needs are recommended based on the knowledge gaps identified from the comprehensive literature search and primarily aim to eliminate technology barriers and promote more sustainable construction practices while ensuring good performance.

One major research need for all the lightweight and alternative backfill materials investigated in this report is to establish standardized test procedures to correctly characterize the materials across different laboratories in the United States and obtain key design aspects for the different highway geotechnical applications of interest. Developing the test procedures is a major task that is deemed essential for these materials to be characterized properly, reveal their full potential, and increase their utilization and market penetration. Another related research need that this report touched on, but that needs to be studied more comprehensively, is performing a nationwide survey of the current state of practice of the investigated materials by the U.S. State DOTs. This research should include an understanding and compilation of what materials each agency uses or allows, what applications these materials are used for, and any performance/material specification each agency has (including what test procedures are followed and what are the key design aspects). The best way to gather this information is for researchers to contact the right personnel in each agency. Such detailed information is deemed necessary to better understand the current knowledge gaps and gear future research toward these pressing needs. Lastly, research is needed to investigate which current test methods are most suitable for the different alternative materials and what new test methods or modifications to the current test methods need to be proposed.

Table 59. Proposed research needs for the studied alternative backfill materials.

Material	Proposed Research Needs
CLSM	• Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for CLSM produced in the United States. • Conducting cost-benefit analyses of using CLSM for geotechnical highway applications. • Conducting pilot projects and collecting further data from construction projects to document case studies for using CLSM in highway fill applications. • Developing postconstruction inspection and testing methods for CLSM used in highway fill applications.
ESCS	• Conducting cost-benefit analyses of using ESCS for geotechnical highway applications. • Conducting laboratory testing of various ESCS materials produced in the United States to obtain design-specific parameters for the various backfill applications.
FGAs	• Evaluating best practices for compacting laboratory samples to test FGAs. • Developing ASTM/AASHTO standards for testing FGA aggregates using a shear box and triaxial shear strength testing. • Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for FGA materials produced in the United States. • Conducting cost-benefit analyses of FGA materials used for geotechnical highway applications. • Conducting laboratory testing of various FGA materials produced and sold in the United States for obtaining design-specific parameters for the various backfill applications. • Developing construction guidelines for using FGA in highway fill applications, including postconstruction QA/QC methods.
LCC	• Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for LCC produced in the United States. • Conducting cost-benefit analyses of using LCC for geotechnical highway applications. • Developing postconstruction inspection and testing methods for LCC used in highway fill applications.
Polystyrene geofoams	• Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for geofoams produced in the United States. • Conducting cost-benefit analyses of using geofoams for geotechnical highway applications. • Examining best practice installation methods for geofoams to reduce buoyancy issues.

Material	**Proposed Research Needs**
	• Developing construction requirements for geofoams in highway fill applications to avoid buoyancy, including postconstruction inspection and testing methods.
RGAs	• Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for RGA materials produced in the United States. • Conducting cost-benefit analyses of RGA materials used for geotechnical highway applications. • Conducting pilot projects and better documentation of case studies for using RGAs in highway fill applications. • Developing construction guidelines for using RGAs in highway fill applications, including postconstruction QA/QC methods.
TDAs	• Developing an ASTM-sponsored PCR for conducting LCA and issuing PCRs for TDA produced in the United States. • Conducting laboratory testing of TDA materials available in the United States for obtaining design-specific parameters for the various backfill applications.

ACKNOWLEDGMENTS

The map in figure 8 was modified. The original map is the property of Google Maps and can be accessed from https://www.google.com/maps (2022). The image location markers were added by the authors.

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