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Guidelines for Using Lightweight Fills in Transportation Infrastructure Applications

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16. Abstract This research investigated the use of lightweight fills as an alternative to conventional fills in transportation infrastructure, particularly for fill applications on soft, compressible soils. The study synthesized current practices through a literature review, survey of state DOTs, evaluation of case studies, and material costs. Through this research, it was concluded that lightweight fills are widely applied nationwide and can significantly reduce vertical and lateral stresses, but their broader adoption is limited by high costs, limited contractor experience, and insufficient long-term performance data. Additionally, TxDOT is provided with recommendations for practical design and construction guidelines, cost considerations and limitations, which can be used to inform project planning and encourage applications of lightweight fills in Texas.		
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Disclaimers

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Products

Product 0-7237-P1 Training Materials for Using Lightweight Fills in Transportation Infrastructure Applications.

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Chapter 1. Lightweight Fill Use Practices

Construction of fill structures such as embankments and Mechanically Stabilized Earth (MSE) walls on soft, compressible soils is challenging and usually requires costly ground improvement, preloading, or staged construction that may significantly impact the construction timeline. The use of alternative lightweight fills in the construction of such structures may largely reduce or limit the use of ground improvement, preloading, or staged construction. This report synthesizes the state of the practice of using lightweight fills in transportation infrastructure and proposes design and construction guidelines based on the current practices.

Lightweight fills have found a multitude of applications in transportation infrastructure in which conventional select fills pose challenges. Lightweight fills have advantages over their conventional counterparts from engineering, environmental, and economic perspectives. Lightweight fills are much lighter than conventional fills, which make them favorable in projects where excessive vertical and/or lateral stresses are a concern. Lightweight fills induce much smaller vertical stresses than conventional fills when constructed at sites involving soft or compressible soils or when used to backfill above culverts or vulnerable utilities. Lightweight fills have also been used to backfill behind retaining structures to reduce the lateral earth pressure behind retains walls and bridge abutments and other vertical structures that may be vulnerable to lateral thrusts from conventional fills. Lightweight fills are a viable option for construction above utilities such as pipelines, especially old utilities that may have not necessarily been designed to accommodate vertical stresses from conventional fills.

Additional benefits of some specific lightweight fills include resistance to fire (useful in areas prone to wildfires), resistance to frost heave (useful in areas prone to frost), low corrosiveness, high drainability, chemical stability, reduction in carbon emissions, deviation of landfill waste, and accelerating project delivery.

The engineering properties of many lightweight fills are not well established and/or not well understood (Qamhia et al. 2023). While the use of recycled and sustainable materials in the construction of transportation infrastructure has always been encouraged by transportation agencies, their use should not compromise the intended infrastructure performance. Accordingly, further research and demonstration projects on the performance of lightweight materials are necessary to ensure the suitability and longevity of lightweight fills in the various infrastructure applications (Tutumluer and Qamhia 2024).

1.1. Lightweight Fill Types

Lightweight fill is a general term that encompasses a number of products, which can be categorized into (1) discrete fills (i.e., granulated materials) such as tire-derived aggregate, pumice, wood chips, fly ash, boiler slag, air-cooled slag, foamed glass aggregate, and expanded shale, clay, or slate; and (2) continuum fills (i.e., monolithic materials), such as controlled density flowable fill, expanded polystyrene and extruded polystyrene geofoam, and cellular concrete. This section reviews newly emerging, highly potential, lightweight fill materials of unit weights less than the unit of water (62.4 pcf) that could benefit from further investigation.

1.1.1. Expanded Shale, Clay, and Slate (ESCS) Aggregate

Expanded Shale, Clay, and Slate (ESCS) fills are discrete fills that consist of lightweight ceramic aggregates formed by expanding and vitrifying shales, clays, or slates, in a rotating kiln at elevated temperatures. Heating raw materials to incipient fusion form cellular structure through the evolution of gases within the pyroclastic mass, causing materials to undergo expansion that is irreversible upon cooling (Tutumluer and Qamhia 2024). In this process, the clay minerals of montmorillonite, illite, and kaolinite become completely dehydrated and will not re-hydrate under atmospheric conditions (Schaefer et al. 2016). These aggregates have hard ceramic skeletons and are highly porous with and largely non-connected pores, which make them extremely light (Schaefer et al. 2016; ESCSI 2007). These fills have unit weights ranging from 45 to 60 pcf (Qamhia et al. 2023, ESCSI 2007). The particle shape may be rounded, cubical, or sub-angular in shape (Schaefer et al. 2016).

The ESCS Institute (ESCSI) offers a thorough examination of ESCS products manufactured across the US, as well as recommendations for design specifications and construction controls for the use of ESCS fills. These products are manufactured by US-based manufacturers fairly distributed across the country.

1.1.2. Foamed Glass Aggregate (FGA)

Foamed Glass Aggregate (FGA) is a discrete fill derived from foam glass, a technology that was introduced in the 1920s to produce insulation panels for use in building envelopes. It has been used as a lightweight fill alternative in Europe since the 1990s (Loux et al. 2019a). In the literature, FGA is also referred to as glass-foam aggregate (e.g., Betti et al. 2014), granulated foamed glass (e.g., Aabøe and Øiseth 2004), foamglass aggregate (e.g., Frydenlund and Aabøe 2014), foam glass gravel (e.g., Hibbert 2016), cellular glass aggregate (e.g., Aabøe and Øiseth 2004; Skogstad et al. 2005; Zegowitz 2010), and foamed recycled glass aggregate (e.g., Arulrajah et al. 2015a,b). Foamed glass should not, however, be confused with expanded glass, which is a broader term that may include foamed glass and other products that may differ from foamed glass in properties. Foamed glass aggregate was first used in Norway to counter frost driven by the cold Scandinavian climate (Loux et al. 2019b). Thereafter, FGA found applications in several other European construction markets and was recently introduced to the US (Loux 2018) through US-based producers. At least three producers or distributors have been identified in the US (in Texas, Pennsylvania, and Vermont) and several producers have been identified outside the US including in Norway, Germany, UK, Italy, Czech Republic, Netherlands, Sweden, Finland, Estonia, Hungary, Japan, Switzerland, Austria, Poland, and Russia.

Foamed glass aggregate is manufactured from recycled glass treated with a foaming agent such as gypsum, limestone (Hibbert 2016), glycerin, manganese dioxide (Ghafari et al. 2019) and, most commonly, silicon carbide (Aabøe and Øiseth 2004; Hibbert 2016). The color of the FGA produced depends primarily on the foaming agent, which can be ash gray if silicon carbide is used, dim gray if glycerin is used, and sienna if manganese dioxide is used (Ghafari et al. 2019). The recycled glass used as a feedstock in producing FGA in the US is sourced from toxin-free glass waste such as curbside-collected container glass (Loux et al. 2019b). The manufacturing process involves milling glass waste to fine powder, mixing it with the foaming agent, and heating the mixture in a kiln to activate the foaming agent. Foamed glass exits the kiln on a cooling belt in the form of a foamed glass cake (Loux et al. 2019a) that consists of approximately 8% glass and 92% gas (Aabøe and Øiseth 2004). The abrupt drop in temperature induces thermal stresses that crack the foamed glass cake into gravel-size aggregates (Aabøe and Øiseth 2004; Zegowitz 2010; Loux et al. 2019a). The predominant particle size of the produced aggregate ranges from 10 to 75 mm (Aabøe and Øiseth 2004; Zegowitz 2010; Loux et al. 2019a). The individual particles of FGA produced in this process are composed of closed-cell glass matrices with entrapped gas bubbles introduced by the foaming agent (Aabøe and Øiseth 2004; Loux 2018).

Generally, FGA offers high shear strength and stiffness, drainability, insulation, chemical stability, and favorable electrochemical properties (Hibbert 2016). In addition to its function in reducing stresses as a lightweight fill, FGA can also be used to prevent frost heave under roadway structures and as an insulating fill around underground structures and utilities.

1.1.3. Tire-Derived Aggregate (TDA)

Tire-Derived Aggregate (TDA), also known as tire shreds or shredded tires, is produced by mechanically shredding discarded tires into light, durable chips that generally range in size from 4 to 8 inches (Schaefer et al. 2016). It can be made of 100% tire chips or by mixing tire chips with soil; both compositions produce drainable, lightweight fills. Another form of tire-derived lightweight fill can be created by binding scrap tires with steel wires into bales (Zornberg et al. 2005). Tire-derived aggregate has been used in a range of transportation projects including backfills for retaining walls, reinforced fills for MSE walls, fills for embankments, pavements, landslide stabilization, and vibration mitigation.

Historically, the research and development of engineering criteria for the use of TDA as a lightweight fill progressed in the 1990s (Schaefer et al. 2016). A user guideline for TDA was published by the FHWA in 1997 (FHWA 1997), which noted that at least 15 states had used TDA as a lightweight fill and demonstrated that more than 70 successful projects had been completed on state and private roads (Humphrey 1996). A survey of 45 state agencies conducted by Stroup-Gardiner and Wattenberg-Komas (2013a) reported that 14 states use TDA in embankment construction.

The state of the practice for embankment construction with TDA is presented in ASTM D6270. Per FHWA-NHI-16-027 (Schaefer et al. 2016), current practice follows ASTM D6270 Type A gradation for TDA fills in construction of embankments up to 10 ft in thickness provided that TDA fills are encased in geotextiles, covered with soil, and used above the groundwater table. Additional design and construction guidelines are provided by some state agencies, including NYSDOT (2015a) and CalRecycle (Cheng 2016).

ASTM D6270 separates TDA into two basic types—Type A and Type B—used in engineering applications; and two associated classes of fill, Class I and Class II. Type A and Type B are size classifications used for different applications. Class I and Class II describe the lift thicknesses of the fill as defined by ASTM D6270. Type A material is roughly 3 to 4 in. in size, and Type B material is roughly 6 to 12 in. in size. Class I fills are TDA layers less than 3 ft in height and Class II fills describe TDA layers between 3 and 10 ft high. Typically, Type A material is used in Class I fills and Type B is used in Class II fills.

The engineering properties of TDA have been reported in technical publications and summarized by Humphrey (1998). The use of TDA for transportation embankment construction has been evaluated by Washington DOT (Baker et al. 2003) and Texas DOT (Sonti et al. 2003). The NCHRP 435 synthesis (Stroup-Gardiner and Wattenberg-Komas 2013b) summarized physical, chemical, environmental, and engineering properties of scrap tire byproducts and various applications including embankment fill.

Manufactured from a recycled material, TDA has some environmental payoffs. Annually, more than 500 million waste tires are dumped in the US, only 22% of which are recycled (Edinçliler et al. 2010). Tires are composed of synthetic rubber, fibers, and steel strands, creating a distinct composite material for building purposes (El Naggar and Iranikhah 2021). The economics of using TDA depend on the location. Tires are a waste product, and in some locations, the costs are primarily associated with the shredding process and transportation to the project site (Schaefer et al. 2016). In some states, there are incentives for using waste tires in civil engineering projects, such as those by CalRecycle in California.

1.1.4. Lightweight Cellular Concrete (LCC)

Lightweight Cellular Concrete (LCC), also known as Low Density Cellular Concrete (LDCC) and Lightweight Foamed Concrete Fill (LFCL), is a cement water slurry typically created by mixing Portland cement, water and air introduced through a foaming agent, and may include some sand (Schaefer et al. 2016; ASCE Texas Section 2022). This material may include supplementary admixtures such as fly ash, slag, silica fume and fibers, as long as they do not have detrimental effects on the fill porosity. The produced fill is composed of a cement matrix with a network of discrete air cells. Taylor and Halsted (2021) provide a comprehensive report on the use of LCC in geotechnical applications and recommendations for design and construction considerations to achieve high-quality LCC fills. An LCC mix should be produced on site as transport of premixed LCC may adversely affect the density of the final product due to the vibrations associated with transportation (Taylor and Halsted 2021). Prolonged periods in a ready-mixed concrete truck may also cause the properties of the LCC to change. It can be pumped at 100 cubic yards per hour (Caltrans 2021). The three pumping systems most used for LCC are progressive cavity pumps, peristaltic pumps, and piston pumps (Taylor and Halsted 2021).

This fill is characterized by its low viscosity and self-leveling ability, which makes it easy to handle and allows for long-distance placements (Halsted 2020). It solidifies within 10 to 14 hours under optimal temperatures ranging from 59 to 81°F (Elastizell 2022). Lightweight cellular concrete is generally cast in lifts ranging from 1 to 4 ft or more and subsequent lifts can generally be placed after a minimum of 12 hours of curing (Schaefer et al. 2016). The quality of cast fill is monitored through its cast density, starting with the wet cast density, which correlates to the compressive strength of the fill (Schaefer et al. 2016). In addition to its use as a lightweight fill, LCC has also been used to provide shock absorption in seismic-susceptible areas and fill voids in silos and abandoned mines (Caltrans 2021). Lightweight cellular concrete fills have unit weights ranging from 25 to 80 pcf

(Caltrans 2021) and are generally produced by either batch mixing or auger mixing (Taylor and Halsted 2021). Batch mixing provides an excellent mix quality at low production rates ranging from 30 to 50 yd^3/hr.; high-shear batch mixing results in higher strength mixes and can produce 50 to 150 yd^3/hr. (Taylor and Halsted 2021). On the other hand, auger mixing provides a convenient and fast means for producing large quantities of LCC at high production rates ranging from 30 to 500 yd^3/hr. (Taylor and Halsted 2021).

1.1.5. Rigid Cellular Polystyrene (RCPS) Geofoam

Rigid Cellular Polystyrene (RCPS) geofoam is produced in the form of extremely lightweight blocks and has been widely used in the construction of transportation infrastructure. In addition to being lightweight, it offers frost heave resistant solutions in areas with harsh cold climates, thermal insulation, and vibration dampening in seismic-susceptible areas (Mohajerani et al. 2017). This fill is formed either by expansion of polystyrene resin beads or granules in a molding process to produce Expanded Polystyrene (EPS) or by expansion of polystyrene base resin in an extrusion process to produce Extruded Polystyrene (XPS). Standard specifications for RCPS are offered by ASTM D6817. Expanded polystyrene geofoams are more commonly used in transportation infrastructure applications due to their consistent properties and adequate strengths. Per Caltrans Geotechnical Manual (Caltrans 2021), the most comprehensive design, material, and construction guidelines on the use of EPS for highway construction have been summarized in NCHRP 24-11 (Stark et al. 2004) for embankments and NCHRP 24-11(2) (Arellano et al. 2011) for slope stability projects. Additional design information is summarized by Horvath (1995). These fills have unit weights ranging from 11 to 48 kg/m^3 or 0.7 to 3 pcf (Tutumluer and Qamhia 2024).

Expanded polystyrene is resistant to alkalis, dilute inorganic acids, gypsum plaster, most alcohols, Portland cement, silicone oil, and solvent-free bitumen. However, EPS may be damaged by chemicals that 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). Where geofoams are used as a structural backfill, a reinforced gasoline-resistant geomembrane should be used to protect the geofoam from spilled liquid hydrocarbons and other fluids (Tutumluer and Qamhia 2024). When placed in the ground, EPS is resistant to decay (Schaefer et al. 2016).

1.2. Pros and Cons

The pros and cons of each lightweight fill material studied are summarized in Table 1.1 and were compiled from various sources (FHWA 1997; Edinçliler et al. 2010;

Schaefer et al. 2016; Taylor and Halsted 2021; Caltrans 2021; ESCSI 2007; Tutumluer and Qamhia 2024) in addition to the authors' interpretation.

Table 1.1. Pros and cons.

Material	Pros	Cons
ESCS	- Lightweight - High shear strength - Insoluble in water and acids - Drainable - Chemically inert - Highly durable - Frost resistant - Fire resistant - Good thermal insulator - Controlled gradations	- Manufacturing costs can be high - Transportation can be costly if the project site is far from the manufacturing plant
FGA	- Extremely lightweight - High shear strength - High compression stiffness - Low creep potential - Frost resistant - Drainable - Fire resistant - Decay resistant - Favorable electrochemical properties - Chemically inert - Ultraviolet resistant - Construction is insensitive to weather conditions - No specialty construction equipment - Transportable in large quantities - Made of recycled waste - Recyclable in temporary applications	- Transportation can be costly if the project site is far from the manufacturing plant - Glass powder can lead to respiratory and skin irritation - Highly crushable if specific construction guidelines are not followed - Highly buoyant when submerged if not topped by counterweights

Material	Pros	Cons
TDA	- Lightweight - Drainable - Cost effective compared to other lightweight fill types. - No specialty construction equipment - Tires exist in abundance - Made of recycled waste - Vibration dampening	- Hazardous exothermic reactions if specific construction guidelines are not followed - May produce toxic leachate in the long term
LCC	- Lightweight - Durable - Self-compacting - Excellent mechanical properties - Rapid installation - Noncorrosive - High slump and self-leveling - Absorbent to shock waves - High freeze-thaw resistance - Low water absorption and permeability - No compaction is required	- Strength and viscosity are highly sensitive to water content - Final product is highly sensitive to small variations in mix designs - Requires specialty contractors and suppliers - Relatively costly for small jobs - Brittle and prone to cracking under significant differential settlement
RCPS	- Extremely lightweight - Accelerated construction - Construction is insensitive to weather conditions - No heavy earthmoving equipment - Excellent mechanical properties - Reduced labor and labor costs - No environmental permitting - Decay resistant	- Flammable if not treated by fire-retardants - Degradable by petroleum and organic compounds - Prone to UV degradation if not protected against prolonged sunshine exposure

1.3. State of the Practice in Design and Construction

The state of the practice was assessed through an evaluation of the technical literature, which included technical information available not only in published reports but also from plans and specifications of projects in which lightweight fills were used. The evaluation focused on the current use of lightweight fills in transportation fill applications, including MSE walls and embankments. Design, construction, and environmental considerations were summarized in Table 1.2, Table 1.3, and Table 1.4, respectively.

Table 1.2. Design considerations.

Material	Design Considerations
ESCS	• Follow product-specific manufacturer guidelines. ESCSI recommends consulting with the manufacturers for information on material properties and construction methods (ESCSI 2018). • ESCS should meet the ASTM C330 requirements (TxDOT Project # NH 2B20(015) Construction Specifications 2021). • Consider long-term water absorption in design. ESCS fills may absorb some water during construction and when submerged under water for prolonged periods of time. Schaefer et al. (2016) reported that the moisture content of ESCS fills increased from 8.5% during construction to 28% one year after construction. They reported that over a longer period of time, the estimated long-term water content may increase to about 34%. Accordingly, long-term water content needs to be considered when designing with ESCS fills. • Ensure that the factor of safety against buoyancy/uplift of ESCS is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). FDOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. • When ESCS fills are used in the construction of embankments, use a minimum of 2.5 ft of soil cover on embankment side slopes. Use side slopes of 1.5H:1V or flatter to confine the material and provide internal stability (Schaefer et al. 2016). • When ESCS fills are used in the construction of retaining walls, use an angle of shearing resistance of 35° in lateral earth pressure calculations (Schaefer et al. 2016).
FGA	• Follow product-specific manufacturer guidelines. • Use geotextiles to separate FGA fills from adjacent soils to prevent particle migration from the neighboring soils into the FGA fills (Loux et al. 2024). Geotextiles have to be seamed or overlapped; a typical overlap of 0.3 m may suffice in most applications and conditions. In cases where significant displacement is expected such as instruction on soft soils, a larger overlap may be needed (Loux et al. 2024). • Ensure that the factor of safety against buoyancy/uplift of FGA is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). FDOT (2022) requires that

Material	Design Considerations
	lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. AeroAggregates (2020) suggests applying a factor of safety of 1.5 to the estimated buoyant unit weight. • Place FGA fills with side slopes 1H:1V or flatter. • Provide drainage piping to drain infiltrating water (Loux and Filshill 2021). • Design for global stability, bearing strength, and settlement due to compression and creep (AeroAggregates 2020). • Design a protective capping for FGA fills. Capping materials may include embankment material subbase, topsoil, or rock (AeroAggregates 2020). Capping thickness should be 6 in. at minimum in cases without live loads and should be determined by design in cases involving live loads (AeroAggregates 2020). • When FGA fills are used as reinforced fill in MSE walls full-scale pullout tests (ASTM D 6706) are required to be submitted to verify the properties used in the internal stability analysis (AeroAggregates 2020).
TDA	• Follow standard practice for use of scrap tires in civil engineering applications (ASTM D6270). • Tire wire strands must be firmly attached to the tire rubber to prevent damaging construction equipment (Schaefer et al. 2016). Tire rubber should be free of any loose wire or metal fragments, wood chips or fragments, and other fibrous organic matters (Tutumluer and Qamhia 2024). • Preload TDA fills with a 2-ft soil surcharge for 60 days to minimize post-construction settlement due to TDA compressibility (Schaefer et al. 2016). • Separate TDA fills from the surrounding soils by geotextiles (Schaefer et al. 2016) to minimize the migration of soil particles. This separation layer is essential for pavement, drainage, and retaining wall backfill applications (Tutumluer and Qamhia 2024). • Place a minimum 3-ft thick soil cap on the top and side slopes of the TDA fill to provide confinement and minimize deformation (Schaefer et al. 2016). • Keep the top elevation of TDA embankments 5 ft at minimum below the top elevation of subgrades (Schaefer et al. 2016). • Keep TDA fills above the groundwater table (Schaefer et al. 2016).

Material	Design Considerations
	• Provide good surface drainage of TDA fill structures to avoid water infiltration into the TDA fills. Locate drainage pipes at 3 ft at minimum below the bottom of the TDA fills. Drainage features that could provide free access to air should be avoided at the bottom of TDA fills (Schaefer et al. 2016). • Ensure that the factor of safety against buoyancy/uplift of TDA is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). FDOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. • Anticipate 35% volume reduction during compaction, plus 10% compression under loading of soil cover and pavement base course. (Schaefer et al. 2016).
LCC	• Follow ASTM D7180 and product-specific manufacturer guidelines. • Preformed foam must conform to the properties listed in ASTM C869 when tested following the procedures in ASTM C796. • Design for external stability, including settlement, bearing capacity, and overall stability under the projected loading conditions (Caltrans 2021). • Design for internal stability, including adequate material support for the overlaying structures (e.g., pavements and traffic loads) without cracking and creep compression (Caltrans 2021). • Design LCC elevations below the zone of freezing to avoid the LCC compressive strength degradation by freeze-thaw cycles. Alternatively, design with LCC of higher compressive strengths; LCC with densities larger than 37 pcf have reported excellent freeze-thaw resistance (Schaefer et al. 2016). • Design for uplift pressure considering a 100-year flood event (Caltrans 2021). Cutoff walls (Caltrans 2021) or sufficient vertical confinement (Schaefer et al. 2016) should be used to achieve a minimum safety factor of 1.3 against uplift under normal operational conditions and 1.1 under extreme conditions (EM 1110-2-2100). FDOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. • Design a drainage blanket and drains to prevent the saturation of LCC by water, which could affect the density and compressive strength (Schaefer et al. 2016).

Material	Design Considerations
	• The foundation under the LCC must be prepared to create a smooth surface and dry condition. In cases where groundwater exists, dewatering may become necessary (Caltrans 2021). In addition, a layer of permeable material (8 to 12 in.) wrapped in filter fabric including a layer of geomembrane on top directly below LCC may become necessary when excess groundwater is present (Caltrans 2021).
RCPS	• Follow product-specific manufacturer guidelines. • Design for external stability, including settlement, bearing capacity, and overall stability under the projected loading conditions (Caltrans 2021). External stability analyses generally follow traditional geotechnical design procedures. For shear strength, NCHRP- 24-11 recommends using only ¼ of EPS geofoam compressive strength. • Design for internal stability, including adequate material support for the overlaying structures (e.g., pavements and traffic loads) without excessive compression or creep. The design approach for internal stability is a deformation-based methodology using the total stress from all loads on EPS blocks, elastic limit stress, and the initial tangent modulus to evaluate load-induced deformations (Caltrans 2021). • Design to protect the EPS to resist hazards like fire and gasoline leakage. EPS dissolves in gasoline and other organic fluids or vapors and therefore must be protected against the potential reach of such organics (Caltrans 2021). EPS should be encapsulated in a gasoline resistant geomembrane (Caltrans 2021) or covered by a geomembrane and/or a reinforced concrete slab (typically 4 in. thick at minimum) when used under roadways in case of accidental spills (NYSDOT 2015b; Schaefer et al. 2016). When concrete is used, the protective cap may also serve to enhance the overall performance by aiding in the distribution of loads (NYSDOT 2015b). • Design for uplift pressure considering a 100-year flood event (Caltrans 2021). Cutoff walls (Caltrans 2021) or adequate counterweight cover (Schaefer et al. 2016) should be used to achieve a minimum safety factor of 1.3 against buoyancy/uplift under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). FDOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. • Design using total unit weights that account for long-term water absorption (Caltrans 2021). EPS blocks placed below water may have 2 to 2.5 times higher unit weights than those placed above water after 10 years (Schaefer et al. 2016). • The foundation under the EPS must be prepared to create a smooth surface and dry condition. In cases where

Material	Design Considerations
	groundwater exists, dewatering may become necessary (NYSDOT 2015b; Caltrans 2021). Final grade should be sufficient to allow 4 ft cover over EPS blocks (NYSDOT 2015b). • Design a subsurface drainage system to aid in the lowering of the groundwater table and/or maintain a positive drainage path in the vicinity of the EPS fill. Typically, a subsurface drainage system includes the installation of a layer of graded crushed stone placed behind and below the EPS fill, connected to a positive outlet. The graded crushed stone may also include a network of perforated drainage pipes (NYSDOT 2015b). • Design considering differential icing potential of pavement (Caltrans 2019). Differential icing can be minimized by using a soil layer of a sufficient thickness between the EPS and pavement surface (Schaefer et al. 2016). • Use side slopes 2H:1V or flatter and a minimum cover thickness of 0.8 ft. If a vertical face is needed, cover exposed face of blocks with shotcrete or other material to provide long-term protection against UV (Schaefer et al. 2016). • Utilities (or future utility work) should not interfere with the EPS (NYSDOT 2015b).

Table 1.3. Construction considerations.

Material	Construction Considerations
ESCS	• Follow product-specific manufacturer guidelines. • Place ESCS fills in uniform lifts. Fill should be unloaded at side of fill area, then distributed with lightweight equipment with a contact pressure of 4.5 psi or less (Schaefer et al. 2016). A common practice is to limit the thickness of each uniform layer to 12 in. or less in a loose state before compaction (Tutumluer and Qamhia 2024) but can be up to 3 ft (Schaefer et al. 2016). The material can be placed in any weather with no waiting time between placing lifts (Tutumluer and Qamhia 2024). • Wet ESCS fills for at least 24 hours prior to use to allow the aggregate to become fully saturated and avoid segregation when handling (TxDOT Project # NH 2B20(015) Construction Specifications 2021). • Compact each ESCS layer to the specified target density. Field density may be approximated in the laboratory by conducting a modified one-point AASHTO T 272 density test (Schaefer et al. 2016). A target relative density of 65% as per ASTM D 4253 and D4254 is recommended (TxDOT Project # NH 2B20(015) Construction Specifications 2021). No special equipment is needed on the jobsite for compacting ESCS (ESCSI 2008). However, compaction should be conducted with rubber-tired roller equipment to prevent excessive particle crushing by steel-tracked equipment (Schaefer et al. 2016). Compaction can be achieved using vibratory compaction equipment weighing no more than 12 tons static weight or vibratory plate compaction equipment (3.7-14.9 kW; 5-20 hp) in confined areas. A minimum of two passes should be applied when compacting 6-in. lifts with a 5-hp plate power or 12-in. lifts with a 20-hp plate power (ESCSI 2008, 2018). • Ensure that the ESCS fill 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; TxDOT Project # NH 2B20(015) Construction Specifications 2021).
FGA	• Follow product-specific manufacturer guidelines. • Place FGA fills in uniform lifts. Limit lift thickness to 24 in. when compacting using tracked equipment and to 12 in. when compacting using plate compactors (Loux et al. 2019b). • Compact each FGA fill layer to a target compression ratio of 1.25 by applying four passes of tracked equipment, such as excavators or dozers, with a ground pressure ranging from 625 to 1025 psf (Loux et al. 2019b). In areas inaccessible

Material	Construction Considerations
	by tracked equipment, apply four passes of plate compactor with a weight ranging from a 110-220 lb. (Loux et al. 2019b). Avoid excessive compaction or compaction using more powerful energy to prevent excessive crushing of the FGA particles. Avoid operating construction equipment on FGA fills other than for placement and compaction (Loux et al. 2019b; Tutumluer and Qamhia 2024). • Use a non-woven geotextile to separate FGA from other contiguous soils with smaller particles to prevent the migration of the smaller particles into the FGA pores (Loux et al. 2019b). Care should be taken during placement of capping layer to prevent damage to geotextile. Adjacent panels of geotextile may be sewn together or overlapped a minimum of 12 inches. The geotextile shall not be left exposed for longer than 14 days (AeroAggregates 2022). • Evaluate field compaction through observance and verification of the method-based specification (Loux et al. 2019b).
TDA	• Follow standard practice for use of scrap tires in civil engineering applications (ASTM D6270) • Place and spread using a tracked dozer in lifts 3 ft or less in thickness (Schaefer et al. 2016). • Limit TDA layers to 10 ft in thickness. Multiple 10-ft TDA layers should be separated by 3 ft of inorganic soil fill (Schaefer et al. 2016; Tutumluer and Qamhia 2024). • Compact each TDA layer by applying a minimum of six passes of a vibratory smooth drum steel roller with a minimum static weight of 10 tons (Tutumluer and Qamhia 2024). Sheep foot rollers, smooth drum rollers, or D-8 dozers may be used (Schaefer et al. 2016).
LCC	• Follow product-specific manufacturer guidelines. • LCC mix should be produced on site as transportation of premixed LCC may adversely affect the density of the final product due to the vibrations associated with transportation (Taylor and Halsted 2021). • Considering the fluidity of LCC fills during placement, formwork should be tight to avoid leakage of the mix through formwork joints. Polyethylene film may be used to prevent leakage (Schaefer et al. 2016). • Monitor weather conditions before LCC placement. LCC fills should not be placed if heavy rain is imminent, but they may be placed in light rain. Placing LCC fills is not recommended in ambient temperatures below 32 °F (0 °C) to avoid the inhibition of the LCC curing time, which may adversely affect the quality of the final product (Taylor and Halsted 2021). LCC should not be placed on a frozen ground or when freezing conditions are expected in less than 24 hours unless precautions are taken to maintain temperatures above freezing (IADOT 2017). Placing LCC fills is not

Material	Construction Considerations
	recommended in ambient temperatures above 100 °F (38 °C) to avoid the evaporation of the water in the LCC mix, which may cause excessive shrinkage (Taylor and Halsted 2021). • Cast LCC fills in lifts 4 ft or less in thickness. Allow a minimum of 12 hours between casting subsequent lifts (Schaefer et al. 2016). IADOT (2017) requires a minimum of 24 hours between casting subsequent lifts. Scarify each lift to a minimum depth of 0.5 in. and clean the surface of each lift before casting the subsequent lift (Schaefer et al. 2016; IADOT 2017). Once they set, LCC fills should not be remixed (Taylor and Halsted 2021). Scarifying shall be done after sufficient curing time such that foot traffic will not excessively damage the lift surface (IADOT 2017). • Coordinate the placement of the LCC fills with the construction of pavement longitudinal subdrains, storm intakes and any underground utility or structural element that will be placed within the LCC (IADOT 2017). • LCC density should be checked in accordance with ASTM D6023 before and after pumping. • Field observations during placement should include the following (Taylor and Halsted 2021): o Metered cement content or flow rate. o Metered water content or flow rate o Density of cement, and water slurry. o Density of preformed foam. o Density of the final product. o Pumping distance. o Metered pumping pressure. o Time required to fill the area. o Material segregation in the placement. o Depth of daily placement. o Drainage that might lead to buoyancy. o Excessively hot or cold temperatures. o Lumps of cement in the mix. o Leakage in the formwork. o Excessively high cure heat.

Material	Construction Considerations
	o Location of any bleed water after curing. • During placement, slurry density checks should be performed, and the mix wet density and temperature should be monitored. 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. Hardened LCC fills should be inspected, and LCC samples should undergo material density and unconfined strength testing in accordance with ASTM C495 (Taylor and Halsted 2021).
RCPS	• Follow ASTM D7180 and product-specific manufacturer guidelines. • Level subgrades before the placement of the geofoam blocks. A layer of sand/gravel is commonly placed as a leveling course (Schaefer et al. 2016). • Ensure that the site is free of any standing water (Tafreshi et al. 2020), vegetation, or debris (Tutumluer and Qamhia 2024). • Except where the designer has considered the effect of thawing in permafrost regions, geofoam should not be placed directly on a frozen ground (Tutumluer and Qamhia 2024). • A minimum of two layers of blocks must be used. When multiple layers of geofoam blocks are placed, they should be placed at right angles to avoid continuous vertical joints and to promote interlocking (NYSDOT 2015b; Schaefer et al. 2016). Place blocks in a "running bond" and rotate the pattern by 90 degrees in each successive layer (NYSDOT 2015b). Use galvanized barbed plates to provide mechanical connections between adjacent blocks for shear transfer (Schaefer et al. 2016). • Only small, rubber-tired equipment should operate directly on the EPS to avoid damage (NYSDOT 2015b). • Place a cover material over the geofoam blocks as soon as possible to prevent their displacement by wind or buoyancy, and to avoid prolonged exposure to sunlight that may embrittle them (Schaefer et al. 2016). • Place a separating sand layer 0.5 to 1 inch in thickness between the geofoam blocks and any neighboring coarse granular soils (Tutumluer and Qamhia 2024). • Perform on-site density tests by weighing and measuring an EPS block randomly chosen from each truck load or 2500± ft^3 of EPS delivered to the site (NYSDOT 2015b).

Table 1.4. Environmental considerations.

Material	Environmental Considerations
ESCS	ESCS fills have no known health, safety, leachate toxicity issues (Tutumluer and Qamhia 2024) or environmental concerns (Schaefer et al. 2016) related to their use. ESCS materials are water and acid insoluble and chemically inert (ESCSI 2008).
FGA	FGA fills are not considered hazardous for transportation infrastructure applications (Tutumluer and Qamhia 2024). Leachate analysis showed hazardous concentrations much lower than those of the drinking water standards (Arulrajah et al. 2015; Lenart and Kaynia 2019).
TDA	Tire shreds should be free of any contaminants, such as oil, grease, gasoline, or diesel fuel, among other chemical substances (Tutumluer and Qamhia 2024). In addition, leachate from TDA fills should be minimized (Schaefer et al. 2016). While TDA may produce leachate containing various metals and organic compounds, toxicity levels are below applicable water quality thresholds (Cheng 2016). TDA leachate analysis has shown that TDA leachate is not hazardous as per the Toxicity Characteristic Leaching Procedure (TCLP) (Tutumluer and Qamhia 2024). Toxicity has been reported in leachate from TDA fills submerged below groundwater level, but the metals quickly formed immobile and insoluble particles in the subsurface soil (Sheehan et al. 2006). TDA fills can be combustible; accordingly, TDA should follow design considerations that prevent their combustion, which should prevent or minimize the amount of water and air infiltration into tire shred fill (Schaefer et al. 2016). Environmental considerations of TDA fills are discussed in ASTM D6270, Stroup-Gardiner and Wattenberg-Komas (2013b, NCHRP 435 report), Edstrom et al. (2008), and Baker et al. (2003).
LCC	Schaefer et al. (2016) reported that there are no known environmental concerns. Although LCC may produce toxic leachate from a byproduct material used in the mix, toxicity levels are non-concerning. Heavy metal concentrations, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, passed the Toxicity Characteristic Leaching Procedure (TCLP), indicating non-concerning levels of heavy metals (Tutumluer and Qamhia 2024).
RCPS	EPS fills have no known environmental concerns (Schaefer et al. 2016) or leachate toxicity issues (Tutumluer and Qamhia 2024). While EPS and XPS are flammable materials, ASTM D6817 has requirements on geofoams used in highway applications to restrict their flammability. Such geofoams are manufactured with fire-retardant additives (Tutumluer and Qamhia 2024).

1.4. Engineering Properties and Design Parameters

The recommended design parameters for the various lightweight fills studied were compiled from the available literature and are summarized in Table 1.5. Additionally, the properties of the various products of each lightweight fill type were compiled from the available manufacturer technical specifications. Table 1.6 and Table 1.7 present a summary of the properties of ESCS fill products. Table 1.8 and Table 1.9 present a summary of the properties of FGA fill products.

The properties of TDA fills vary by the ratio of tire chips to soil in the mixture and the properties of the tire shreds and soil used in the mixture. The properties of optimum TDA mixtures developed by El Naggar and Iranikhah (2021) for mixtures of tire shreds and gravels, sands, and clays at varied ratios are summarized in Table 1.10. ASTM 6270 provides guidance to the standard practice for using scrap tires in civil engineering applications, which includes grain size distribution requirements for the tire chips and guiding engineering properties for TDA mixtures from the literature.

Similar to other concrete products, LCC mixes are designed to achieve project-specific properties. Accordingly, no summary was created for LCC products given the variable nature of their designs and properties.

Given the long history of RCPS manufacturing and usage, a large number of RCPS producers have been identified. The majority of producers follow the ASTM D6817 specifications. Accordingly, ASTM physical property requirements were summarized herein and are presented in Table 1.11. Not all the types presented in the ASTM standard are used as lightweight fill in civil engineering projects. Table 1.12 presents RCPS that have been proposed in NCHRP 529 for use in transportation infrastructure projects. The material designation by ASTM D6817 denotes the type (EPS or XPS) followed by the material density in kg/m^3, whereas the material designation by NCHRP 529 denotes the type followed by the material elastic stress in kPa.

Table 1.5. Recommended design parameters.

Material	Physical	Mechanical	Hydraulic	Electrochemical
ESCS	• Compacted dry unit weight: 50-65 pcf (Schaefer et al. 2016) • Compacted bulk unit weight < 65 pcf (TxDOT 2021) or < 70 (Tutumluer and Qamhia 2024) • Particle size range: 3/16 to 1 in. (Schaefer et al. 2016) • Magnesium sulfate soundness loss < 30% as per AASHTO T 104 (Tutumluer and Qamhia 2024)	• Maximum LA abrasion loss < 40% as per ASTM C131 (Tutumluer and Qamhia 2024; TxDOT 2021) • Durability test index > 35 as per AASHTO T 210 (TxDOT 2021) • Angle of internal resistance: 37-44° (Schaefer et al. 2016) or 35-45° (Tutumluer and Qamhia 2024) • Coefficient of subgrade reaction: 140-155 pci (Schaefer et al. 2016)	• Highly permeable and drainable (Schaefer et al. 2016; TxDOT 2021)	• Resistivity between 30000 and 40000 ohm.cm as per AASHTO T 288 (TxDOT 2021) • pH value between 7 and 9 (TxDOT 2021) or 5 between 10 (Tutumluer and Qamhia 2024) as per AASTHO T 289 • Chloride content < 100 ppm as per AASHTO T 291 (Tutumluer and Qamhia 2024; TxDOT 2021)
FGA	• Compacted unit weight (by producer) • Particle size range (by producer) • Magnesium sulfate soundless loss < 30% (Loux and Filshill 2021) • Fines content < 15% after compaction (Loux and Filshill 2021) • Buoyant unit weight (by producer)	• Angle of internal resistance > 34° (Loux and Filshill 2021) • Compacted compressive strength at 1% > 18000 psf, at 5% > 20000 psf, and at 10% > 24000 psf (compression ratio 1.3) as per EN 826 (AeroAggregates 2022)	• Highly permeable and drainable • Water absorption (by producer)	• Resistivity > 3000 ohm.cm (Loux and Filshill 2021) • Chloride content < 100 ppm (Loux and Filshill 2021) • Sulfate content < 200 ppm (Loux and Filshill 2021) • pH value between 5 and 10 (Loux and Filshill 2021)
TDA	• Compacted dry unit weight: 30-73 pcf (Schaefer et al. 2016) • Type A Gradation (ASTM D6270): 8-inch maximum dimension; 100% passing 4-inch, a minimum of 95% passing 3-inch, a maximum of 50% passing the 1.5-inch, and a maximum of 5% passing the 0.2-inch sieve (Schaefer et al. 2016)	• Angle of internal resistance 19-30° (Schaefer et al. 2016) • Compressibility: 5 to 40 percent vertical strain over a range of 200 to 4,200 psf vertical stress (Schaefer et al. 2016) • Coefficient of Lateral Earth Pressure: 0.25 to 0.47 (Schaefer et al. 2016)	• Permeability 0.5 to 60 cm/s (Schaefer et al. 2016)	

Material	Physical	Mechanical	Hydraulic	Electrochemical
LCC	• Wet unit weight 20-80 pcf (Schaefer et al. 2016). IADOT (2017) requires dry unit weight between 40 and 48 pcf per ASTM C796 without oven drying • Freeze-thaw resistance (100 cycles) > 92-98%, depending on density (Schaefer et al. 2016). IADOT (2019) requires Freeze-Thaw Resistance (300 cycles) relative Young's modulus > 80% at 300 cycles (ASTM C666 Procedure B) • Frost heave at 250-hr exposure < 0.5 in. for a sample 1.5 in. high x 4 in diameter per British Road Research Laboratory, Lab Report LR 90, 1967 (IADOT 2017)	• Compressive strength 10-300 psi, depending on density (Schaefer et al. 2016). IADOT (2017) requires 120 psi compressive strength at 28 days. • Coefficient of lateral earth pressure from adjacent soils may be transmitted undiminished (Schaefer et al. 2016) • Coefficient of lateral earth pressure by LCC is negligible (Schaefer et al. 2016) • Internal friction angle > 45° per ASTM D3080 (IADOT 2017)	• Water absorption 1.4-5 psf, depending on density (Schaefer et al. 2016) • Hydraulic conductivity 10^{-5} cm/s at 2 psi (IADOT 2017)	
RCPS	• Dry unit weight > 1.00 pcf for EPS40; 1.25 pcf for EPS50; 1.50 pcf for EPS70; and 2.00 pcf for EPS100 (NCHRP 529) • Flammability Oxygen Index < 24% for EPS (ASTM C578)	• Compressive strength > 10 psi for EPS40; 13 psi for EPS50; 15 psi for EPS70; and 25 psi for EPS100 • Flexural strength > 25 psi for EPS40; 30 psi for EPS50; 40 psi for EPS70; and 50 psi for EPS100 (NCHRP 529) • Elastic limit stress > 5.8 psi for EPS40; 7.2 psi for EPS50; 10.1 psi for EPS70; and 14.5 psi for EPS100 (NCHRP 529) • Initial tangent Young's modulus > 580 psi for EPS40; 725 psi for EPS50; 1015 psi for EPS70; and 1450 psi for EPS100 (NCHRP 529) • California Bearing Ratio (CBR) 2 to 4 (Schaefer et al. 2016) • Coefficient of lateral earth pressure from adjacent soils may be reduced to 0.1 (PIARC 1997)	• Water absorption < 2-4% (ASTM C578)	

Table 1.6. Properties of commercially available ESCS fills (after Zukri et al. 2018).

Producer	Grain Size Range (in.)	Grain Density (pcf)	Dry Unit Weight (pcf)	Angle of Internal Resistance (deg)
Arcosa (Streetman TX Aggregate)	< 0.375	133.8	59.1 Uncompacted 62 Lightly Compacted	43 DST
Argex	–	37.4-77.4 (based on gradation)	28.1-39.6 (based on gradation)	35-42
Optiroc	–	46.8-49.9 (based on gradation)	17.5-20.9 (based on gradation)	37-45 TX
ESCS	–	78-87.4	44.9 Uncompacted 59.9 Compacted	35-45 DST and TX
LECA	–	25.6	13.7-20.3 (based on gradation)	37
LEXCA LECA	–	48.1	16.6-17.7	35 TX
GeoLeca	–	147.9	26.5-32.4 (based on gradation)	–
Norlite	–	78-99.8	40.2 Uncompacted 45.5Compacted	42-53 TX
Techniclay	–	–	20-22.5 (based on gradation)	53 TX
Stalite	–	90.5	48 Uncompacted 55 Compacted	43-46 DST and TX
GBC India	–	–	23.7-44.3	53 TX

Table 1.7. Properties of commercially available ESCS fills (after Zukri et al. 2018; cont.)

Producer	Potential of Hydrogen (pH) Value	Chloride Content (ppm)	Sulfate Content (ppm)	Water Absorption (%) by Weight	Hydraulic Conductivity (cm/s)
Arcosa (Streetman TX Aggregate)	–	–	–	–	0.45
Argex	–	–	–	7-35	–
Optiroc	8-11	–	–	14-45	0.1-5 (based on gradation)
ESCS	5-10	10 to 70	–	8	> 1
LECA	8.05	–	< 450	36	0.1
LEXCA LECA	9	6.8	–	30	2.53
GeoLeca	–	5 to 46	–	–	–
Norlite	7.4	5 to 46	–	–	13.4-15
Techniclay	–	–	–	–	–
Stalite	7-9	0.6 to 7	–	9-12	5-15
GBC India	6-7	–	–	18	–

Table 1.8. Properties of commercially available FGA fills.

Producer	Grain Size Range (in.)	Grain Density (pcf)	Dry Unit Weight (pcf)	Porosity	Compressive Strength (psi)	Angle of Internal Resistance (deg)
AeroAggregates UL-FGA G15	0.375-2.5	25	12-15 Uncompacted 13.3-16.7 at Compaction Ratio = 1.11 15-18.8 at Compaction Ratio = 1.25	0.5 Uncompacted 4.1-14 at Compaction Ratio = 1.25	104 at Strain = 20%	41-55
Glavel	0.375-4	33.7	9-10 Uncompacted 10-11 at Compaction Ratio = 1.11 11.25-12.5 at Compaction Ratio = 1.25	–	110-110 at Strain = 20% 155-160 at Strain = 30%	–
A-Glass	0.39-2.36	–	9.4	92.8-188.5 Compaction Ratio = 1.1-1.3	–	–
Bi-Foam BFS 160	–	–	15-20	–	–	–
Ecoglas	0.39-2.36	–	8.1-10.6	–	91.4 at Strain = 10%	40
Energocel	–	18.1-21.2	9.4-10.9 Uncompacted 13.7 at Compaction Ratio = 1.4	–	–	–
Foamit	0.39-2.36	–	11.1-15.1 Uncompacted 13.7-17.5 at Compaction Ratio = 1.15-1.25	–	130.5 at 20%	36-40
Geomaterials	0.39-2.36	20-23.1	11.2-14.4	–	116 at Strain = 10% at Compression Ratio = 1.3	42-45
Glapor SG800	0.63-2.48	–	6.3-7.5 Uncompacted 8.1-9.7 at Compaction Ratio = 1.3	0.15 at Compaction Ratio = 1.3	> 39.2 at Strain = 2% > 87 at Strain = 10%	–
Glapor SG600	1.26-2.48	–	8.4-10.6 Uncompacted 12.2-13.7 at Compaction Ratio = 1.3	0.15 at Compaction Ratio = 1.3	> 53.7 at Strain = 2% > 116 at Strain = 10%	–
Glapor SG_2000_FGSV	1.26-2.48	15.6-18.7	8.4-10.6 Uncompacted	–	> 53.7 at Strain = 2% > 116 at Strain = 10%	40-42
Glasopor	0.39-2.36	23.7	11.2	–	11.6-17.4	45
Hasopor	0.39-2.36	23.7	11.2	–	11.6-17.4	45
Hoger	0-2.48	–	9.1	–	–	–
ICM Glass Citadel	1.18-2.36	–	8.1-9.4	–	102.3-117.5 at Strain = 10%	–
ICM Glass SolidRock	0.79-1.57	–	10.6-11.9	–	190-224.8 at Strain = 10%	–
Misapor 10/50 (Standard Plus)	0.39-1.97	23.9	10-11.9 Uncompacted 11-13 at Compaction Ratio = 1.1 12-14.2 at Compaction Ratio = 1.2 13-15.4 at Compaction Ratio = 1.3	0.5 at Compaction Ratio = 1.1 0.45 at Compaction Ratio = 1.2 0.4 at Compaction Ratio = 1.3	55.1 at Compression Ratio = 1.1 75.4 at Compression Ratio = 1.2 95.7 at Compression Ratio = 1.3	–
Misapor 10/75 (Standard)	0.39-2.95	–	7.8-9.4 Uncompacted 8.6-10.3 at Compaction Ratio = 1.1 9.4-11.2 at Compaction Ratio = 1.2 10.2-12.2 at Compaction Ratio = 1.3	–	29 at Compression Ratio = 1.1 45 at Compression Ratio = 1.2 60.9 at Compression Ratio = 1.3	–

Producer	Grain Size Range (in.)	Grain Density (pcf)	Dry Unit Weight (pcf)	Porosity	Compressive Strength (psi)	Angle of Internal Resistance (deg)
PoliCell NORM	0.39-2.36	23.1	8.1-9.36	0.55	104.4 at Strain = 10%	–
PoliCell HARD	0.39-2.36	23.1	< 11.23	0.55	145 at Strain = 10%	–
Refaglass	0-2.48	–	9.36	–	–	–
Savelpor	0.39-1.97	–	< 12.5	–	99.6 at Compression Ratio = 1.3	–
Supersol L2	0.032-2.95	25-31.2	18.7-25 Compacted	–	–	> 30
Veriso LDV	0.39-2.36	13.7-18.7	8.11-10.61	–	> 84.1 at Strain = 10% at Compression Ratio = 1.3	42-45
Veriso LFV	0.39-2.48	13.7-20	8.11-10.61	–	> 84.1 at Strain = 10% at Compression Ratio = 1.3	42-45

Table 1.9. Properties of commercially available FGA fills (cont.).

Producer	Potential of Hydrogen (pH) Value	Chloride Content (ppm)	Sulfate Content (ppm)	Water Absorption (%) by Weight	Water Absorption (%) by Volume	Hydraulic Conductivity (cm/s)	Soundness (% Loss by Magnesium Sulfate)	Soundness (% Loss by Sodium Sulfate)
AeroAggregates UL-FGA G15	9.2-9.33	< 10	11	0-60 (typ. 25)	0-10 (typ. 6)	3	4.1-14	3.1-6.9
Glavel	–	< 10	< 10	62	47	0.086	–	4.7-5.3
A-Glass	–	–	–	–	–	–	–	–
Bi-Foam BFS 160	–	–	–	–	–	–	–	–
Ecoglas	–	–	–	–	< 10	1-10	–	–
Energocel	–	–	–	< 10	< 3.5	–	–	–
Foamit	10	–	–	60 after 28 days 100 after 365 days	–	10	–	–
Geomaterials	–	–	–	–	< 10	> 0.1	–	–
Glapor SG800	–	–	–	–	–	0.038	–	–
Glapor SG600	–	–	–	–	–	0.038	–	–
Glapor SG_2000_FGSV	–	–	–	< 10	–	0.038	–	–
Glasopor	–	–	–	–	–	–	–	–
Hasopor	–	–	–	–	–	–	–	–
Hoger	–	–	–	–	–	–	–	–
ICM Glass Citadel	–	–	–	–	–	–	–	–
ICM Glass SolidRock	–	–	–	–	–	–	–	–
Misapor 10/50 (Standard Plus)	5.5	–	–	–	< 6 after 28 days	3	–	–
Misapor 10/75 (Standard)	5.5	–	–	–	< 9 after 28 days	3	–	–
PoliCell NORM	–	–	–	< 40	–	–	–	–
PoliCell HARD	–	–	–	< 40	–	–	–	–
Refaglass	–	< 1	–	2-5	–	–	–	–
Savelpor	–	–	–	–	11	–	–	–
Supersol L2	–	–	–	< 30	–	0.03-1	–	–
Veriso LDV	–	–	–	< 40	< 10	0.1-1	–	–
Veriso LFV	–	–	–	< 40	< 10	0.1-1	–	–

Table 1.10. Optimum TDA mixtures (El Naggar and Iranikhah 2021).

Mixtures	Mixture ID	Tire by Weight (%)	Soil by Weight (%)	Bulk Unit Weight (pcf)	Angle of Internal Resistance (deg)	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	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	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

Table 1.11. Physical property requirements of RCPS (ASTM D6817).

Material Designation	Unit Weight (pcf)	Block Width (in.)	Block Length (in.)	Block Height (in.)	Oxygen Index (% by Volume)	Compressive Resistance at 1% Strain (psi)	Compressive Resistance at 5% Strain (psi)	Compressive Resistance at 10% Strain (psi)	Flexural Strength (psi)
EPS12	0.70	12-48	48-192	1-48	24	2.2	5.1	5.8	10
EPS15	0.90	12-48	48-192	1-48	24	3.6	8	10.2	25
EPS19	1.15	12-48	48-192	1-48	24	5	13.1	16	30
EPS22	1.35	12-48	48-192	1-48	24	7.3	16.7	19.6	35
EPS29	1.80	12-48	48-192	1-48	24	10.9	24.7	29	50
EPS39	2.40	12-48	48-192	1-48	24	15	35	40	60
EPS46	2.85	12-48	48-192	1-48	24	18.6	43.5	50	75
XPS20	1.20	16-48	48-108	1-4	24	2.9	12.3	15	40
XPS21	1.30	16-48	48-108	1-4	24	5.1	16	15	40
XPS26	1.60	16-48	48-108	1-4	24	10.9	26.8	25	50
XPS29	1.80	16-48	48-108	1-4	24	15.2	34.1	40	60
XPS36	2.20	16-48	48-108	1-4	24	23.2	46.6	60	75
XPS48	3.00	16-48	48-108	1-4	24	40.6	77.6	100	100

Material designation denotes material type followed by material density in kg/m^3.

Table 1.12. Design parameters for EPS material designations (NCHRP 529).

Material Designation	Dry Unit weight (pcf)	Permanently Submerged Unit Weight (at Water Content =10%)	Periodically Submerged Unit Weight (at Water Content =4%)	Above Highest GWT Unit Weight (at Water Content =1%)	California Bearing Ratio (CBR) (%)	Elastic Limit Stress (psi)	Initial Tangent Young's Modulus (psi)	Resilient Modulus (psi)
EPS40	1.0	7.2	3.5	1.6	-	5.8	580	-
EPS50	1.25	7.5	3.7	1.9	2	7.2	725	725
EPS70	1.5	7.7	4.0	2.1	3	10.1	1015	1015
EPS100	2.0	8.2	4.5	2.6	4	14.5	1450	1450

Material designation denotes material type followed by material elastic stress in kPa.

Chapter 2. Survey of State DOT Practices

Based on the information synthesized about the practices the use of lightweight fills in Chapter 1, a survey was designed and administered to state DOTs to assess their practices on the use of lightweight fills in MSE walls or embankments and to identify candidate projects for detailed case studies. This survey aimed at gathering the most updated information on the use of lightweight fills in MSE walls or embankments with a focus on the common practices, including fill types, design guidelines, and construction specifications. The survey also aimed at identifying the advantages and disadvantages of different project circumstances, such as types of fill structures, traditional fill types, foundation soil types, and environmental conditions. When all the responses are gathered, the survey shall gauge the satisfaction with using lightweight fills in MSE walls or embankments and the prospects of their continued use in future projects.

A two-stage survey was designed (see Appendix A): (1) the first stage includes a preliminary, brief survey that aimed to collect high-level information necessary to identify the DOTs that have established practices for the use of lightweight fills; and (2) the second stage includes a detailed, comprehensive survey that aimed to collect detailed information about the practices for the use of lightweight fills.

The first-stage survey was conducted by the research team with the support of TxDOT using an online survey platform. The second-stage survey was conducted through follow-up interviews conducted by the research team. The responses of the surveys were narratively synthesized in this document. First-stage survey responses were received from 15 state DOTs (Arkansas, Illinois, Indiana, Louisiana, Michigan, Mississippi, Montana, New Jersey, New York, North Carolina, Oklahoma, Pennsylvania, South Dakota, Texas, and Wyoming), all of which have had some experience using lightweight fills either for research purposes or in actual projects. Second-stage survey responses were received, mostly though teleconference interviews, with personnel from 6 state DOTs (Louisiana, Michigan, Montana, North Carolina, Pennsylvania, and Wyoming).

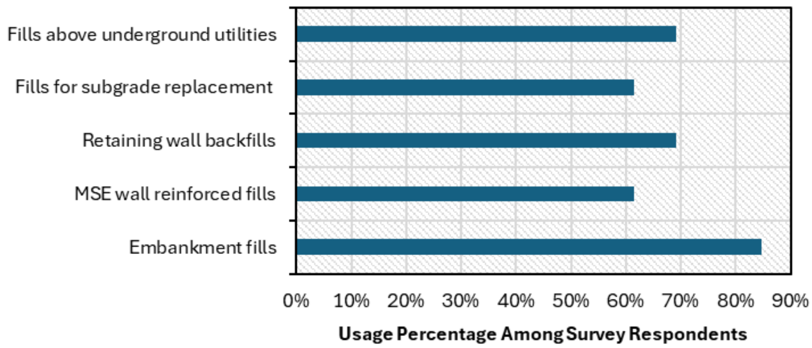
2.1. General Use of Lightweight Fills

Figure 2.1 summarizes the lightweight fill usage percentage among survey respondents by application, demand, and material based on the survey responses from 15 state DOTs.

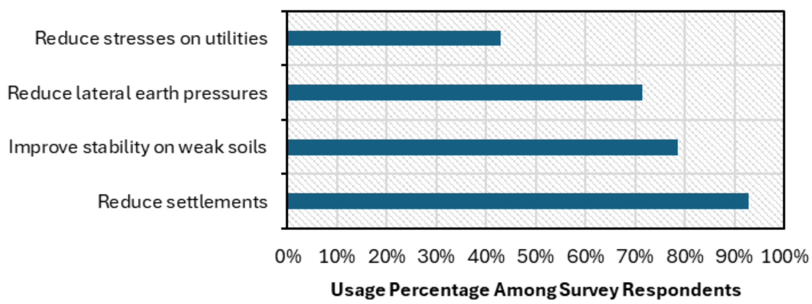
As shown in Figure 2.1a, the most common application for lightweight fills is embankments, which include ramps, roadways, and roadway widenings, as reported by 85% of state DOT survey respondents. The second most common application is retaining wall backfills and backfills above utilities, including drainage pipelines and culverts, as reported by 69% of state DOT survey respondents.

As shown in Figure 2.1b, the use of lightweight fills is often promoted to alleviate settlement (as reported by 93% of state DOT survey respondents) and stresses (as reported by 79% of state DOT survey respondents) when constructing on weak, compressible foundation soils. For instance, construction on the Coastal Plain of North Carolina has always been challenging for the presence of abundant, thick, soft soils, which often require costly ground improvement. The use of lightweight fills in this substantially large region can significantly reduce construction costs.

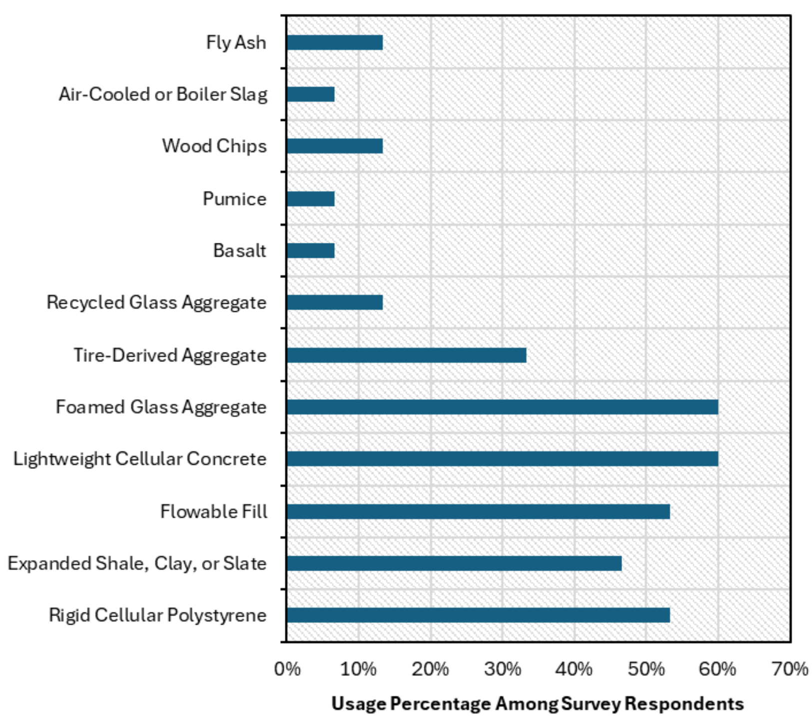
As shown in Figure 2.1c, the most commonly used/recognized lightweight fills by state DOTs at the time of this survey were FGA and LCC, as reported by 60% of state DOT survey respondents, followed by RCPS (53% of survey respondents), and ESCS (47% of survey respondents). Flowable fills have also commonly been used. However, some flowable fills may not necessarily qualify as lightweight fills unless the mix is intentionally designed for this purpose. These usage percentages may have changed over time and may continue to change as lightweight fill usage practices and material availability rapidly evolve. The majority of the survey respondents agreed on the criteria that contribute to considering and selecting fill alternatives, which include cost-effectiveness; environmental impact; availability of materials; transportation distance from fill source to project site; engineering properties; performance; construction time and feasibility; maintenance requirements; proximity to waterbodies, floodplains, or streams; and presence of utilities and structural foundations.



(a)



(b)



(c)

Figure 2.1. Lightweight fill usage percentage among survey respondents: (a) by application; (b) by demand; and (c) by material. Results are based on respondents from 14 state DOTs.

Based on the responses received on the detailed survey questions, the decision to approve using lightweight fills may vary from one state to another. Table 2.1 summarizes the responses from state DOT respondents regarding who typically is in charge of approving fill selections in embankment and wall projects during design. While there is some variation, most agencies assign this responsibility to geotechnical engineers, with involvement from structural or design engineers depending on the project scope and agency structure. Table 2.1 also summarizes the responses from state DOT respondents regarding who typically manages the maintenance of fill structures, including embankments and retaining walls. For maintenance of in-service structures, maintenance engineers are typically in charge of routine maintenance, whereas geotechnical and structural engineers become involved in cases that require intervention.

Table 2.1. Responsibilities for fill approval and selections and in-service structure maintenance by state DOT.

State DOT	In charge of approving fill selections in embankment and wall projects	In charge of maintenance fill structures, including embankments and retaining walls
Michigan	Design engineers with input from geotechnical and structural engineers as needed.	Maintenance engineers with involvement of geotechnical engineers in embankments and structural engineers in retaining walls.
Louisiana	Geotechnical engineers at the agency-wide level; also handled by Specifications	Maintenance engineers or equivalent at a regional or district level.
Pennsylvania	Geotechnical engineers at a regional or district level; new fill types reviewed by central office.	Maintenance engineers for regular maintenance. Geotechnical and structural engineers for cases that require intervention.
Wyoming	Geotechnical and structural engineers at an agency-wide level.	Maintenance engineers for regular maintenance. Geotechnical and structural engineers for cases that require intervention.
North Carolina	Geotechnical and structural engineers at a regional or district level.	Geotechnical engineers or equivalent at a regional or district level.
Montana	Geotechnical engineers.	Maintenance engineers for regular maintenance. Geotechnical engineers for cases that require engineering intervention.

A conclusion about the effect of using lightweight fills in lieu of traditional fills on the project construction time could not be established due to the involvement of many competing factors. The construction time could be reduced by using lightweight fills in projects that would otherwise require implementation of ground improvement or staged construction if traditional fills are used. On the other hand, shipping lightweight fills from their production plants to the project site can significantly delay construction depending on the distance of the project site from the production plant and the transportation logistics.

2.2. Practices of Using ESCS Fills

Expanded shale, clay and slate fills have previously been used at least once by Louisiana, New Jersey, Pennsylvania, and Texas DOTs. Respondents from Louisiana and Pennsylvania DOTs stated that the use of ESCS fills is accepted in their states. The use of ESCS fills was also considered by Wyoming DOT but ultimately not used because ESCS fills available from nearby sources, which are out of state, did not pass the pH-value requirements (pH-value was found to be approximately 11.5); the Pennsylvania DOT respondent also noted instances where ESCS fills did not meet the criteria for acceptable electrochemical characteristics. Louisiana and Pennsylvania DOTs reported challenges with using ESCS fills, including high costs, design/implementation issues, and limited availability, with the former being the major obstacle. The Pennsylvania DOT respondent added that the lack of expertise has also been a barrier.

Both Louisiana and Pennsylvania DOTs have special provisions for the use of ESCS fills. Louisiana DOT is in the process of incorporating guidelines for the use of ESCS fills in the state design manual and specifications. Both agencies have specifications for weight, shear strength, and electrochemical properties. The respondent from Louisiana DOT added that the specifications have requirements for durability. Texas DOT used ESCS fill in a recent project in which ESCS properties were required to comply with project specifications, including meeting the ASTM C 330 requirements. Table 2.2, Table 2.3, and Table 2.4 respectively list the requirements for gradation, mechanical, and electrochemical properties of ESCS fills by state DOTs obtained either through survey responses or provided specifications. Table 2.5 provides a summary of the design and construction considerations of ESCS fills by state DOTs obtained either through survey responses or provided specifications.

Table 2.2. Requirements for gradation properties of ESCS fills by state DOTs.

State DOT	U.S. Sieve Size						
	3/4 inch	3/8 inch	No. 4	No. 8	No. 40	No. 100	No. 200
Louisiana	-	95-100	20-100	0-80	0-40	0-15	0-5
Texas	90-100	10-50	0-15	-	-	-	-

Table 2.3. Requirements for mechanical properties of ESCS fills by state DOTs.

State DOT	In-Place Compacted Dry Unit Weight (pcf)	In-Place Compacted Moist Unit Weight (pcf)	Friction Angle (deg)	Abrasion Loss (%)	Durability Index
Louisiana	45-65 for expanded shale 35-55 for expanded clay	< 70 for expanded shale < 65 for expanded clay	> 34 (AASHTO T236 or AASHTO T296)	< 40 (DOTD TR 111)	-
Texas	-	< 65 pcf	-	< 40 (ASTM C 131)	> 35 (AASHTO T 210)

Table 2.4. Requirements for electrochemical properties of ESCS fills by state DOTs.

State DOT	pH-value	Organic Content (%)	Resistivity (ohm.cm)	Chloride Content (ppm)	Sulfate Content (ppm)
Louisiana	5-10 for metallic reinforcements 3-9 for polyester reinforcements >3 for polypropylene and high-density polyethylene reinforcements	< 0.5 (DOTD TR 413) for metallic reinforcements	> 3000 (DOTD TR 429) for metallic reinforcements	< 100 (AASHTO T 291) for metallic reinforcements	< 200 (AASHTO T 290) for metallic reinforcements
Texas	7-9 (AASHTO T 289)	-	30,000-40,000 (AASTHO T 288)	< 100 (AASHTO T 291)	-

Table 2.5. Design and construction considerations of ESCS fills by state DOTs.

Does your agency specify…	Louisiana DOT	Pennsylvania DOT
…considerations for buoyancy/uplift when designing with ESCS fills?	Yes, this is a consideration during the design process and may lead to alternative designs when considered problematic.	Yes
…considerations for long-term water absorption of ESCS fills in design?	Yes, but only for bearing resistance check.	Yes
…a minimum slope at which ESCS fills have to be constructed?	No	No
…compaction practices for ESCS fills that differ from those for conventional fills?	Yes	-
… special drainage systems when designing with ESCS that differ from those typically used with conventional fills?	No	No
…limitations on ESCS fill placement in rainy or snowy conditions?	No, but may need to refer to our standard specs for installation of embankments.	No
…wetting ESCS fills prior to use placement to allow the aggregate to become fully saturated and avoid segregation when handling?	No, but this is done to some extent to allow for compaction.	No
…practices to limit crushing of ESCS fill particles during construction?	No, but we provide guidance.	No
…a minimum cover thickness (if any) above ESCS fills?	Yes, for embankments, a 1ft. plastic blanket above.	Yes
…a minimum thickness between ESCS fills and roadway structures?	No	Yes
…separation between ESCS fills when placed adjacent to other soils?	Yes, geotextile fabric when against other soils and geomembrane above backfill material to protect from drainage and erosion.	Yes, geotextile fabric is used

2.3. Practices of Using FGA Fills

Foamed glass aggregate fills have previously been used at least once by Arkansas, Louisiana, Michigan, New Jersey, North Carolina, Pennsylvania, and Wyoming DOTs. The respondents from Michigan, Pennsylvania, and Wyoming DOTs reported challenges with using FGA fills, including high costs. The respondents from Michigan and Wyoming DOTs added limited availability and distant shipping as an additional barrier for projects in their states.

While there are not enough projects to establish a comparison between the project construction time using FGA fills and traditional fills, the respondents shared their experience with the project(s) they had in their states. The respondent from Michigan DOT stated that the construction time was similar, the respondent from Wyoming DOT stated that using FGA added to the construction time as FGA had to be shipped from Florida, and the respondent from Pennsylvania DOT stated that using FGA fills typically leads to shorted construction time. Both Michigan and Wyoming DOT respondents stated that the cost of using FGA was much higher than that of using traditional fills, while Pennsylvania DOT respondent stated there has not been enough information at the moment to establish a comparison. The respondents reported that the FGA cost is typically inclusive of transportation, which may vary significantly depending on the distance between the production plant and construction site. It is likely that the cost comparison did not include other costs associated with using traditional fills on problematic foundation soils, often ground improvement, which would be omitted when using lightweight fills.

Pennsylvania DOT recently developed a design manual and specifications for FGA fills. The respondents from Michigan and Wyoming DOTs provided special provisions that were developed for the use of FGA fills in their states. In addition to the developed specifications, the respondents indicated that they rely on manufacturer guidelines. The respondent from Pennsylvania added that European Specifications EN 1097-11 (2013) have also been used in developing their own specifications. The respondent from Louisiana DOT indicated that specifications similar to those developed for ESCS fills will be introduced in the future. Table 2.6 and Table 2.7 list the requirements for gradation and mechanical properties of FGA fills by state DOTs, respectively, obtained either through survey responses or provided specifications. Table 2.8 provides a summary of the design and construction considerations of FGA fills by state DOTs obtained either through survey responses or provided specifications.

Table 2.6. Requirements for gradation properties of FGA fills by state DOTs.

State DOT	U.S. Sieve Size		
	4"	2-1/2"	3/8"
Pennsylvania	100	85-100	0-15

Table 2.7. Requirements for mechanical properties of FGA fills by state DOTs.

State DOT	Unit Weight (pcf)	Constrained Compression Resistance (psi)	Friction Angle (deg)
Michigan	15-25 (target 15) “Compaction to 80% of the original lift thickness is desired and must not be exceeded (a final nominal thickness of 19 inches is expected based on a 24-inch original thickness). Density acceptance testing is waived.”	-	-
Pennsylvania	< 15 dry loose (ASTM C29/C29M Method C) < 20 moist loose (ASTM C29/C29M Method C)	48.6 at 10% strain (EN 1097-11:2013) 104 at 20% strain (EN 1097-11:2013)	45 for normal stresses up to 1200 psf (Guidance) 38 for normal stresses up to 3000 psf (Guidance)
New York	< 18 pcf moist loose (ASTM C29 Method C)	> 100 at 20% strain (EN 1097-11)	

Table 2.8. Design and construction considerations of FGA fills by state DOTs.

Does your agency specify…	Michigan DOT	Pennsylvania DOT	Wyoming DOT
…considerations for buoyancy/uplift when designing with FGA fills?	Yes, while it was not a factor in the trial project, it should be considered in future projects for the 500-year flood event.	Yes	Yes
…considerations for long-term water absorption of FGA fills in design?	No, it is assumed that water will always be drained.	No	There has been a discussion on FGA water absorption, especially during hurricanes. It was concluded that water absorption is not an issue.
…a minimum slope at which FGA fills have to be constructed with?	Not at this point.	No	No, for the current project a reinforced slope 1:1.5 was used
…compaction practices for FGA fills that differ from those for conventional fills?	Yes, compaction should follow the special provision to avoid material breakdown. "Do not place and compact layers more than 24 inches in thickness when using tracked equipment and not more than 12 inches in thickness when using a walk behind plate compactor;" and "Place and spread the first layer of FGA on the geotextile without damaging the geotextile or breaking down the FGA."	Yes, 4 passes with tracked equipment of a specific ground pressure.	Yes
…special drainage systems when designing with FGA that differ from those typically used with conventional fills?	No, standard practice is adopted.	No, standard practice is adopted.	Yes, a robust drainage system has been used that includes an encompassing drainage blanket 3 ft thick including around the sides and the base. This was a design requirement to prevent saturation.
…practices to limit crushing of FGA fill particles during construction?	Yes, compaction should follow the special provision to avoid material breakdown. "Wheeled equipment is prohibited on the FGA;" and " Do not operate equipment directly on the geotextile."	Yes, "during construction, vehicles and other construction equipment may have limited travel over the FGA layer after a minimum of 6 inches compacted of capping material is placed."	Yes

Does your agency specify…	Michigan DOT	Pennsylvania DOT	Wyoming DOT
…a minimum cover thickness (if any) above FGA fills?	Yes, a cover of > 4 ft below pavements.	Yes. "The minimum compacted lift thickness of capping material in non-live load situations will be 6 inches."	Yes, a cover of around 6-8 ft.
…a minimum thickness between FGA fills and roadway structures?	Yes, a cover of > 4 ft below pavements.	Yes, a cap is used. "The anticipated dynamic loads in flexible pavement systems must be properly considered in the pavement design where FGA is an underlying layer"	-
…separation between FGA fills when placed adjacent to other soils?	Yes, a nonwoven geotextile is used to completely encapsulate FGA.	Yes, a geotextile is used.	Yes, a drainage blanket.

2.4. Practices of Using TDA Fills

Survey respondents indicated that there has not been any regular use of TDA as a lightweight fill material. However, TDA fills were used in the past in some projects either for research or trial purposes, such as in Louisiana, Texas, and Wyoming.

2.5. Practices of Using LCC Fills

Lightweight cellular concrete fills have previously been used at least once by Illinois, Louisiana, Michigan, New Jersey, North Carolina, Pennsylvania, and South Dakota DOTs. North Carolina DOT used LCC fills in a recent project that used 250,000 cu.yd of LCC fills. The respondent from Wyoming DOT stated that the use of LCC fills had been researched but was not moved forward. The projects in Wyoming are typically design-built, and contractors do not propose using LCC fills because of their limitations, including material and water delivery to remote, high-altitude areas, and concerns about the heat of hydration during LCC mixing. The respondent from Louisiana DOT stated that LCC fills were used once at the New Orleans Airport to mitigate settlement.

The respondents from Michigan, Pennsylvania, and North Carolina DOTs reported challenges with using LCC fills, including high costs. The respondent from Michigan DOT added that they have experienced a push-back from contractors on the specified placement lift thickness, which is required not to exceed 2 ft with a 24-hour wait time between successive lifts and no more than 3 lifts in 96 hours. The respondent from Michigan DOT stated that the construction time of LCC fills is similar to that of traditional fills but the transportation cost is lower since LCC fills are mixed on site.

The respondents from Michigan, Pennsylvania, and North Carolina DOTs stated that special provisions were developed for the use of LCC fills in their states. The respondent from Louisiana DOT stated that LCC fills are currently being incorporated into their specifications. In addition to the specifications, manufacturer guidelines are followed in the mix design. The respondent from Michigan DOT stated that ASTM C 869 is also followed.

Table 2.9 lists the requirements for mechanical properties of LCC fills by state DOTs obtained either through survey responses or provided specifications. Per the special provision of the North Carolina DOT, as part of the mix design and before LCC placement, direct shear testing is required to be performed on LCC samples at 14, 28, and 56 days, with normal stresses of 500, 1000, and 2000 psf for each age. The results should be correlated with the compressive strength to ensure that the minimum parameters from the design are met.

The respondent from North Carolina DOT stated that electrochemical properties of LCC fills are evaluated as part of the MSE design and construction according to the specifications for traditional fills. Table 2.10 provides a summary of the design and construction considerations of LCC fills by state DOTs obtained either through survey responses or provided specifications.

Table 2.9. Requirements for mechanical properties of LCC fills by state DOTs.

State DOT	In-Place Unit Weight (pcf)	Compressive Strength (psi)
Michigan	< 30 for Class II (typically used class) < 36 for Class III < 42 for Class IV	> 10 at 3 days and > 40 at 28 days for Class II (typically used class) > 10 at 3 days and > 80 at 28 days for Class III > 10 at 3 days and > 120 at 28 days for Class IV (ASTM C495/C495M without oven drying)
Pennsylvania	Yes	Yes
North Carolina	18-24 for Class I 24-30 for Class II 30-36 for Class III 36-42 for Class IV 42-55 for Class V 55-75 for Class VI	20 at 10% at 28 days for Class I 40 at 10% at 28 days for Class II 100 at 10% at 28 days for Class III 140 at 10% at 28 days for Class IV 200 at 10% at 28 days for Class V 300 at 10% at 28 days for Class VI (ASTM C495 without oven drying)
Illinois	30+/-2 for Class I 36+/-2 for Class II 42+/-2 for Class III 50+/-2 for Class IV (ASTM C 796)	> 30 at 7 days and > 40 at 28 days for Class I > 60 at 7 days and > 80 at 28 days for Class II > 90 at 7 days and > 120 at 28 days for Class III > 115 at 7 days and > 150 at 28 days for Class IV (ASTM C495 without oven drying)
Iowa	< 48 and > 40 for Class B (ASTM C 796 without oven drying)	120 at 28 days for Class B (ASTM C495 without oven drying)

Table 2.9. Requirements for mechanical properties of LCC fills by state DOTs (Cont.).

State DOT	Friction Angle (deg)	Frost Heave (in.)	Freeze-Thaw Resistance
Michigan	-	-	-
Pennsylvania	-		
North Carolina	> 43 (and > 5 psi cohesion)	-	-
Illinois	-	-	-
Iowa	> 45 (AASHTO T236 or ASTM D3080-72)	< 0.5 at 250-hr exposure (specimens 4.5 in. in height and 4 in. in diameter) per British Road Research Laboratory, Lab Report LR 90, (Croney 1967).	Relative Young's Modulus, E >= 80% at 300 cycles min. cycles at relative E = N/N >= 70% per ASTM C666 Procedure B modified per Bidwell (1975).

Table 2.10. Design and construction considerations of LCC fills by state DOTs.

Does your agency specify…	Michigan DOT	North Carolina DOT
…considerations for buoyancy/uplift when designing with LCC fills?	Yes, uplift is considered for the 500-year flood event.	Yes
…placement practices for LCC fills?	Mix LCC on site. Place in lifts. Each lift is required not to exceed 2 ft with 24-hour wait time between successive lifts and no more than 3 lifts in 96 hours.	Yes, max lift thickness is 5 ft. LCC is mixed on site. Ready-mix LCC can be accepted in small projects.
…special drainage systems when designing with LCC that differ from those typically used with conventional fills?	No, drainage is always kept outside LCC (above and below).	No
…limitations on placing LCC fills rainy, snowy, or high temperature conditions?	Yes, do not place LCC on a rainy day, on frozen ground, or when the air temperature is below 45 F. It does not get too hot in Michigan to specify an upper temperature limit.	Yes, do not place LCC during rain, on a frozen ground, or when the air temperature is below 32 F or above 100 F, unless placement is in accordance with a previously approved cold/hot weather placement submittal.
…limitations on placing LCC within frost zones?	Yes	No, there is not much frost in North Carolina.
…a minimum cover thickness (if any) above LCC fills?	Yes, a cover of > 4 ft.	Yes
…a minimum thickness between LCC fills and roadway structures?	Yes, a cover of > 4 ft.	Yes
…separation between LCC fills when placed adjacent to other soils?	No	Yes, a geotextile is used.

2.6. Practices of Using EPS Fills

Expanded polystyrene fills have previously been used at least once by Illinois, Michigan, Montana, New Jersey, Pennsylvania, Texas, and Wyoming DOTs. The respondents from Michigan, Pennsylvania, Wyoming, and Montana DOTs reported challenges with using EPS fills, including high costs, especially for projects that require distant shipping. The respondent from Montana DOT added that they have experienced challenges due to the lack of expertise of contractors who may not have been involved in construction with EPS fills in many projects. The respondent from Montana DOT also added that on-site storage and stockpiling of EPS can be challenging, especially on windy days. The respondents indicated that construction with EPS fills could be faster than conventional fills except in projects with complex geometries and curves that may require excessive tailoring of EPS blocks.

The respondents from Michigan, Pennsylvania, Wyoming, and Montana DOTs stated that specifications or special provisions were developed for the use of EPS fills in their states. In addition to the specifications, ASTM standards (ASTM D6817) and manufacturer guidelines are also followed. Table 2.11 and Table 2.12 respectively list the requirements for physical and mechanical properties of EPS fills by state DOTs obtained either through survey responses or provided specifications.

Table 2.13 provides a summary of the design and construction considerations of EPS fills by state DOTs obtained either through survey responses or provided specifications.

Table 2.11. Requirements for physical properties of EPS fills by state DOTs.

State DOT	Oxygen Index (% by Vol.)	Water Absorption (% by Vol.)
Pennsylvania	< 24 (ASTM D 2863)	< 3 for EPS22 < 2 for EPS39 (ASTM C 272)
Montana	< 24	< 2
New York	< 24	-

Table 2.12. Requirements for mechanical properties of EPS fills by state DOTs.

State DOT	Density (pcf)	Compressive Strength at 1% (psi)	Compressive Strength at 5% (psf)	Compressive Strength at 10% (psf)	Flexural Strength (psi)	Elastic Modulus (psi)
Michigan	> 1.8 (ASTM D 1622)	> 10.9 (ASTM D 1621)	-	-	-	-
Pennsylvania	> 1.35 +/- 5% for EPS22 > 2.40 +/- 5% for EPS39 (ASTM D 1622)	> 7.3 for EPS22 > 15 for EPS39 (ASTM D 1621)	> 16.7 for EPS22 > 35 for EPS39 (ASTM D 1621)	> 19.6 for EPS22 > 40 for EPS39 (ASTM D 1621)	> 35 for EPS22 > 60 for EPS39 (ASTM C 203)	-
Montana	> 1.8 (ASTM D 1622)	> 10.9 (ASTM D 1621)	> 24.7 (ASTM D 1621)	> 29.0 (ASTM D 1621)	> 50 (ASTM C 203)	> 1090 (ASTM D 1621)
New York	> 1.25 (ASTM D 1622)	> 5.8 (ASTM D 1621)	-	> 16 (ASTM D 1621)	> 30 (ASTM C 203)	-

Table 2.13. Design and construction considerations of EPS fills by state DOTs.

Does your agency specify…	Michigan DOT	Pennsylvania DOT	Wyoming DOT	Montana DOT
…considerations buoyancy/uplift when designing with EPS fills?	Yes, uplift is considered for the 500-year flood event.	Yes	Yes	Yes. This is project specific. Groundwater tends to rise to the ground surface during the winter in Montana.
…considerations for long-term water absorption when designing with EPS fills?	It depends on the project. Typically, no as EPS is assumed to be dry most of time given that drainage is diverted.	No	No	Yes
…placement practices for EPS fills? If yes, please explain (include information about operating equipment above EPS, UV exposure time, block orientation and layout)	Yes. There is also a standard layout.	Yes	Yes	Yes. There are also requirements regarding layout.
…special drainage systems when designing with EPS that differ from those typically used with conventional fills?	Yes, drainage is always diverted above and to the sides the EPS using PVC liner and concrete base course.	No	No, typically a base drainage layer similar to conventional fills.	Yes, Geocomposite strip drains are used in some projects.
…limitations for the use of EPS within frost zones?	Yes, > 4 ft away from frost zones.	Yes	Typically, below frost zones.	No
…a minimum cover thickness (if any) above EPS fills?	Yes, > 4 ft.	Yes	Yes, it varies (about 2 to 4 ft on average).	Yes. Typically, about 3 ft but could differ from one project to another.
…a minimum thickness between EPS fills and roadway structures?	Yes, > 4 ft away from frost zones.	Yes, a cap is used.	Yes	Yes. Typically, about 3 ft but could differ from one project to another.
…requirements to protect EPS against fire?	No, EPS have fire retardants.	No, EPS have fire retardants.	No, EPS have fire retardants.	No, EPS have fire retardants.

Does your agency specify…	Michigan DOT	Pennsylvania DOT	Wyoming DOT	Montana DOT
…requirements to protect EPS against gasoline spills?	Yes, through the use of a PVC liner and a concrete base course.	Yes	Yes, EPS is wrapped by an impermeable membrane.	Yes, EPS is wrapped by a geomembrane to protect EPS against hydrocarbons.
…separation between EPS fills when placed adjacent to other soils?	Yes, PVC liner is used over the top and the sides of EPS to protect it against spills. No concerns about EPS being in contact with other earth materials.	Yes	Yes, EPS is wrapped by an impermeable membrane.	Yes, typically a geotextile.

Chapter 3. Case Studies

Projects that involved the use of lightweight fills in MSE walls and embankments were selected and documented as case studies. This shall provide an illustration for the ultimate design and detailed recommendations compiled as part of this synthesis. The compilation of case histories focused on assessing the applicability of common structure and foundation soil types in Texas, as well as the cost comparison between the selection of lightweight fills over conventional fills for the construction of MSE walls and embankments on soft, compressible foundation soils, which may require ground improvement, preloading, and/or staged construction. One MSE wall case study and one embankment case study were compiled for each of the studied lightweight fill types where applicable. The selection of the case studies was based on the level of detailed information available on foundation soil conditions, design documentation, construction records, and performance monitoring data.

3.1. Expanded Shale, Clay, or Slate (ESCS)

3.1.1. SH 360 across Green Oaks Blvd

This project involved the construction of a 30-ft high approach embankment on the south side of a new bridge along State Highway 360 across Green Oaks Boulevard, Arlington, TX. The construction took place between 2005 and 2006. Information about this case study was obtained from Puppala *et al.* (2017) and Saride *et al.* (2008, 2010).

The site is underlain by 20 ft of soft moist clay followed by 10 ft of dense sand. The geotechnical investigation indicated that the foundation soil is a highly compressible soft clay and would lead to a substantial settlement in the bridge approach if supported by an embankment constructed from conventional fills. Accordingly, Fort Worth District of TxDOT chose to use a lightweight fill for the construction of the embankment, specifying ESCS lightweight fill for this project to alleviate the vertical stresses from the embankment on the foundation soil and control the approach settlement. The particle sizes of the ESCS fill ranged mostly from 0.8 to 10 mm. Additionally, the soft foundation soil was stabilized with 6% lime to a depth of 18 in. prior to the construction of the embankment. Figure 3.1 shows a typical cross-section of the embankment.

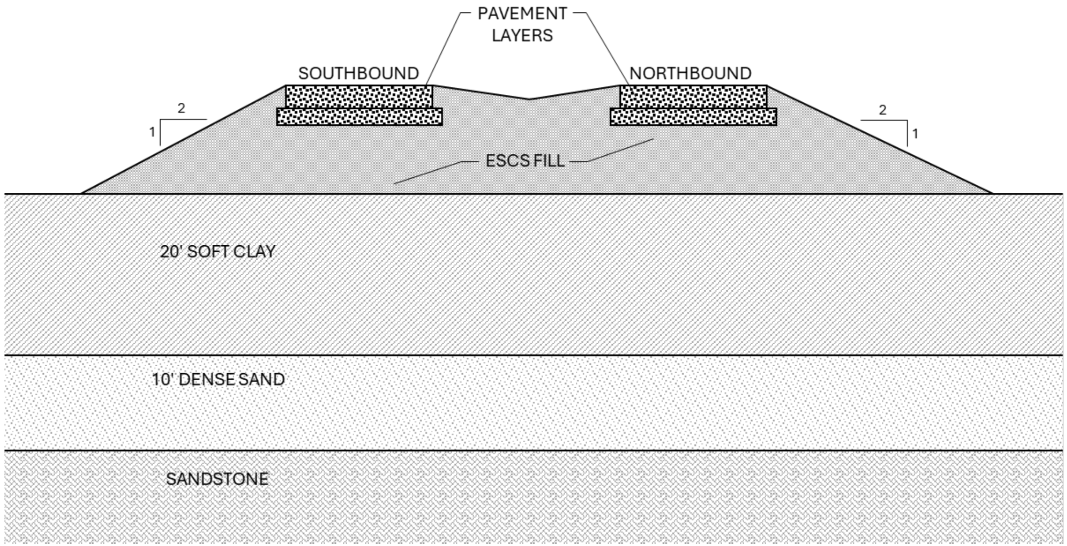


Figure 3.1. Typical cross-section of the embankment (redrawn from Saride et al. 2010).

The foundation soils and ESCS fill were characterized to evaluate their shear strength and compressibility. The embankment was also modeled numerically by Saride *et al.* (2010) and Puppala *et al.* (2017) to evaluate its long-term performance. Table 3.1 summarizes the material parameters used in numerical analyses.

Table 3.1. Summary of material parameters used in numerical analyses (after Puppala et al. 2017).

Material	Bulk Unit Weight (pcf)	Cohesion Intercept (psf)	Angle of Internal Resistance (°)
ESCS Fill	50	1570	49.5
Foundation Soil (Soft Clay)	109.5	940	5
Foundation Soil (Dense Sand)	109.9	0	33

To compact the fill to the required target density, the contractor tried several combinations of conventional vibratory drum rollers, hauling dozers, and heavy 33-cu.yd-capacity haul trucks with wide tires. The bridge abutments were supported by drilled shaft, which required installation of vertical conduits through the ESCS fill to house the shafts. Once the embankment construction reached the required grade, flowable fill was placed followed by the approach slabs. The side slopes of the embankment were maintained between 2:1 and 3:1 and were covered by an approximately 36 in. of seeded local clay soil for erosion control. A total of about 26,159 cu.yd of ESCS fill was used in this project.

The embankment was instrumented with vertical inclinometers at the center at the outer slope of the embankment to evaluate the fill displacements and their patterns (see Puppala et al. 2017). Additionally, surface profiles of the embankment section were recorded using a total station at frequent intervals. The performance of the lightweight embankment was evaluated in terms of settlement due to foundation compression. Both numerical and field data indicated that the compression of foundation soil can be reduced by two-thirds when ESCS fill is used instead of conventional fill. This implies less pavement settlement and fewer maintenance and repair costs.

3.1.2. Eleventh Street Bridge

This $400-million project involved the replacement of twin bridges from the 1960s that carried Interstate 295 traffic over the Anacostia River in the southeast quadrant of the District of Columbia. The bridges were replaced by three new bridges that improved mobility by providing separate freeway and local traffic connections to both directions of DC 295, the Southeast-Southwest Freeway (Interstate 295/395), and local streets on both sides of the river. The owner is District DOT (DDOT) and was considered the largest project ever constructed by DDOT. The construction took place between 2009 and 2015. Information about this case study was obtained from the project profile webpage published by FHWA (2025), Wall and Castrodale (2019).

The project was featured for its extensive use of ESCS lightweight fill to speed the construction, reduce settlement under the roadway, and protect historic structures. Construction of MSE walls in the project also used ESCS fill, which was required to meet specifications for pH value, chlorides and sulfates contents, minimum resistivity, and Los Angeles abrasion. The results are summarized in Table 3.2. The MSE wall used steel strips as reinforcement and segmental precast concrete panels as facing.

Table 3.2. Summary of material properties and specifications (after Wall and Castrodale 2019).

Test	Value	Project Specifications
pH value	8.3	7 to 9
Chlorides Content	< 1 ppm	< 100 ppm
Sulfates Content	32.1 ppm	Not specified
Minimum Resistivity	35,209 Ohm.cm	30,000 to 40,000 Ohm.cm
LA Abrasion	27.3% loss	< 40% loss

The project specifications required that all lightweight fills used have documentation submitted by the lightweight fill producer of a compacted wet density of less than 65 pcf determined from a one-point standard Proctor test. The test protocol was modified to suit the nature of the ESCS aggregate. The fill was specified to be compacted to a minimum of 65% relative density. The determination of the in-place compacted density was a challenge due to the nature of coarse aggregate since most of the in-place density tests do not work on coarse aggregate. Accordingly, a test method was developed to determine the in-place density from various compaction efforts. Steel boxes of known volumes were placed in the area where fill was to be placed and were filled during fill placement and compaction. After compaction, the boxes were removed, and their contained fills were weighed to determine the in-place compacted density. The results indicated that the density was lower than the project-specified maximum density and larger than the project-specified minimum density (which corresponds to the 65% relative density).

3.2. Foamed Glass Aggregate (FGA)

3.2.1. Route 6/10 Interchange

This project involved reconstruction of the Route 6/10 interchange in Providence, RI. The project was considered the largest design-built project in the history of the Rhode Island DOT (RIDOT). The construction took place between 2018 and 2024. Information about this case study was obtained from Loux and Filshill (2021, 2022) and Palombo and Paiva (n.d.).

The project involved ramp construction over challenging subsurface soils and existing subsurface utilities that included a large 100-year-old brick sewer. The relocation of the existing utilities was not feasible and construction above them would have increased the stresses exerted on them, which was not permitted. Accordingly, a solution had to be devised to achieve a net-zero stress increase on the subsurface utilities.

A number of other solutions were considered, including soil-mixed rigid inclusions, EPS geofoam, foamed concrete, and expanded shale aggregate. According to Palombo and Paiva (n.d.), EPS geofoam was considered too costly and involved undesirable practical limitations; foamed concrete involved undesirable practical limitations and uncertainties, including time for installation; expanded shale aggregate required excessive over-excavation to satisfy the net-zero stress constraint; and ground improvement was found to be a very costly and time-consuming solution, costing more than $5 million and adding more than six months to the construction schedule.

Rhode Island DOT and the design-build team decided to use back-to-back MSE walls with FGA lightweight fill. The near-surface existing soil had to be excavated to compensate for the added weight of the walls to satisfy the net-zero stress increase constraint on the subsurface buried utilities. Figure 3.2 shows a cross-section of the ramp, which reached 40 ft at its maximum height. The excavation depth varied with wall height up to 6.2 ft. The MSE walls were constructed with 4-ft U-shaped precast concrete panels and alternating layers of geogrid and geostrap reinforcements extended between the backs of the opposite wall facings.

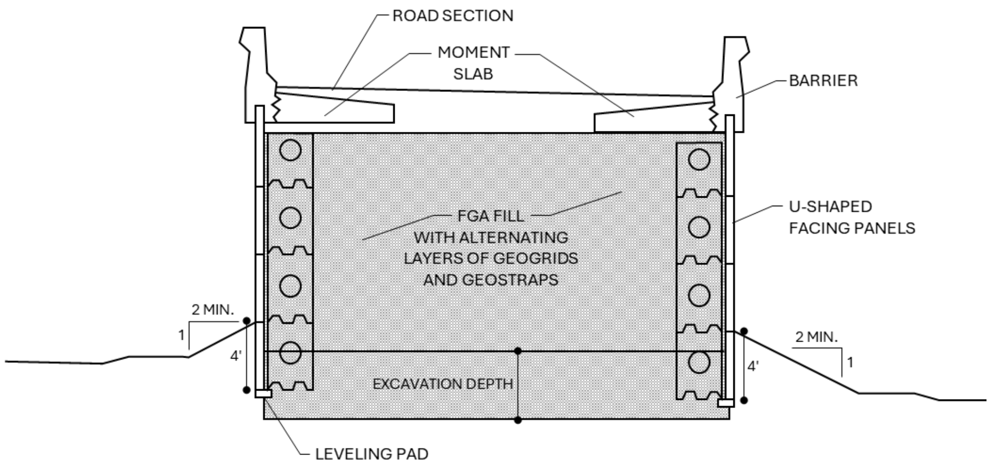


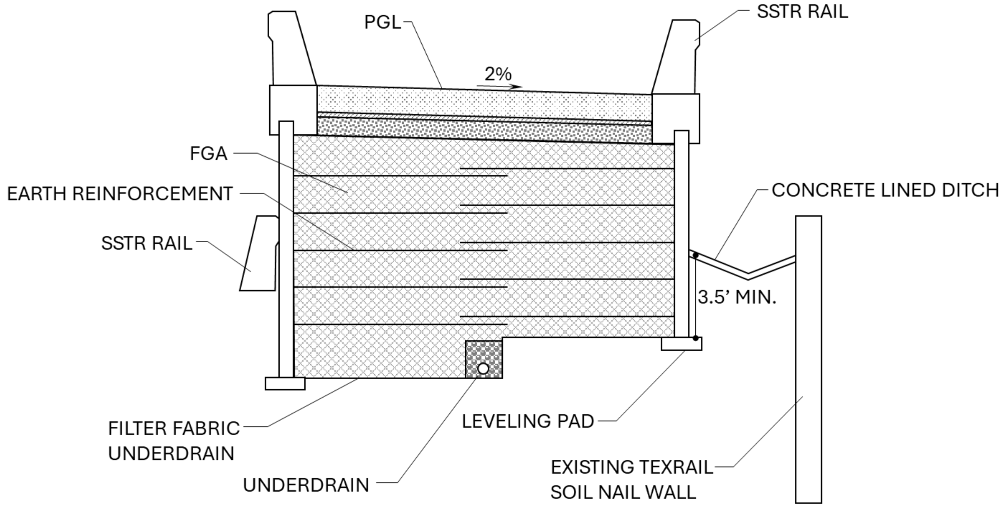
Figure 3.2. Typical cross-section of ramp (redrawn from Loux and Filshill 2022).

A total of 21,000 cu.yd of FGA fill was used in this project. The use of FGA lightweight fills with MSE walls in this project led to a reduction in the number of trucks required for fill delivery and a reduction in the time needed for ramp construction. This led to more than $3 million in savings when compared to the second cheapest design alternative.

3.2.2. Dallas Fort Worth Airport Terminal B

This project is ongoing and involves the construction of back-to-back MSE walls as part of the DFW International Parkway right exits at Terminal B. Information about this project was obtained from the interim review drawings for the proposed retaining walls, the construction of which took place in early 2025. Foamed glass aggregate fill was selected for this project for being ultra-lightweight to mitigate settlements at areas with preexisting underground utilities (Personal Communications 2025). Figure 3.3a shows a typical cross-section of the walls, and Figure 3.3b shows a photo of the walls during construction. As shown in the figures, the wall is situated close to an existing soil-nail wall for a TEXRail line, which could have contributed to the selection of an ultra-lightweight fill for the new MSE walls to mitigate the increase in lateral earth pressure on the existing soil-nail wall.

The near-surface existing soil was excavated for wall embedment. The MSE walls were constructed with precast concrete panels and steel reinforcements extended between the backs of the opposite wall facings. Geotextiles were used to separate the FGA fill from the surrounding soils.



(a)

(b)

Figure 3.3. (a) Typical cross-section of walls (redrawn from interim review drawings courtesy of AeroAggregates); and (b) photo of MSE walls during construction (courtesy of John Ratiu of AeroAggregates).

3.3. Tire-Derived Aggregate (TDA)

3.3.1. El Paso Embankment

The Texas Natural Resource Conservation Commission (TNRCC) approached TxDOT for help with finding an end use for scrap tires accumulating in El Paso. Texas DOT agreed to construct an experimental embankment using tire shreds as a fill material, and TNRCC agreed to pay for shredding the scrap tires to TxDOT specifications. Construction of the embankment took place in 1998 and was the first TDA embankment built in Texas. Figure 3.4 shows a typical cross-section of the walls. Information about this project was obtained from a report published by TxDOT (n.d.) *Year of the Recycled Roadway Materials*, TxDOT (1995) special specification on tire use in embankments, and Tandon et al. (2007).

This project involved the construction of an embankment on the Loop 375 overpass that crosses over Alcan, Dyer, McCombs, and Bomarc streets in El Paso, TX. Tire-derived aggregate was also used as backfill for the earth retaining structures at the bridges. Approximately 4,500 tons of tire shreds were used in this project.

The specifications proposed by TxDOT (1995) and adopted during this project (Special Specification Item 5160 for Tires for Use in Embankment) suggested that the TDA shred size should not be larger than 12 in. However, whole tires were observed during the compaction of the shredded tires. These tires were typically shredded but they were held together by the steel wires. The specifications required that no exposed steel wire should be in the tire shreds, and no soil should be present in the TDA, although actual construction deviated on some occasions from these TxDOT (1995) specifications.

One embankment was constructed with 100% tire shreds wrapped in a geotextile fabric, resembling a "burrito," and covered with compacted soil. The maximum shred size was 12 in. and the uncompacted fill unit weight was 22 pcf. The gradation of the TDA used in the project conforms to Type B, as shown in Table 3.3. This embankment was 80.7 ft wide and 26.6 ft high, with TDA placed in the center of the embankment. The width of the 100% TDA fill was 48 ft and the suggested height was 5.4 ft. The TDA was spread with track-mounted bulldozers and compacted with a sheep-foot roller in six 12-in lifts. An additional 14-in layer of TDA was placed and compacted on the top to compensate for the settlement due to the placement of the overlying soil. The compacted TDA was then wrapped by the geotextile fabric with a minimum overlap of 18 in. A compacted soil layer was placed on the side slopes (16 in. thick) and on the crest (13 in. thick). The TxDOT (1995) specifications required that 100% TDA fills should be spread with track-mounted bulldozers, rubber-tired motor graders, backhoes, or other equipment as needed to obtain uniform lifts. Each fill lift should be compacted to a maximum 12-in. thickness with six passes of a vibratory smooth drum roller with a minimum static weight of approximately 20,000 lb.

A second embankment was constructed with a mix of 50% soil and 50% TDA. This embankment was also covered by a compacted soil layer. The maximum shred size was 4 in. and the uncompacted fill unit weight was 25 pcf. The gradation of the TDA used in the project conforms to Type A, as shown in Table 3.3. This embankment was 80.7 ft wide and 26.2 ft high, with TDA placed in the center of the embankment. The width of the 50% TDA fill was 48 ft and the suggested height was 6.6 ft. The TDA mix was spread and compacted in seven 12-in lifts. An additional 16-in layer of TDA mix was placed and compacted on the top. The TxDOT (1995) specifications required that 50% TDA mixed fills should be spread with layer of uncompacted TDA in lifts less than 12 in. in thickness followed by a lift of embankment soil of equal uncompacted thickness.

Table 3.3. TDA gradation (after TxDOT n.d.).

Sieve Size	Percent Passing	
	Tire Shreds in the 100% TDA (Type B)	Tire Shreds in the 50% TDA (Type A)
12 in. (300 mm)	100% min.	-
8 in. (200 mm)	75% min.	-
4 in. (100 mm)	-	100% min.
3 in. (75 mm)	-	95% min.
2 in. (50 mm)	-	50% min.
1.5 in. (37.5 mm)	25% min.	-
No. 4 (4.75 mm)	1% max.	15% max.

Notes:

1. Exposed steel should not exceed 1% by weight of the tire shreds.
2. Tire shreds must be free of any contaminant, such as oil or gasoline.

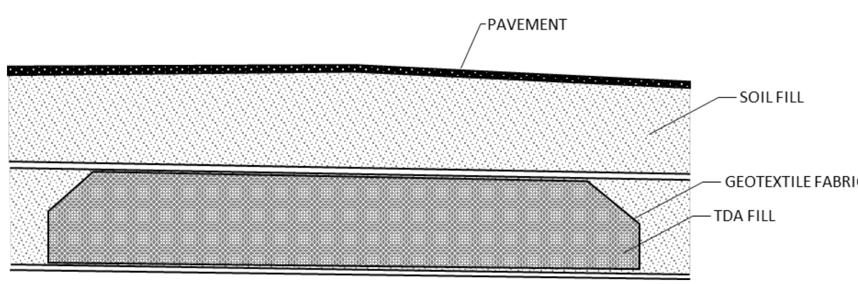


Figure 3.4. Typical cross-section of embankment (redrawn from Tandon et al. 2007).

Due to the absence of side constraints in this project, the TDA spread and occupied a larger width than intended. While this significantly reduced the settlement, it diminished the advantage of the TDA being a lightweight fill and increased the quantity of shredded tires used in the project. Based on this observation, it was recommended that retaining walls be constructed to a level slightly higher elevation than the proposed top elevation of the TDA fill. A geotextile fabric should then be placed to separate the TDA fill from the compacted soil.

The short-term and long-term performance of the embankments were evaluated through field monitoring of settlement, leachate, and temperature. Instrumentation included horizontal inclinometers and magnetic extensometers to monitor vertical displacements, a system of thermocouples to monitor temperature, a sump pump to monitor leachate, and air ducts to monitor air quality. Minimal settlements were observed in both the 100% TDA and the 50% TDA embankments, which were less than expected. The maximum settlement recorded in the 100% TDA embankment was 1 in., and the maximum settlement recorded in the 50% TDA embankment was 0.8 in. No significant temperature elevations were reported within the 100% TDA embankment or the 50% TDA embankment. Overall, it was reported that the TDA embankments were performing without problems.

The cost of using TDA in this project was considered high ($8.9/cu.yd for the 100% TDA and $7.4/cu.yd for the 50% TDA), which was more than twice the cost of using a conventional fill ($3.8/cu.yd). The high cost was attributed to the 30-mile haul distance to deliver the TDA to the project site at a rate of $2.4/cu.yd (at the time of construction), and the contractor's lack of experience compacting TDA. These cost rates do not include the expenditures by TNRCC, which totaled more than $600,000 to transport and shred the tires used in the project. These rates also do not include the costs necessary to address the problems of constructing with conventional fills on weak foundation soils, which may require ground improvement and/or staged construction and longer construction schedules.

3.3.2. Dixon Landing Road

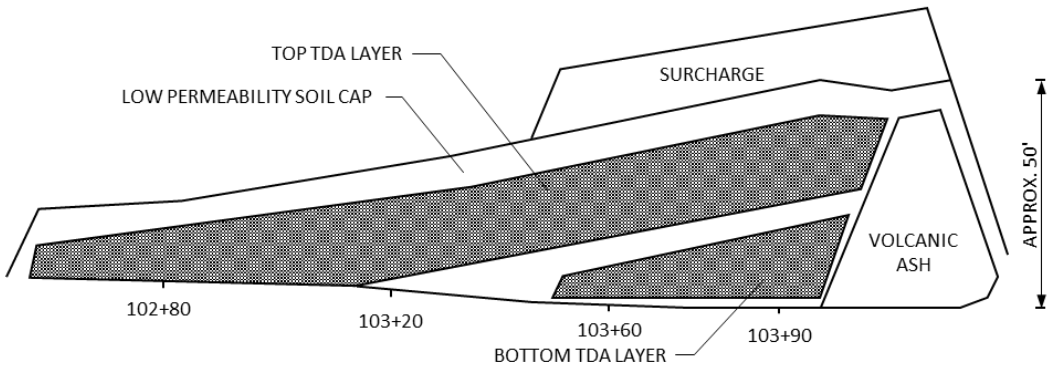
This project involved the construction of a highway on-ramp in Milpitas, CA, connecting Dixon Landing Road to the southbound lane of Interstate I-880. The project owner is the California Department of Transportation (Caltrans), and the construction took place between 2000 and 2001. Information about this case study was obtained from Humphrey (2004, 2008), Cheng (2016) CalRecycle *Tire-Derived Aggregate Usage Guide*, and the project profile webpage published by CalRecycle (2025).

The site is underlain by approximately 30 ft of soft San Francisco Bay mud. Due to the poor load bearing of the Bay mud, lightweight fill was specified for most fill sections of the project in order to reduce total settlement due to the compression of the Bay mud under the added stress by the fill. If conventional fill had been used, the project would have been delayed by an additional year to allow adequate settlement of the fill due to the compression of the foundation soil. Tire-derived aggregate (in-place unit weight of 50 pcf) and pumice aggregate (in-place unit weight of 70 pcf) were considered as lightweight fill alternatives. Caltrans eventually selected TDA for the Dixon Landing Project due to the significantly lower unit weight and unit cost as compared to pumice aggregate.

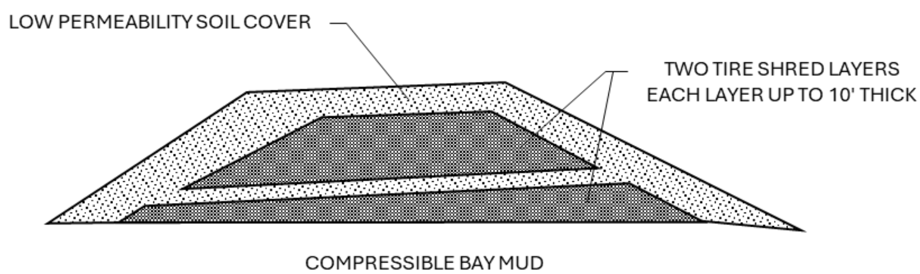
The ramp was constructed to be 26 ft high, 700 ft long, and 50 ft wide. To limit internal heating, the core of the embankment was constructed with two TDA fill layers separated by 3 ft of low permeability conventional fill. Each layer was up to 10 ft in thickness wrapped in nonwoven geotextiles. The side slopes were covered by 6 ft of conventional fill with a minimum 30% fines content. Figure 3.5a and Figure 3.5b show a longitudinal section and a typical cross-section of the embankment, respectively. Volcanic ash, which is also a lightweight material, was used beneath the bridge abutment instead of TDA because of concerns with driving piles through TDA.

The TDA was specified for this project with no shreds larger than 18 in. and with 90% by weight shreds smaller than 12 in., which is commonly referred to as Type B TDA. These relatively large-sized shreds ensure that the exposed steel of freshly cut tires is minimal. The TDA was delivered by tractor trailers at up to 37 cu.yd per truckload. It was spread into 12-in. lifts with a bulldozer and compacted with six passes of a vibratory smooth drum roller weighing 9.1 tons. As the compaction of TDA is insensitive to water content, no water content control was necessary. The construction of this embankment used approximately 6,627 tons of tire shreds, which is equivalent to 662,700 passenger tire equivalents. The same volume of conventional fill would have weighed about 2.5 times the TDA.

Overall, no performance issues related to the embankment have been reported since its construction completion in 2001. The TDA zone was instrumented with thermistors to monitor the internal temperature of the TDA fill. The recorded temperature of the TDA was 80°F at the time of placement, which was typical of the season temperature at the construction site and during the construction time. The internal temperature of the TDA fill dropped slowly with time to about 68°F within eight months of placement. It was concluded that the measures taken to mitigate internal heating were effective.



(a)



(b)

Figure 3.5. Typical sections of embankment: (a) longitudinal section (redrawn from Humphrey 2004); and (b) cross-section (redrawn from Humphrey 2008).

The contractor provided bid prices for the two lightweight fill alternatives, TDA and pumice aggregate, proposed during design. The TDA was supplied by three tire processors at a cost of $23.7/cu.yd, including delivery. The placement cost of the TDA, including the nonwoven geotextiles used to wrap the fill, was $3.7/cu.yd. That is, the total in-place cost, including purchase and placement, was $27.4/cu.yd. This cost was much higher than the total in-place cost of conventional fill (estimated at $7.5/cu.yd) but was approximately half the in-place cost of the pumice aggregate transported from Oregon (estimated at $50/cu.yd). The market for TDA in California made it economically justifiable for one processor located in the Los Angeles area to make a 700-mile round-trip haul to supply TDA to the project. It was estimated that the use of TDA instead of pumice aggregate resulted in $230,000 savings.

3.3.3. Ortega Ridge Road

This project involved the construction of an MSE wall with TDA fill (also known as Mechanically Stabilized Tire-Derived Aggregate or MSTDA) to replace a historical embankment that was constructed in the 1950s on Ortega Ridge Road.

The project site is located in Santa Barbara County south of California State Route 192 and north of State Route 1. A geotechnical site investigation was performed in February 2016, and project construction took place in June 2019. Information about this case study was obtained from McCartney (2021) CalRecycle report *Design of Mechanically Stabilized Tire Derived Aggregate (MSTDA) Retaining Walls*, and a web article published by CalRecycle (2019).

The site is underlain by approximately 14 ft of clay followed by sandy silt. The historical embankment was constructed from sandy clay fill. Approximately 200 ft of the historical embankment on Ortega Ridge Road was undergoing settlement over many years due to the compression of the foundation soil. This settlement damaged the roadway structure and the road needed to be resurfaced multiple times, which added to the weight on the embankment and exacerbated its settlement. To fix the road, this project was implemented to replace part of the embankment with an MSE wall with lightweight fill. The use of lightweight fill was stipulated to alleviate the stresses on the foundation soil. Tire-derived aggregate was selected as a lightweight fill for the MSE wall. Uniaxial geogrids (Tensar UX 1100) spaced at 18 in. were used as reinforcements in the MSE wall. Crushed rock-filled gabions 18 in. in height were used as facing at a batter angle of 72°. The TDA fill was capped by 3 ft of granular fill.

After the historical embankment was excavated, TDA fill was placed in alternating lifts of gabion rows and reinforcement layers. The TDA fill was wrapped in a geotextile fabric to separate it from the adjacent soils beneath and behind the wall, as well as the overlying granular fill. Additional geotextiles were placed behind each row of gabions to separate the crushed rock infill from the TDA. Figure 3.6 shows a typical cross-section of the wall. The wall was embedded at a minimum depth of 3 ft below the ground surface. The maximum exposed height of the wall is approximately 12 ft with up to 10 ft of TDA. A drainage pipe was included in a granular layer below the TDA.

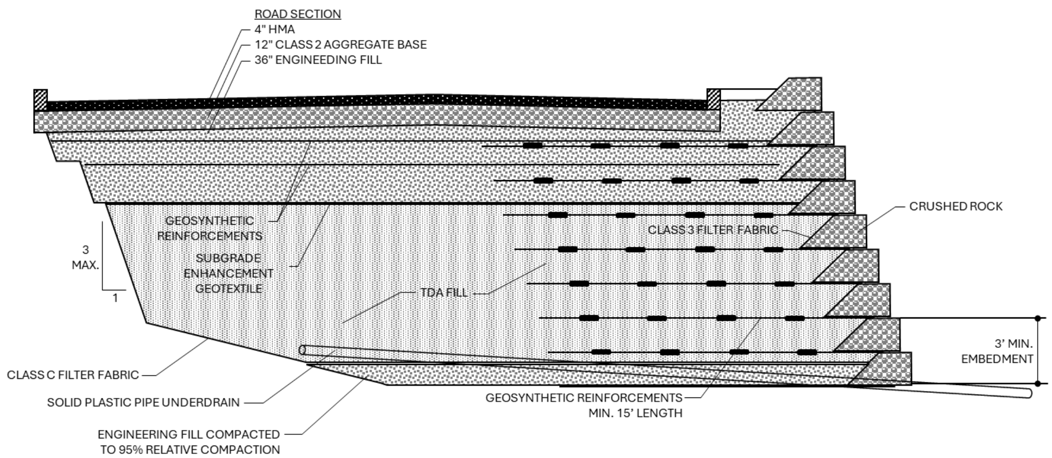


Figure 3.6. Typical cross-section of wall (redrawn from McCartney 2021).

The design of the wall involved global, external, and internal stability analyses in static and seismic loading conditions. The global stability analysis was conducted using a limit equilibrium software (Slope/W). The external and internal stability analyses were conducted using an MSE wall design software by Tensar, which included checks for overturning, sliding on base, bearing capacity, reinforcement rupture, reinforcement pullout, connection with facing (ultimate and service limits), and internal sliding on reinforcement. The material parameters used in both analyses are summarized in Table 3.4. A 1,000-psf was used for the pullout capacity of the geogrid reinforcement in the TDA. Conventional lateral earth pressure distribution was adopted for the reinforced TDA fill. The internal analysis rendered a reinforcement length of 15 ft for a 15-ft high wall.

Table 3.4. Summary of material parameters used in stability analyses (after McCartney 2021).

Material	Bulk Unit Weight (pcf)	Cohesion Intercept (psf)	Angle of Internal Resistance (°)
Historical Fill (Sandy Clay)	110	1000	5
Foundation Soil (Clay)	110	550	5
Foundation Soil (Sandy Silt)	125	500	36
TDA Fill	45	0	35
Granular Cap Fill (above TDA)	125	0	34
Roadway Structure	140	0	36

CalRecycle awarded $158,000 in support of the project through its TDA grant program that incentivizes the use of recycled tires. It was estimated that 810 tons of waste tires were used in the project, which is equivalent to 81,000 recycled tires. The project was featured as the first infrastructure project in California to use TDA material as fill material in an MSE wall.

3.4. Lightweight Cellular Concrete (LCC)

3.4.1. I-29/80 Interchange

This project involved the construction of an embankment as part of the improvement of the interchange between Interstate 29 and Interstate 80 in Council Bluffs, Pottawattamie County, Iowa. Information about this case study was obtained from the project plans prepared for the Iowa DOT and Iowa DOT (2017) special provision for LCC fills.

The reconstruction involved a significant amount of soft soil remediation underneath the bridge abutments and the approaching interstates. Iowa DOT chose to use LCC as a fill material for its lightweight and high compressive strength to minimize the potential for settlement due to the compression of foundation soils. A total of 113,900 cu.yd of 32-pcf LCC was used at a rate over 1,500 cu.yd/day. Figure 3.7 shows a typical cross-section of the embankment.

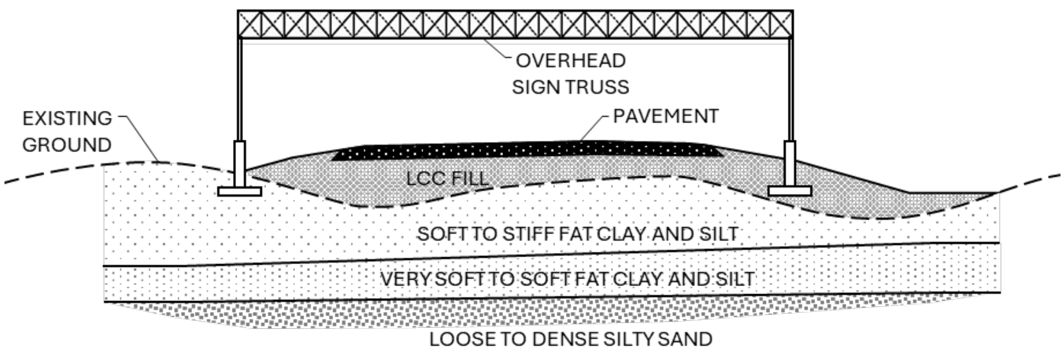


Figure 3.7. Typical cross-section of embankment (redrawn from Iowa DOT design plans).

Iowa DOT (2017) issued a special provision for LCC fills that was adopted in this project. The specifications required that the LCC fill is made of Portland cement and Portland cement type 1. Pozzolans and admixtures were permitted if designated and approved by the LCC manufacturer. The specifications require checking the density of the initial batch of LCC and adjusting the mix as required to obtain the specified cast density at the point of placement. The check was specified through four test specimens for each 300 cu.yd placed or every four hours of placing. It was required that the tests be performed on cylindrical specimens (3 in. in diameter and 6 in. in height) in accordance with ASTM C796 without oven drying specimens. It was required that the foaming agent from the manufacturer produce LCC fill that complies with the specifications in Table 3.5.

Table 3.5. Summary of material specifications (after Iowa DOT 2017).

Property	Requirements	Test Method
Class B Max./Min. Dry Density	48 pcf / 40 pcf	ASTM C796 without oven drying
Class B Min. Unconfined Compressive Strength at 28 days	120 psi	ASTM C495 without oven drying
Internal Friction Angle	45 degrees min.	AASHTO T236 (ASTM D3080-72)
Frost Heave at 250-hr exposure (specimens 4.5 in. in height and 4 in. in diameter)	< 0.5 in.	British Road Research Laboratory, Lab Report LR 90, 1967, by Croney, Jacobs.
Freeze-Thaw Resistance (min. cycles at relative E = N/N >= 70% per ASTM C666 modified per Bidwell Report dated April 1975	Relative Young's Modulus, E >= 80% at 300 cycles	ASTM C 666 Procedure B (rapid freezing in air and thawing in water)
Coefficient of permeability at 2 psi	10^{-5} cm/s	-

The specifications by Iowa DOT (2017) required that the placement the LCC fill be coordinated with the placement of the MSE reinforcement. A suitable arrangement was required to hold the reinforcement in place before placing the LCC fill. Precast panels and MSE steel reinforcing strips were required to be fully or partially encased in the LCC fill and properly set and stable prior to the placement of the LCC fill. The back facing panels and wire mesh were specified to be covered with geotextile fabrics at the vertical and horizontal joints prior to the placement of the LCC fill. The placement of the LCC fill was also required to be coordinated with other construction activities, including the construction of the sign foundations, pavement longitudinal subdrains, storm intakes and any underground utility or structural element. Drainage pipes, or any other items to be encased in the LCC fill were required to be set and stable prior to placement of the LCC fill.

Lightweight cellular concrete fills were specified to be placed in lifts 30 in. in thickness at maximum. Each lift was required to be scarified to a minimum depth of 0.5 in. prior to the placement of the subsequent lift. A minimum wait time of 24 hours was required between subsequent lifts. Paving machines, heavy construction equipment or other unusual loading of the LCC fill were not permitted until the LCC fill attained the specified 28-day compressive strength.

It was specified that areas where the LCC fill was placed be free of any standing water prior to placement of the LCC fill. Placement of the LCC fill was not permitted at a temperature below 32°F, nor when freezing conditions were expected in less than 24 hours unless precautions were taken to maintain temperatures above freezing.

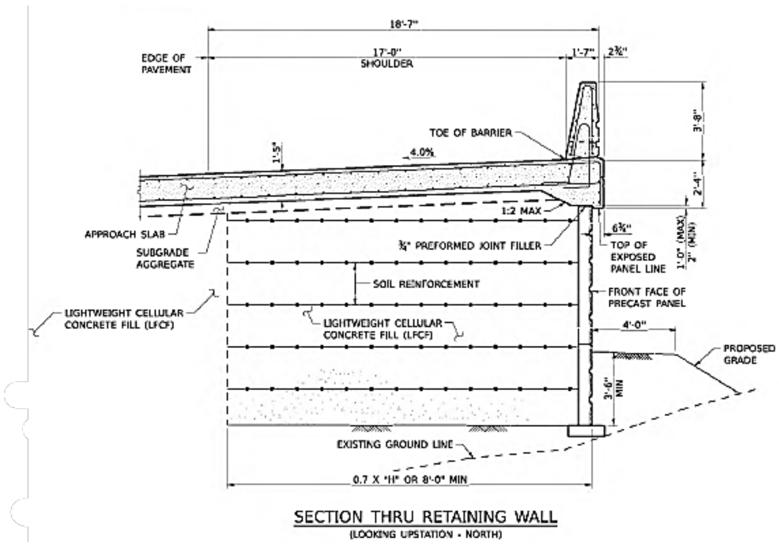
3.4.2. I-294 Interchange Roosevelt Rd to St. Charles Rd

This project involved the construction of an MSE wall as part of the tri-state tollway (I-294) roadway and bridge reconstruction northbound I-294 / I-290 / I-88 Interchange Roosevelt Road to St. Charles Road. Information about this case study was obtained from the project plans prepared for the Illinois State Toll Highway Authority.

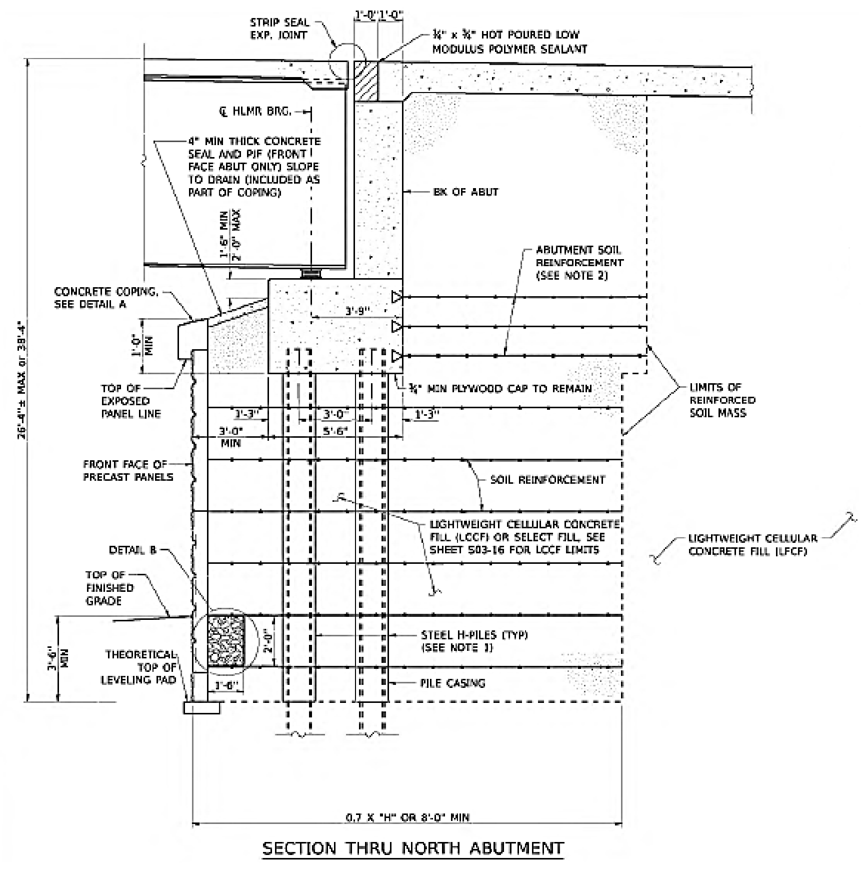
To mitigate the added stress on the foundation soil, LCC was used as a lightweight fill. Figure 3.8a shows a typical cross-section of the wall through the retaining wall and Figure 3.8b shows a typical cross-section of the wall through the abutment wall. The LCC specified for this project was Class III according to the LCC special provision used in the project. This class requires that LCC is placed in 30-in. lifts at a maximum as-cast density 42±2 pcf and minimum compressive strength of 90 psf at seven days and 120 psf at 28 days.

The MSE walls used precast facing panels and steep strip reinforcements. The project specified that the facing and reinforcement elements be fully or partially encased in the LCC fill and properly set and stable prior to the placement of the LCC fill. A suitable arrangement was required to be made to hold the reinforcement in place during the placement of the LCC fill. The back facing panels and wire mesh were specified to be covered with geotextile fabrics at the vertical and horizontal joints prior to the placement of the LCC fill. Project specifications also required that any drainage pipes or other items encased in the LCC fill be set and stable prior to the placement of the LCC fill.

The LCC fill was required to be placed on and keyed into the existing embankment slope. This required the existing embankment slope to be stepped with >2-ft high steps at a rate equivalent to the original slope inclination. Foreslopes constructed with LCC fill were also required to be constructed with a stepped surface at a rate equivalent to the proposed slope inclination and capped with 1 ft of vegetative soil.



(a)



(b)

Figure 3.8. Typical cross-section of wall: (a) section through retaining wall; and (b) section through abutment wall (from project plans, Illinois State Toll Highway Authority).

For bridge abutment walls, abutment piles were sleeved from the bottom of the abutment to bottom of pre-cored pile depth before the placement of the LCC fill. The annular space between the pile and sleeve was filled with clean sand. The MSE abutment walls were required to be designed to resist a factored horizontal force of 8.0 kips/ft. The internal stability design was required to account for bearing pressure surcharge of 1.0 ksf and horizontal sliding force of 1.15 kips/ft at the moment slab.

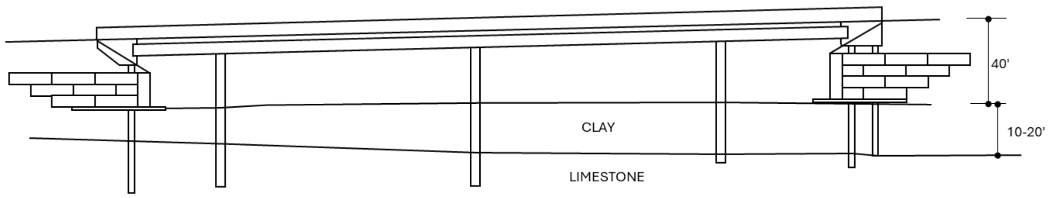
Wall displacements were required to be monitored during wall construction at specified monitoring points at least twice a week (every three to four days) until the full height of the MSE wall, including wall backfill and embankment fill, was achieved. The project specifications required delaying the construction of wall coping, approach slabs, moment slabs, and roadway pavement or any other structure sensitive to settlement until the settlement of the MSE wall stabilizes to a rate of less than 0.1 in./month and the post-construction settlement is assessed to be less than 1 in.

3.5. Rigid Cellular Polystyrene (RCPS)

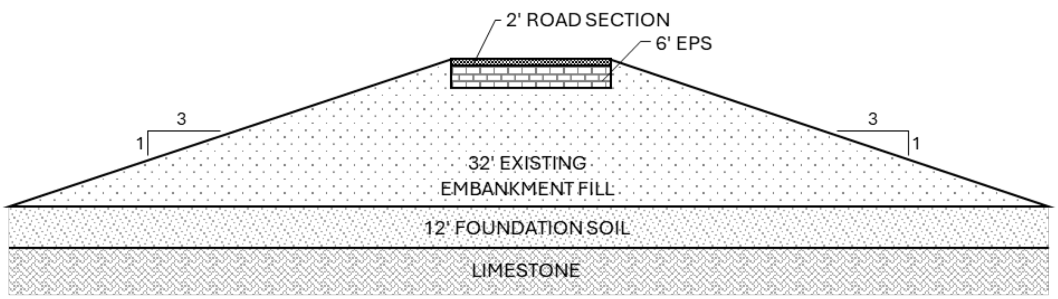
3.5.1. US 67 Bridge over SH 174

This project involved the repair of bridge embankments as part of the rehabilitation of the US 67 bridge over SH 174 in Cleburne, Johnson County, TX, in 2012. Information about this project was obtained from the project summary webpage published by TxDOT (2017), a presentation by Puppala (n.d.), Ruttanaporamakul (2014), and Puppala et al. (2019).

The original construction used readily available moderate-plasticity clay as the fill material for the approximately 40-ft-high approach embankments. The embankments are underlain by 10-20 ft of clay followed by limestone. Figure 3.9a shows a longitudinal section for the US 67 bridge over SH 174. This rehabilitation project was carried out to repair the historical approach slabs at both ends of the bridge, which had experienced more than 17 in. of settlement since the bridge was originally constructed in 1995 (over 16 years). The repair involved replacing part of the existing embankment fill with lightweight fill. TxDOT Fort Worth District adopted EPS geofoam as a lightweight fill material for one of the new embankments. Specifically, EPS22 (ASTM 6817) was used in construction, which has a significantly lower unit weight than that of removed soil. This EPS was designed to replace 6 ft of soil from the bottom of the bridge abutment upward and overlain by a 2-ft road section. Figure 3.9b shows a typical cross-section of the embankment. A compacted sand leveling layer (2 to 6 in.) was placed prior to the installation of the EPS blocks. The installation of the EPS blocks took three to four days to complete. The blocks were connected with barbed connection plates. The finished fill was incapsulated with geomembrane. Finally, the 2-ft road section was constructed above the EPS fill, which included flex base, hot mix asphalt concrete, and concrete pavement layers.



(a)



(b)

Figure 3.9. (a) Longitudinal section of US 67 bridge over SH 174 (redrawn after Puppala et al. 2019); and (b) typical cross-section of embankment (redrawn from Puppala n.d.).

The EPS fill was instrumented by horizontal inclinometers and vertical and horizontal pressure cells to monitor mechanical behavior of the embankment in response to the pavement dead load and traffic live load. The monitoring data indicated less than 1.5 in. settlement during the first three service years. However, no visible deformation or bump were observed in the concrete pavement surface at the end of the bridge.

Chapter 4. Material Cost Benefit

The lightweight fill costs reported in the literature were synthesized as part of this project. This synthesis aims to assist in performing material cost-benefit analysis of lightweight fills to compare the cost difference involved in using lightweight fills in lieu of conventional fills in the construction of MSE walls and embankments.

4.1. Factors Contributing to Lightweight Costs

Costs for lightweight fills can vary significantly from one project to another based on a number of factors:

Manufacturing Costs. If the material is a waste product that can be used directly, the cost will be relatively low. Recycled materials are also affordable, though the cost may slightly increase due to processes such as crushing, shredding, and sieving (Schaefer et al. 2006).

Transportation Costs. If the project site is distant from the supply source, transportation costs can become significant. The mode of transportation and the number of truckloads also influence the overall cost (Schaefer et al. 2006). Because lightweight fills are much lighter than conventional fills, they can be shipped with larger trucks and fewer trips, as their transportation is typically governed by the truck volume capacity rather than truck load capacity. Another factor that affects transportation costs is the difference between the fill Free-On-Board (FOB) density (uncompacted, loose) and in-place (compacted) density. For example, the density of TDA typically ranges from 25 to 35 pcf when shipped and ranges from 45 to 50 pcf after compaction (see Cheng 2016), which is a significant difference when compared to conventional soils and other lightweight fill types. Because LCC fills are typically mixed on site, their transportation costs are computed based on the delivery of their mixture components, including water.

Quantity of Materials. The quantity of material required for a project, along with the necessary on-site staging, can affect the average transportation cost and may also affect the base material cost, especially when dealing with smaller quantities (Schaefer et al. 2006).

Availability of Materials. Some fill materials may not be readily available in some regions. If production rates are low, there might not be enough supply to meet the demands of a project unless the product is sourced from multiple suppliers (Schaefer et al. 2006), which may not necessarily be applicable.

Construction Costs. Placement and compaction costs for lightweight fill materials can be higher than those for traditional fills. This may involve special materials or construction activities that are only required when lightweight fills are used (Schaefer et al. 2006), such as the use of geotextiles, geomembranes, and/or concrete covers; the need for tailoring geofoam blocks to project geometry requirements; the need for additional compaction passes when using TDA fills; or the use of special placement equipment for LCC fills.

Design Demands. Using lightweight fills is likely to reduce the structural and geotechnical design demands, which will reduce the total cost of the project. While the initial costs of using lightweight fills can be high, these costs are compensated by economic designs and/or omission of ground improvement techniques for soft compressible foundations.

4.2. Review of Lightweight Fill Costs

When estimating the costs of lightweight fills, it is essential to use a common basis for comparison (Schaefer et al. 2006) to allow for an unbiased comparative analysis. Generally, conventional fills are quoted by suppliers (e.g., quarries) on a tonnage basis. However, because lightweight materials exhibit significant variability in density (Schaefer et al. 2006), and because their loose and compacted densities often differ, direct comparisons based on tonnage can be misleading. For instance, the density of TDA when stockpiled and shipped typically ranges from 25 to 35 pcf, while its in-place compacted density ranges from 45 to 50 pcf (Cheng 2016). As a result, a ton of lightweight fill covers a substantially greater volume than conventional, denser soils. Thus, cost comparisons should be based on the price per in-place cubic yard. To convert a dollar-per-ton price into a dollar-per-cubic-yard value, the estimated in-place density and the delivered cost per ton can be used (Schaefer et al. 2006). Moreover, differences amongst the lightweight fill types and their engineering properties introduce additional design and cost considerations. For example, the use of several types and densities of lightweight fill in a project can result in different computed performance indicators (e.g., stability safety factors). This can be introduced in the cost comparison by weighing the change in the computed performance indicator against the reduction in fill density.

Table 4.1 summarizes the material unit costs reported in the literature by suppliers and/or manufacturers for the lightweight fill types synthesized in this project. Available cost information is limited and could vary significantly from one location to another and based on the quantity needed.

Table 4.1. Lightweight fill material unit costs.

Material	Material Unit Cost
ESCS	• $65/cu.yd for expanded clay (Personnel Communication 2025) • $24.5/cu.yd for expanded shale (SiteOne 2025) • $125/cu.yd for expanded shale (Soil Builders Systems 2025) • $179/cu.yd for expanded shale (The Organic Recycler 2025) • $147.5/ton for expanded shale (Strata Landscape 2025) • $20-60/ton for expanded shale (Tutumluer and Qamhia 2024) • $27-64/ton for expanded slate (Tutumluer and Qamhia 2024) • $85/cu.yd (Tutumluer and Qamhia 2024) • $30-45/cu.yd (Schaefer et al. 2017)
FGA	• $103/cu.yd (Personnel Communication 2025) • $180/cu.yd (Lancaster Lime Works 2025) • $65/cu.yd (Salandro 2022) • $65/cu.yd (Walsh 2021) • $70-100/cu.yd (Gibson 2019)
TDA	• $12/ton for 2-inch TDA (El Naggar and Iranikhah 2021) • $31/ton for <2-inch TDA (El Naggar and Iranikhah 2021) • $31-68/ton for <0.5-inch TDA (El Naggar and Iranikhah 2021) • $15-30/cu.yd, including delivery; as low as $2/cu.yd; costs may be significantly offset with recycling incentives (Schaefer et al. 2016) • $23.7/cu.yd, including delivery (Humphrey 2004, 2008)
LCC	• $56/cu.yd; varies with mixture design (Richway 2025)
EPS	• $55-100/cu.yd (Sutmoller 2018) • $40-60/cu.yd (Schaefer et al. 2016) • $75-148/cu.yd (Geotech Tools n.d. for projects bids between 2008 and 2010)

Table 4.2. Comparative cost analysis for transportation infrastructure fill projects.

Project	Traditional Fill	Lightweight Fill				
		ESCS	TDA	EPS	Pumice Rock	Wood Chips
Embankment – Confusion Hill/Hwy 101 Realignment, Mendocino County, CA	$316,358	$632,716	$187,500	$643,539	$514,354	$307,138
Embankment – Dixon Landing Road, Milpitas, CA	$562,864	$489,829	$333,600	$1,144,984	$632,726	$545,226
Slide Repair – Marina Dr, Mendocino County, CA	$937,612	-	$190,555	-	-	-

Notes:

1. Data reported by Cheng (2016) citing the following source: Cost Benefit Assessment: Evaluation of Tire-Derived Aggregate Against Alternate Fill Options for Civil Engineering Applications. Prepared for CalRecycle by GHD, Inc. February 2015.
2. Reported costs include material, transportation, and longevity costs and exclude installation costs and contractor's overhead and profit.

Table 4.2 summarizes a few case histories with detailed cost comparison assessments that compared various fill options in transportation infrastructure fill projects. The data were obtained from Cheng (2016), citing a cost-benefit assessment conducted for CalRecycle in February 2015. The reported costs include material, transportation, and longevity costs but exclude installation costs and the contractor's overhead and profit.

4.3. Comparison with Ground Improvement

This section provides a qualitative comparison between the use of lightweight fills as a solution to the construction of fill structures, such as MSE walls and embankments, over soft foundation soils and the use of conventional fills that require ground improvement. Table 4.3 summarizes the readiness of some geotechnical solutions in terms of the degree of technology establishment, rapid renewal of transportation facilities, minimal disruption to traffic, and production of long-lived facilities. The table presents readiness ratings reported by the ASCE Geo-Institute on the Geotech Tools Database for the construction of embankments over soft soils. Table 4.4 summarizes the costs involved in ground modification technologies for the construction of embankments over soft soils. The data were primarily obtained from Schaefer et al. (2016) and the ASCE Geo-Institute on the Geotech Tools database of ground modification technologies (Geotech Tools n.d.). The data are typically scarce or nonexistent, especially from recent projects and/or bids. The costs can also vary significantly from one region to another and also over short periods.

Table 4.3. Readiness of geotechnical solutions for construction of embankments over soft soils (Geotech Tools n.d.).

Geotechnical Solution	Degree of Technology Establishment	Rapid Renewal of Transportation Facilities	Minimal Disruption of Traffic	Production of Long-Lived Facilities
	Rating Scale: 1 = Very Low; 2 = Low; 3 =Moderate; 4 = High; 5 = Very High			
Prefabricated Vertical Drains and Fill Preloading	5	3	1	1
Mass Mixing	3	3	1	1
Lightweight Fill	5	5	3	3
Excavation and Replacement	5	2	1	1
Column-Supported Embankments	4	5	1	1
Deep Dynamic Compaction	5	4	1	1
Vibrocompaction	5	4	1	1
Compaction Grouting	4	3	3	3

Table 4.4. Costs of ground modification technologies for construction of embankments over soft soils.

Geotechnical Solution	Unit Cost	Other Costs
Prefabricated Vertical Drains and Fill Preloading	• $0.7-$4.0 per linear foot for projects with less than 50,000 linear feet (Pile Buck Magazine 2020) • $0.5-1.0 per linear foot for projects with 50,000 to 300,000 linear feet (Pile Buck Magazine 2020) • $0.3-$0.5 per linear foot for projects with over 300,000 linear feet (Pile Buck Magazine 2020) • $0.5-1.5 per linear foot for projects with over 10,000 linear feet (Geotech Tools n.d. based on 2005-2010 projects)	• $15,000-25,000 per rig for mobilization (Pile Buck Magazine 2020) • $7.5-25 per ton for granular drainage layer (Geotech Tools n.d. based on 2005-2010 projects) • $0.5-1.5 per linear foot for horizontal strip drain (Geotech Tools n.d. based on 2005-2010 projects) • $3-10 per cubic yard for surcharge embankment (Geotech Tools n.d. based on 2005-2010 projects) • $3-10 per cubic yard for surcharge removal (Geotech Tools n.d. based on 2005-2010 projects) • $5-15 per linear foot for augers holes (Geotech Tools n.d. based on 2005-2010 projects) • Instrumentation
Mass Mixing	• $15-75 per cubic yard (Schaefer et al. 2016)	• $15,000-40,000 for mobilization (Geotech Tools n.d. based on 2009-2011 projects)
Lightweight Fills	• $75-150 per cubic yard for EPS and LCC (Schaefer et al. 2016) • $3-15 per cubic yard for wood fiber; blast furnace slag; fly ash; boiler slag; ESPS; TDA (Schaefer et al. 2016)	-
Column Supported Embankments	• $9 per square foot (Schaefer et al. 2016) + $30-80 per linear foot for non-compressible columns or $20-100 per linear foot for compressible columns (Schaefer et al. 2016) • $15-60 per linear foot for stone columns and rammed aggregate piers (Schaefer et al. 2016) • $20-60 per linear foot for aggregate columns (Geotech Tools n.d. based on 2007-2010 projects) • $60-125 per linear foot for deep mix columns (Schaefer et al. 2016; Geotech Tools n.d. based on 2009-2011 projects)	• $2.5-12 per square yard for geosynthetics used in load transfer platform (Geotech Tools n.d. based on 2005-2010 projects) • $2.5-12 per square yard for geosynthetics used in working platform (Geotech Tools n.d. based on 2005-2010 projects) • $7-20 per ton for the granular fills (Geotech Tools n.d. based on 2005-2010 projects)
Deep Dynamic Compaction	• $10-30 per square yard (Schaefer et al. 2016) • $10-25 per square yard (Geotech Tools n.d.)	• $20,000-0,000 for mobilization (Geotech Tools n.d.) • $3-10 per cubic yard for material backfilling and leveling craters (Geotech Tools n.d.)
Vibro-Compaction	• $5-9 per linear foot (Schaefer et al. 2016)	• $20,000-30,000 for mobilization (Geotech Tools n.d.) • $7-20 per ton for the granular fills (Geotech Tools n.d.)
Compaction Grouting	• $75-750 per cubic yard grouting (Schaefer et al. 2016; Geotech Tools n.d. based on 2009-2011 projects)	• $25,000-50,000 for mobilization. Equipment mobilized includes drill rig(s), compressor(s), grout mixers and pumps (Geotech Tools n.d. based on 2009-2011 projects) • $25-75 per linear foot for drilling (Geotech Tools n.d. based on 2009-2011 projects)

Chapter 5. Design Guidelines and Construction Controls

Recommendations for design guidelines and construction controls for the use of lightweight fills were developed as part of this project. These recommendations were developed using the information synthesized from the literature review, developed practices from other state DOTs, and case studies. The recommendations were prepared following the style of the TxDOT Geotechnical Manual of 2024 (TxDOT 2024a). Additionally, construction specification guides for each of the lightweight fills considered in this study were developed in Appendix B. The specification guides were prepared following TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges of 2024 (TxDOT 2024b).

5.1. Recommendations for ESCS Fills

Expanded Shale, Clay or Slate (ESCS) fills are discrete fills that consist of lightweight ceramic aggregates formed by expanding and vitrifying shales, clays or slates in a rotating kiln at elevated temperatures. The ESCS Institute (ESCSI) offers a thorough examination of ESCS products manufactured across the US, as well as recommendations for the design specifications and construction controls for the use of ESCS fills. ESCS products are manufactured by US-based manufacturers fairly distributed across the country.

5.1.1. Design Guidelines

Follow product-specific manufacturer guidelines. The ESCSI recommends consulting with the manufacturers for information on material properties and construction methods (ESCSI 2018). ESCS fills should meet the ASTM C330 requirements (TxDOT Project # NH 2B20(015) Construction Specifications 2021).

Consider long-term water absorption in design. ESCS fills may absorb some water during construction and when submerged under water for prolonged periods of time. Schaefer et al. (2016) reported that the moisture content of ESCS fills increased from 8.5% during construction to 28% one year after construction. They reported that over a longer period of time, the estimated long-term water content may increase to about 34%. Accordingly, long-term water content needs to be considered when designing with ESCS fills.

Ensure that the factor of safety against buoyancy/uplift of ESCS is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). Florida DOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm.

Design a protective capping for ESCS fills. When ESCS fills are used in the construction of embankments, use a minimum of 2.5 ft of soil cover on embankment side slopes. Use side slopes of 1.5H:1V or flatter to confine the material and provide internal stability (Schaefer et al. 2016).

When ESCS fills are used in the construction of retaining walls, use an angle of shearing resistance of 35° in lateral earth pressure calculations (Schaefer et al. 2016).

5.1.2. Design Parameters

The following parameters can be used as guidance when designing with ESCS fills. Fill parameters should be evaluated to ensure they meet the specifications.

5.1.2.1. Physical Parameters

- In-place compacted dry unit weight: 35-65 pcf.
- In-place compacted moist unit weight: 65-70 pcf.
- Particle size range: No. 200 to 1 in. (by producer).
- Soundness loss (Magnesium Sulfate): < 30% per AASHTO T 104.

5.1.2.2. Mechanical Parameters

- LA abrasion loss: < 40% per ASTM C131.
- Durability test index: > 35 per AASHTO T 210.
- Angle of internal resistance: > 34° per AASHTO T236 or AASHTO T296.
- Coefficient of subgrade reaction: 140-155 pci.

5.1.2.3. Hydraulic Parameters

- Highly permeable and drainable.
- Water absorption (by producer).

5.1.2.4. Electrochemical Parameters

- Resistivity: > 3,000 ohm.cm per AASHTO T 288.
- pH value: 5-10 per AASTHO T 289.
- Chloride content: < 100 ppm per AASHTO T 291.
- Sulfate content: < 200 ppm per AASHTO T 291.
- Organic content: < 1% per AASHTO T267.

5.1.3. Construction Controls

Follow product-specific manufacturer guidelines. Place ESCS fills in uniform lifts. Fill should be unloaded at the side of the fill area, then distributed with lightweight equipment with a contact pressure of 4.5 psi or less (Schaefer et al. 2016). A common practice is to limit the thickness of each uniform layer to 12 in. or less in a loose state before compaction (Tutumluer and Qamhia 2024) but can be up to 3 ft (Schaefer et al. 2016). The material can be placed in any weather with no waiting time between placing lifts (Tutumluer and Qamhia 2024).

Compact each ESCS layer to the specified target density. Field density may be approximated in the laboratory by conducting a modified one-point AASHTO T 272 density test (Schaefer et al. 2016). A target relative density of 65% as per ASTM D 4253 and D4254 is recommended (TxDOT Project # NH 2B20(015) Construction Specifications 2021). No special equipment is needed on the jobsite for compacting ESCS (ESCSI 2007). However, compaction should be conducted with rubber-tired roller equipment to prevent excessive particle crushing by steel-tracked equipment (Schaefer et al. 2016). Compaction can be achieved using vibratory compaction equipment weighing no more than 12 tons static weight or vibratory plate compaction equipment (3.7-14.9 kW; 5-20 hp) in confined areas. A minimum of two passes should be applied when compacting 6-in. lifts with a 5-hp plate power or 12-in. lifts with a 20-hp plate power (ESCSI 2007, 2018).

Ensure that the ESCS fill 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 2007, 2018; TxDOT Project # NH 2B20(015) Construction Specifications 2021).

Evaluate the in-place compacted density. This can be done using steel boxes of known volumes and weights placed in the area where fill is placed. After fill placement and compaction, remove and weigh the steel boxes. Determine the in-place compacted density of the compacted fill compare it to the target density. This method was successfully implemented in the Eleventh Street Bridge project (District DOT).

5.1.4. Limitations

While widely produced across the nation, ESCS fills may still require distant transportation if the jobsite is located far from the nearest by manufacturer. Additionally, the properties of ESCS fills can vary widely from one manufacturer to another or from one manufacturing plant to another. Caution must be exercised when sourcing ESCS fills. Some ESCS fills have typically large pH values that make them unsuitable for fills where corrosion of buried metals is a concern.

ESCS particles have a relatively high water retentivity and can store water, especially when inundated for extended periods. Wetting ESCS fills during construction to minimize segregations may be discouraged; alternative practices should be explored. Additionally, ESCS particles are relatively brittle and can degrade under excessive compaction efforts or driving earth moving equipment directly on them.

5.2. Recommendations for FGA Fills

Foamed Glass Aggregate (FGA) is a discrete fill manufactured from recycled glass treated with a foaming agent such as gypsum, limestone (Hibbert 2016), glycerin, manganese dioxide (Ghafari et al. 2019), and, most commonly, silicon carbide (Aabøe and Øiseth 2004; Hibbert 2016).

5.2.1. Design Guidelines

Follow product-specific manufacturer guidelines. Place FGA fills with side slopes 1H:1V or flatter. Design for global stability, bearing strength, and settlement due to compression and creep (AeroAggregates 2020). When FGA fills are used as reinforced fill in MSE walls full-scale pullout tests (ASTM D 6706) are required to be submitted to verify the properties used in the internal stability analysis (AeroAggregates 2020).

Use geotextiles to separate FGA fills from adjacent soils to prevent particle migration from the neighboring soils into the FGA fills (Loux et al. 2024). Geotextiles have to be seamed or overlapped; a typical overlap of 0.3 m may suffice in most applications and conditions. In cases where significant displacement is expected such as instruction on soft soils, a larger overlap may be needed (Loux et al. 2024).

Design a protective capping for FGA fills. Capping materials may include embankment material subbase, topsoil, or rock (AeroAggregates 2020). Capping thickness should be 6 in. at minimum in cases without live loads and should be determined by design in cases involving live loads (AeroAggregates 2020).

Ensure that the factor of safety against buoyancy/uplift of FGA is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). Florida DOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm. AeroAggregates (2020) suggests applying a factor of safety of 1.5 to the estimated buoyant unit weight. Provide drainage piping to drain infiltrating water (Loux and Filshill 2021).

5.2.2. Design Parameters

The following parameters can be used as guidance when designing with FGA fills. Fill parameters should be evaluated to ensure they meet the specifications.

5.2.2.1. Physical Parameters

- As-delivered loose dry unit weight: < 15 pcf.
- In-place compacted moist unit weight: < 25 pcf.
- Particle size range: 3/8 in. to 4 in. (by producer).
- Fines content after compaction: < 15%.
- Soundless loss (Magnesium Sulfate): < 30% per AASHTO T 104.

5.2.2.2. Mechanical Parameters

- Angle of internal resistance: > 34° per AASHTO T 236.
- Compressive strength at 10% strain: > 7,000 psf per EN 1097-11.
- Compressive strength at 20% strain: > 15,000 psf per EN 1097-11.

5.2.2.3. Hydraulic Parameters

- Highly permeable and drainable.
- Water absorption (by producer).

5.2.2.4. Electrochemical Parameters

- Resistivity: > 3,000 ohm.cm per AASHTO T 288.
- pH value: 5-10 per AASTHO T 289.
- Chloride content: < 100 ppm per AASHTO T 291.
- Sulfate content: < 200 ppm per AASHTO T 291.

5.2.3. Construction Controls

Follow product-specific manufacturer guidelines. Place FGA fills in uniform lifts. Limit lift thickness to 24 in. when compacting using tracked equipment and to 12 in. when compacting using plate compactors (Loux et al. 2019b).

Compact each FGA fill layer to a target compression ratio of 1.25 by applying four passes of tracked equipment, such as excavators or dozers, with a ground pressure ranging from 625 to 1025 psf (Loux et al. 2019b). In areas inaccessible by tracked equipment, apply four passes of plate compactor with a weight ranging from a 110-220 lb. (Loux et al. 2019b). Avoid excessive compaction or compaction using more powerful energy to prevent excessive crushing of the FGA particles. Avoid operating construction equipment on FGA fills other than for placement and compaction (Loux et al. 2019b; Tutumluer and Qamhia 2024). Evaluate field compaction through observance and verification of the method-based specification (Loux et al. 2019b).

Use a non-woven geotextile to separate FGA from other contiguous soils with smaller particles to prevent the migration of the smaller particles into the FGA pores (Loux et al. 2019b). Care should be taken during placement of capping layer to prevent damage to geotextile. Adjacent panels of geotextile may be sewn together or overlapped a minimum of 12 inches. The geotextile shall not be left exposed for longer than 14 days (AeroAggregates 2022).

5.2.4. Limitations

The number of FGA manufacturers and suppliers in the US is small and can therefore require distant transportation if the jobsite is located far from the nearest supplier. Additionally, the properties of FGA fills may vary from one manufacturer to another or from one manufacturing plant to another. Caution must be exercised when sourcing FGA fills in future should the number of FGA manufacturers in the US increases. FGA particles are relatively brittle and can degrade under excessive compaction efforts or driving earth moving equipment directly on them. Furthermore, FGA fills have relatively large-sized particles, which makes it difficult to characterize them using conventional aggregate characterization lab equipment. Information regarding the mechanical behavior of FGA types produced in the US is scarce or exists from tests conducted on samples with modified gradation.

FGA leachate analysis has shown hazardous concentrations much lower than those of the drinking water standards (Arulrajah et al. 2015; Lenart and Kaynia 2019). Information regarding the leachate analysis of FGA types produced in the US is scarce.

5.3. Recommendations for TDA Fills

Tire-Derived Aggregate (TDA) is produced by mechanically shredding discarded tires into light, durable chips that generally range in size from 4 to 8 inches (Schaefer et al. 2016). It can be made of 100% tire chips or tire chips mixed with soil, both of which produce drainable lightweight fills.

The state of practice for embankment construction with TDA is presented in ASTM D6270. Per FHWA-NHI-16-027 (Schaefer et al. 2016), current practice follows ASTM D6270 Type A gradation for TDA fills in construction of embankments up to 10 ft in height thickness provided that TDA fills are encased in geotextiles, covered with soil, and used above the groundwater table. Additional design and construction guidelines are provided by some state agencies, including NYSDOT (2015a), and CalRecycle (Cheng 2016).

5.3.1. Design Guidelines

Follow standard practice for use of scrap tires in civil engineering applications (ASTM D6270). Tire wire strands must be firmly attached to the tire rubber to prevent damaging construction equipment (Schaefer et al. 2016). Tire rubber should be free of any loose wire or metal fragments, wood chips or fragments, and other fibrous organic matters (Tutumluer and Qamhia 2024).

Limit TDA layers to 10 ft in thickness. Multiple 10-ft TDA layers should be separated by 3 ft of inorganic soil fill (Schaefer et al. 2016; Tutumluer and Qamhia 2024). Place a minimum 3-ft thick soil cap on the top and side slopes of the TDA fill to provide confinement and minimize deformation (Schaefer et al. 2016). Keep the top elevation of TDA embankments 5 ft at minimum below the top elevation of subgrades (Schaefer et al. 2016). Keep TDA fills above the groundwater table (Schaefer et al. 2016). Anticipate 35% volume reduction during compaction, plus 10% compression under loading of soil cover and pavement base course. (Schaefer et al. 2016).

Separate TDA fills from the surrounding soils by geotextiles (Schaefer et al. 2016) to minimize the migration of soil particles. This separation layer is essential for pavement, drainage, and retaining wall backfill applications (Tutumluer and Qamhia 2024).

Ensure that the factor of safety against buoyancy/uplift of TDA is 1.3 at minimum under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). Florida DOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to the 500-year storm.

Provide good surface drainage of TDA fill structures to avoid water infiltration into the TDA fills. Locate drainage pipes at 3 ft at minimum below the bottom of the TDA fills. Drainage features that could provide free access to air should be avoided at the bottom of TDA fills (Schaefer et al. 2016).

5.3.2. Design Parameters

The following parameters can be used as guidance when designing with TDA fills. Fill parameters should be evaluated to ensure they meet the specifications.

5.3.2.1. Physical Parameters

- Compacted dry unit weight: 30-73 pcf.
- Shred size ranges: No. 4 to 4 in. (Type A) and No. 4 to 12 in. (Type B).
- Longest shred size: 12 in. (Type A) and 18 in. (Type B).

5.3.2.2. Mechanical Parameters

- Angle of internal resistance: 19-30° per AASHTO T 236.
- Compressibility: 5-40% vertical strain over a range of 200-4,200 psf vertical stress.

5.3.2.3. Hydraulic Parameters

- Highly permeable and drainable.

5.3.2.4. Electrochemical Parameters

- Resistivity: > 3,000 ohm.cm per AASHTO T 288.
- pH value: 5-10 per AASTHO T 289.

- Chloride content: < 100 ppm per AASHTO T 291.
- Sulfate content: < 200 ppm per AASHTO T 291.

5.3.3. Construction Controls

Follow standard practice for use of scrap tires in civil engineering applications (ASTM D6270). Place and spread using a tracked dozer in lifts 3 ft or less in thickness (Schaefer et al. 2016). Compact each TDA layer by applying a minimum of six passes of a vibratory smooth drum steel roller with a minimum static weight of 10 tons (Tutumluer and Qamhia 2024). Sheep foot rollers, smooth drum rollers, or D-8 dozers may be used (Schaefer et al. 2016). Avoid direct exposure to heavy equipment or excessive compression. Do not compact TDA with pneumatic or vibratory plate compactors. Evaluate the in-place compacted density.

Limit TDA layers to 10 ft in thickness. Multiple 10-ft TDA layers should be separated by 3 ft of inorganic soil fill (Schaefer et al. 2016; Tutumluer and Qamhia 2024). Place a minimum 3-ft thick soil cap on the top and side slopes of the TDA fill to provide confinement and minimize deformation (Schaefer et al. 2016). Keep the top elevation of TDA embankments 5 ft at minimum below the top elevation of subgrades (Schaefer et al. 2016). Preload TDA fills with a 2-ft soil surcharge for 60 days to minimize post-construction settlement due to TDA compressibility (Schaefer et al. 2016).

5.3.4. Limitations

Tire shreds should be free of any contaminants, such as oil, grease, gasoline, or diesel fuel, among other chemical substances (Tutumluer and Qamhia 2024). In addition, leachate from TDA fills should be minimized (Schaefer et al. 2016). While TDA may produce leachate containing various metals and organic compounds, toxicity levels are below applicable water quality thresholds (Cheng 2016). Leachate analysis has shown that TDA leachate is not hazardous according to the Toxicity Characteristic Leaching Procedure (TCLP) (Tutumluer and Qamhia 2024). Toxicity has been reported in leachate from TDA fills submerged below groundwater level, but the metals quickly formed immobile and insoluble particles in the subsurface soil (Sheehan et al. 2006). TDA fills can be combustible; accordingly, TDA should follow design considerations that prevent their combustion, which should prevent or minimize the amount of water and air infiltration into tire shred fill (Schaefer et al. 2016). Environmental considerations of TDA fills are discussed in ASTM D6270, Stroup-Gardiner and Wattenberg-Komas (2013b, NCHRP 435 report), Edstrom et al. (2008), and Baker et al. (2003).

5.4. Recommendations for LCC Fills

Lightweight Cellular Concrete (LCC) is a cement water slurry typically created by mixing Portland cement, water, air introduced through a foaming agent and may include some sand (Schaefer et al. 2016; ASCE Texas Section 2022). This material may include supplementary admixtures such as fly ash, slag, silica fume, fibers, as long as they do not have detrimental effects on the fill porosity. The produced fill is composed of a cement matrix with a network of discrete air cells. Taylor and Halsted (2021) provide a comprehensive report on the use of LCC in geotechnical applications and recommendations for design and construction considerations to achieve high-quality LCC fills.

5.4.1. Design Guidelines

Follow ASTM D7180 and product-specific manufacturer guidelines. Preformed foam must conform to the properties listed in ASTM C869 when tested following the procedures in ASTM C796.

Design for external stability, including settlement, bearing capacity, and overall stability under the projected loading conditions (Caltrans 2021). Design for internal stability, including adequate material support for the overlaying structures (e.g., pavements and traffic loads) without cracking and creep compression (Caltrans 2021).

Design LCC elevations below the zone of freezing to avoid the LCC compressive strength degradation by freeze-thaw cycles. Alternatively, design with LCC of higher compressive strengths; LCC with densities larger than 37 pcf have reported excellent freeze-thaw resistance (Schaefer et al. 2016).

Design for uplift pressure considering a 100-year flood event (Caltrans 2021). Cutoff walls (Caltrans 2021) or sufficient vertical confinement (Schaefer et al. 2016) should be used to achieve a minimum safety factor of 1.3 against uplift under normal operational conditions and 1.1 under extreme conditions (EM 1110-2-2100). Florida DOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to a 500-year storm.

The foundation under the LCC must be prepared to create a smooth surface and dry condition. In cases where groundwater exists, dewatering may become necessary (Caltrans 2021). In addition, a layer of permeable material (8 to 12 in.) wrapped in filter fabric including a layer of geomembrane on top directly below LCC may become necessary when excess groundwater is present (Caltrans 2021). Design a drainage blanket and drains to prevent the saturation of LCC by water, which could affect the density and compressive strength (Schaefer et al. 2016).

5.4.2. Design Parameters

The following parameters can be used as guidance when designing with LCC fills. Fill parameters should be evaluated to ensure they meet the specifications.

5.4.2.1. Physical Parameters

- In-place unit weight: 18-75 pcf (varies by LCC Class).

5.4.2.2. Mechanical Parameters

- Compressive strength at 28 days: 20-300 psi at 10% strain (varies by LCC Class).

5.4.2.3. Hydraulic Parameters

- Water absorption: 1.4-5 psf (varies by LCC Class).
- Hydraulic conductivity: 10^{-5} cm/s (varies by LCC Class).

5.4.3. Construction Controls

Follow product-specific manufacturer guidelines. LCC mix should be produced on site as transportation of premixed LCC may adversely affect the density of the final product due to the vibrations associated with transportation (Taylor and Halsted 2021).

Monitor weather conditions before LCC placement as fills should not be placed if heavy rain is imminent but may be placed in light rain. Placing LCC fills is not recommended in ambient temperatures below 32 °F (0 °C) to avoid the inhibition of the LCC curing time, which may adversely affect the quality of the final product (Taylor and Halsted 2021). LCC should not be placed on a frozen ground or when freezing conditions are expected in less than 24 hours unless precautions are taken to maintain temperatures above freezing (IADOT 2017). Placing LCC fills is not recommended in ambient temperatures above 100 °F (38 °C) to avoid the evaporation of the water in the LCC mix, which may cause excessive shrinkage (Taylor and Halsted 2021).

Cast LCC fills in lifts 4 ft or less in thickness. Allow a minimum of 12 hours between casting subsequent lifts (Schaefer et al. 2016). Iowa and Michigan DOTs require a minimum of 24 hours between casting subsequent lifts. Once they set, LCC fills should not be remixed (Taylor and Halsted 2021). Scarify each lift to a minimum depth of 0.5 in. and clean the surface of each lift before casting the subsequent lift (Schaefer et al. 2016; IADOT 2017). Scarifying shall be done after sufficient curing time such that foot traffic will not excessively damage the lift surface (IADOT 2017). Considering the fluidity of LCC fills during placement, formwork should be tight to avoid leakage of the mix through formwork joints. Polyethylene film may be used to prevent leakage (Schaefer et al. 2016).

Coordinate the placement of the LCC fills with the construction of pavement longitudinal subdrains, storm intakes and any underground utility or structural element that will be placed within the LCC (IADOT 2017).

The density of the LCC fills should be checked in accordance with ASTM D6023 before and after pumping. During placement, slurry density checks should be performed, and the mix wet density and temperature should be monitored. 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. Hardened LCC fills should be inspected, and LCC samples should undergo material density and unconfined strength testing in accordance with ASTM C495 (Taylor and Halsted 2021). Field observations during placement should 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.
- Excessively hot or cold temperatures.

- Lumps of cement in the mix.
- Leakage in the formwork.
- Excessively high cure heat.
- Location of any bleed water after curing.

5.4.4. Limitations

LCC fills should be mixed on site. Transportation of premixed LCC may adversely affect the density of the final product due to the vibrations associated with transportation (Taylor and Halsted 2021). LCC fills require delivering large volumes of material and water to the jobsite, which can be a challenge for projects in remote, high-altitude areas. LCC fills require waiting times between successive lifts to allow each lift to cure, which can delay construction.

Although LCC may produce toxic leachate from a byproduct material used in the mix, toxicity levels are non-concerning. Heavy metal concentrations, including arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, passed the Toxicity Characteristic Leaching Procedure (TCLP), indicating non-concerning levels of heavy metals (Tutumluer and Qamhia 2024).

5.5. Recommendations for EPS Fills

Expanded Polystyrene (EPS) geofoam is formed by expansion of polystyrene resin beads or granules in a molding process. Standard specifications for EPS are offered by ASTM D6817. The most comprehensive design, material, and construction guidelines on the use of Expanded Polystyrene (EPS) for highway construction have been summarized in NCHRP 24-11 for embankments and 24-11(02) for slope stability projects.

5.5.1. Design Guidelines

Follow product-specific manufacturer guidelines. Design for external stability, including settlement, bearing capacity, and overall stability under the projected loading conditions (Caltrans 2021). External stability analyses generally follow traditional geotechnical design procedures. For shear strength, NCHRP- 24-11 recommends using only ¼ of EPS geofoam compressive strength. Design for internal stability, including adequate material support for the overlaying structures (e.g., pavements and traffic loads) without excessive compression or creep. The design approach for internal stability is a deformation-based methodology using the total stress from all loads on EPS blocks, elastic limit stress, and the initial tangent modulus to evaluate load-induced deformations (Caltrans 2021).

Design to protect the EPS to resist hazards like fire and gasoline leakage. EPS dissolves in gasoline and other organic fluids or vapors and therefore must be protected against the potential reach of such organics (Caltrans 2021). EPS should be encapsulated in a gasoline resistant geomembrane (Caltrans 2021) or covered by a geomembrane and/or a reinforced concrete slab (typically 4 in. thick at minimum) when used under roadways in case of accidental spills (NYSDOT 2015b; Schaefer et al. 2016). When concrete is used, the protective cap may also serve to enhance the overall performance by aiding in the distribution of loads (NYSDOT 2015b).

Use side slopes 2H:1V or flatter and a minimum cover thickness of 0.8 ft. If a vertical face is needed, cover exposed face of blocks with shotcrete or other material to provide long-term protection against UV (Schaefer et al. 2016).

The foundation under the EPS must be prepared to create a smooth surface and dry condition. In cases where groundwater exists, dewatering may become necessary (NYSDOT 2015b; Caltrans 2021). Final grade should be sufficient to allow 4 ft cover over EPS blocks (NYSDOT 2015b). Utilities (or any future utility work) should not interfere with the EPS (NYSDOT 2015b).

Design for uplift pressure considering a 100-year flood event (Caltrans 2021). Cutoff walls (Caltrans 2021) or adequate counterweight cover (Schaefer et al. 2016) should be used to achieve a minimum safety factor of 1.3 against buoyancy/uplift under normal operational conditions and 1.1 under extreme conditions (recommendation based on EM 1110-2-2100). Florida DOT (2022) requires that lightweight fill embankments be designed with a factor of safety of 1.2 against buoyancy and lateral movement due to a 500-year storm.

Design a subsurface drainage system to aid in the lowering of the groundwater table and/or maintain a positive drainage path in the vicinity of the EPS fill. Typically, a subsurface drainage system includes the installation of a layer of graded crushed stone placed behind and below the EPS fill, connected to a positive outlet. The graded crushed stone may also include a network of perforated drainage pipes (NYSDOT 2015b).

Design using total unit weights that account for long-term water absorption (Caltrans 2021). EPS blocks placed below water may have 2 to 2.5 times higher unit weights than those placed above water after 10 years (Schaefer et al. 2016).

Design considering differential icing potential of pavement (Caltrans 2019). Differential icing can be minimized by using a soil layer of a sufficient thickness between the EPS and pavement surface (Schaefer et al. 2016).

5.5.2. Design Parameters

The following parameters can be used as guidance when designing with EPS fills. Fill parameters should be evaluated to ensure they meet the specifications.

5.5.2.1. Physical Parameters

- Dry unit weight: 1-2 pcf (varies by EPS designation).
- Permanently submerged unit weight (at water content 10%): 7.8-8.2 pcf (varies by EPS designation).
- Periodically submerged unit weight (at water content 4%): 3.5-4.5 pcf (varies by EPS designation).
- Above-highest-groundwater-table unit weight (at water content 1%): 1.6-2.6 pcf (varies by EPS designation).
- Flammability Oxygen Index: < 24% per ASTM D 2863.

5.5.2.2. Mechanical Parameters

- California bearing ratio: 2-4 (varies by EPS designation).
- Elastic limit stress: > 5.8-14.5 psi (varies by EPS designation).
- Initial tangent Young's modulus: > 580-1450 psi (varies by EPS designation).
- Resilient modulus: > 725-1450 psi (varies by EPS designation).
- Compressive strength: > 10-25 psi (varies by EPS designation).
- Flexural strength: > 25-50 psi (varies by EPS designation).

5.5.2.3. Hydraulic Parameters

- Water absorption: < 2-4% per ASTM C 272.

5.5.3. Construction Controls

Follow ASTM D7180 and product-specific manufacturer guidelines. Ensure that the site is free of any standing water (Tafreshi et al. 2020), vegetation, or debris (Tutumluer and Qamhia 2024). Except where the designer has considered the effect of thawing in permafrost regions, geofoam should not be placed directly on a frozen ground (Tutumluer and Qamhia 2024). Level subgrades before the placement of the geofoam blocks. A layer of sand/gravel is commonly placed as a leveling course (Schaefer et al. 2016).

A minimum of two layers of blocks must be used. When multiple layers of geofoam blocks are placed, they should be placed at right angles to avoid continuous vertical joints and to promote interlocking (NYSDOT 2015b; Schaefer et al. 2016). Place blocks in a “running bond” and rotate the pattern by 90 degrees in each successive layer (NYSDOT 2015b). Use galvanized barbed plates to provide mechanical connections between adjacent blocks for shear transfer (Schaefer et al. 2016).

Place a cover material over the geofoam blocks as soon as possible to prevent their displacement by wind or buoyancy, and to avoid prolonged exposure to sunlight that may embrittle them (Schaefer et al. 2016). Place a separating sand layer 0.5 to 1 inch in thickness between the geofoam blocks and any neighboring coarse granular soils (Tutumluer and Qamhia 2024). Only small, rubber-tired equipment can operate directly on the EPS to avoid damage (NYSDOT 2015b).

Perform on-site density tests by weighing and measuring an EPS block randomly chosen from each truck load or 2500± ft^3 of EPS delivered to the site (NYSDOT 2015b).

5.5.4. Limitations

While widely produced across the nation, EPS may still require distant transportation if the jobsite is located far from the nearest by manufacturer. Other limitations for EPS include on-site storage and stockpiling, which can be challenging, especially on windy days. Furthermore, EPS blocks may require excessive cutting and tailoring in projects with complex geometries, which can delay construction.

EPS is resistant to alkalis, dilute inorganic acids, gypsum plaster, most alcohols, Portland cement, silicone oil, and solvent-free bitumen. However, EPS may be damaged by chemicals that 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). Where geofoams are used as a structural backfill, a reinforced gasoline-resistant geomembrane should be used to protect the geofoam from spilled liquid hydrocarbons, and other fluids (Tutumluer and Qamhia 2024). While EPS is flammable, ASTM D6817 has requirements on geofoams used in highway applications to restrict their flammability. Such geofoams are manufactured with fire-retardant additives (Tutumluer and Qamhia 2024).

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Appendix A. Surveys of the State of the Practice of Using Lightweight Fills

Preliminary survey

Survey of the State of the Practice of Using Lightweight Fills in Transportation Projects

Dear survey recipient,

You are receiving this email because you have been identified as a state engineer who may be able to provide useful information to the Texas Department of Transportation (TxDOT) in support of an ongoing research project (project no. 0-7237) to synthesize the state of the practice of using lightweight fills in transportation projects.

The University of Texas at Austin is currently investigating the use of lightweight fills in the state of Texas. As a part of the research efforts, this (extremely brief) survey is being distributed to all state DOTs to better understand the use of this technology throughout the United States. Specifically, we ask you to complete the survey on the current practices in using lightweight fills at your agency. Ultimately, your responses will help us understand the practices, challenges, and advancements associated with lightweight fills and will direct TxDOT's research efforts.

All responses by survey respondents will be treated as confidential. Responses will be compiled, analyzed, and summarized collectively without disclosing respondents' identities.

Thank you for your time. We look forward to receiving your response.

Best Regards,

Jorge G. Zornberg, Ph.D., P.E., BC.GE, F.ASCE
Professor and Joe J. King Chair in Engineering
The University of Texas at Austin

General Information

1. Does your agency allow the use of lightweight fills in the design and construction of fill structures such as embankments and retaining walls?
    - o Yes
    - o No, but it is currently being considered
    - o No, and it is not being considered
2. If you answered "Yes" to Question 1, does your state have specific design guidelines for lightweight fill applications?
    - o Yes
    - o No
    - o Under development
3. If you answered "Yes" to Question 1, does your state have construction specifications for lightweight fills?
    - o Yes
    - o No
    - o Under development
4. If you answered "Yes" to Question 1, for what applications has your agency used lightweight fills? (Choose all that apply)
    - o Embankment fills, including embankment ramps and embankment widenings
    - o MSE wall reinforced fills (reinforced fill component of an MSE wall)
    - o Retaining wall backfills, including MSE wall retained fills (retained fill component of an MSE wall)
    - o Fills for subgrade replacement
    - o Fills around culverts
    - o Fills above underground utilities
    - o Other (please specify): _________
5. If you answered "Yes" to Question 1, what types of lightweight fills have been used in your state? (Choose all that apply)
    - o Rigid Cellular Polystyrene (RCPS): Expanded polystyrene (EPS) geofoam
    - o Rigid Cellular Polystyrene (RCPS): Extruded polystyrene (XPS) geofoam
    - o Expanded shale, clay, or slate (ESCS): Expanded shale aggregate
    - o Expanded shale, clay, or slate (ESCS): Expanded clay aggregate
    - o Expanded shale, clay, or slate (ESCS): Expanded slate aggregate
    - o Foamed glass aggregate (FGA)
    - o Recycled glass aggregate (RGA)
    - o Tire-derived aggregate (TDA)
    - o Pumice
    - o Wood chips
    - o Air-cooled slag

- Boiler slag
- Fly ash
- Flowable fill: Controlled low-strength material (CLSM)
- Flowable fill: Controlled density fill (CDF)
- Lightweight cellular concrete (LLC)
- Other (please specify): _________

6. If you answered "Yes" to Question 1, what were the main reasons that prompted the use of lightweight fills? (Choose all that apply)
   - Reduce settlements
   - Improve stability on weak soils
   - Reduce lateral earth pressures
   - Reduce stresses on utilities
   - Other (please specify): _________
7. If you answered "Yes" to Question 1, approximately, how many structures have been constructed to date using lightweight fills in your state? (Please provide a range if you are unsure). __________
8. If you answered "No" to Question 1, did your agency use lightweight fills in the past and then discouraged using them?
   - Yes, and then discouraged using them
   - Yes, and stopped using them for no reason
   - No, lightweight fills were never used at my agency
9. Would you want to share any additional comments or suggestions with the research team? __________

Contact Information

- Date (MM/DD/YYYY): __________
- First name: __________
- Last name: __________
- Title: __________
- Agency/organization: _________
- City: __________
- State: _________
- Zip code: __________
- Email address: __________
- Phone number (XXX-XXX-XXXX): __________

Thank you for your participation! If you have any questions, please contact Amr Morsy at amr.morsy@utexas.edu

Detailed survey

Survey of the State of the Practice of Using Lightweight Fills in Transportation Projects

You are receiving this email and associated attachment because you have been identified as a state engineer that may be able to provide useful information to the Texas Department of Transportation (TxDOT) in support to an ongoing research project (project no. 0-7237) to synthesize the state of the practice of using lightweight fills in transportation projects.

The University of Texas at Austin is currently investigating the possible use of lightweight fills in the state of Texas. As a part of the research efforts, the attached survey is being distributed to all state DOTs to better understand the use of this technology throughout the United States. Your response to the attached survey will be greatly appreciated and will provide highly invaluable assistance to the research team.

Thank you for your participation! If you have any questions, please contact Dr. Amr Morsy at amr.morsy@utexas.edu

Best Regards,

Jorge G. Zornberg, Ph.D., P.E., BC.GE, F.ASCE
Professor and Joe J. King Chair in Engineering
The University of Texas at Austin

Section 1: Overview of Lightweight Fill Use at your Agency

1. Who in your agency typically has responsible charge for approving fill selections in embankment and wall projects in your state? (Choose all that apply)
    - Geotechnical engineers or equivalent at an agency-wide level
    - Geotechnical engineers or equivalent at a regional or district level
    - Structural engineers or equivalent at an agency-wide level
    - Structural engineers or equivalent at a regional or district level
    - Other (please specify): _________
2. What criteria does your agency use when considering fill alternatives? (Choose all that apply)
    - Cost-effectiveness
    - Environmental impact
    - Availability of materials
    - Transportation distance from fill source to project site
    - Engineering properties (e.g., mechanical, hydraulic, electrochemical)
    - Performance (e.g., settlement reduction, stability, drainability)
    - Construction time and feasibility
    - Maintenance requirements
    - Proximity to waterbodies, floodplains, or streams.
    - Other (please specify): _________
3. Have you identified poor performance or failure cases in your state?
4. What were the primary problems experienced with lightweight fills in the past?
    - Settlement issues
    - Erosion or scouring
    - Buoyancy problems
    - Water absorption problems
    - Crushing during compaction
    - Creep due to crushing
    - Other (please specify): _________
5. How were the problems in the previous question (if any) addressed?
6. Who in your agency principally manages/maintains fill structures such as embankments and retaining walls?
    - Geotechnical engineers or equivalent at an agency-wide level
    - Geotechnical engineers or equivalent at a regional or district level
    - Structural engineers or equivalent at an agency-wide level
    - Structural engineers or equivalent at a regional or district level
    - Maintenance engineers or equivalent at an agency-wide level
    - Maintenance engineers or equivalent at a regional or district level
    - Other (please specify): _________

7. How does the use of lightweight fills impact the life-cycle cost of MSE walls and embankments?
8. How often do MSE walls or embankments constructed with lightweight fills require maintenance?

Section 2(A): Design and Construction Practices of ESCS Fills at your Agency

9. Has ESCS been used by your agency? If yes, answer the following questions regarding design and construction with ESCS. If not, skip this section and move to Section 2(B).
   - o Yes
   - o No

A-1. Does your state have specific design and/or construction guidelines for ESCS fill applications?
- o Yes (please attach)
- o No
- o Under development.

A-2. If you answered yes to the previous question, check any of the following that address new design with lightweight fills within your agency? (Choose all that apply)
- o Design manuals
- o Standard drawings
- o Specifications
- o Inspection and maintenance
- o Recommended analysis methods and/or software
- o Other (please specify): _________

A-3. Does your agency require that ESCS follow any standards or specifications developed by your agency or other parties, such as other agencies or product manufacturers?
- o Yes (please specify)
- o No

A-4. Does your agency specify a range for target unit weight for ESCS fills?
- o Yes (please specify)
- o No

A-5. Does your agency consider buoyancy/uplift when designing with ESCS fills?
- o Yes (please specify)
- o No

A-6. What are the target ranges for the following properties of ESCS fills (if different from traditional fills)?
- o Shear strength (specify design parameters and their ranges): __________
- o Compressibility (specify design parameters and their ranges): __________
- o Creep (specify design parameters and their ranges): __________
- o Permeability (specify design parameters and their ranges): __________

A-7. Does your agency have specific design considerations for dynamic or live loads when using ESCS fills that differ from those for traditional fills?
- o Yes (please specify)
- o No

A-8. Does your agency have specific design considerations for lateral earth pressure when using ESCS fills in retaining structures and abutments that differ from those for traditional fills?
- o Yes (please specify)
- o No

A-9. How does foundation soil type affect ESCS fill designs?

A-10. How do you evaluate the following properties of ESCS fills?
- o Mechanical properties in the short and long terms (specify properties and their evaluation methods): _________
- o Hydraulic properties in the short and long terms (specify properties and their evaluation methods): ________
- o Electrochemical properties in the short and long terms (specify properties and their evaluation methods): _________

A-11. What challenges have you encountered when using ESCS fills? (Choose all that apply)
- o High costs
- o Limited availability of materials
- o Lack of expertise
- o Design/implementation issues
- o Other (please specify): _________

A-12. Does your agency consider long-term water absorption of ESCS fills in design?
- o Yes (please specify)
- o No

A-13. Does your agency specify a minimum slope at which ESCS fills have to be constructed?
- o Yes (please specify)
- o No

A-14. Does your agency specify a minimum cover thickness (if any) above ESCS fills?
- o Yes (please specify)
- o No

A-15. Does your agency specify compaction practices for ESCS fills that differ from those for conventional fills? If yes, please explain (include information about compaction lifts, equipment, compaction energy and passes, field compaction evaluation).
- o Yes (please specify)
- o No

A-16. Does your agency specify any special drainage systems when designing with ESCS that differ from those typically used with conventional fills?

- Yes (please specify)
- No

A-17. Does your agency limit ESCS fills placement in rainy or snowy conditions?

- Yes (please specify)
- No

A-18. Does your agency require wetting ESCS fills prior to use placement to allow the aggregate to become fully saturated and avoid segregation when handling?

- Yes (please specify)
- No

A-19. Does your agency specify any practices to limit crushing of ESCS fill particles during construction?

- Yes (please specify)
- No

A-20. Does your agency specify a minimum thickness between ESCS fills and roadway structures?

- Yes (please specify)
- No

A-21. Does your agency require separation between ESCS fills when placed adjacent to other soils?

- Yes (please specify)
- No

A-22. How does the construction time compare between ESCS fills and conventional fills?

A-23. How does the number of truckloads compare between ESCS fills and conventional fills?

A-24. How does the transportation cost compare between ESCS fills and conventional fills?

Section 2(B): Design and Construction Practices of FGA Fills at your Agency

10. Has FGA been used by your agency? If yes, answer the following questions regarding design and construction with FGA. If not, skip this section and move to Section 2(C).
    - Yes
    - No

B-1. Does your state have specific design and/or construction guidelines for FGA fill applications?
- Yes (please attach)
- No
- Under development.

B-2. If you answered yes to the previous question, check any of the following that address new design with lightweight fills within your agency? (Choose all that apply)
- Design manuals
- Standard drawings
- Specifications
- Inspection and maintenance
- Recommended analysis methods and/or software
- Other (please specify): _________

B-3. Does your agency require that FGA follow any standards or specifications developed by your agency or other parties, such as other agencies or product manufacturers?
- Yes (please specify)
- No

B-4. Does your agency specify a range for target unit weight for FGA fills?
- Yes (please specify)
- No

B-5. Does your agency consider buoyancy/uplift when designing with FGA fills?
- Yes (please specify)
- No

B-6. What are the target ranges for the following properties of FGA fills (if different from traditional fills)?
- Shear strength (specify design parameters and their ranges): __________
- Compressibility (specify design parameters and their ranges): __________
- Creep (specify design parameters and their ranges): __________
- Permeability (specify design parameters and their ranges): __________

B-7. Does your agency have specific design considerations for dynamic or live loads when using FGA fills that differ from those for traditional fills?

- Yes (please specify)
- No

B-8. Does your agency have specific design considerations for lateral earth pressure when using FGA fills in retaining structures and abutments that differ from those for traditional fills?

- Yes (please specify)
- No

B-9. How does foundation soil type affect FGA fill designs?

B-10. How do you evaluate the following properties of FGA fills?

- Mechanical properties in the short and long terms (specify properties and their evaluation methods): _________
- Hydraulic properties in the short and long terms (specify properties and their evaluation methods): ________
- Electrochemical properties in the short and long terms (specify properties and their evaluation methods): _________

B-11. What challenges have you encountered when using FGA fills? (Choose all that apply)

- High costs
- Limited availability of materials
- Lack of expertise
- Design/implementation issues
- Other (please specify): _________

B-12. Does your agency consider long-term water absorption (if any) of FGA fills in design?

- Yes (please specify)
- No

B-13. Does your agency specify a minimum slope at which FGA fills have to be constructed?

- Yes (please specify)
- No

B-14. Does your agency specify a minimum cover thickness (if any) above FGA fills?

- Yes (please specify)
- No

B-15. Does your agency specify compaction practices for FGA fills that differ from those for conventional fills? If yes, please explain (include information about compaction lifts, equipment, compaction energy and passes, field compaction evaluation).

- Yes (please specify)
- No

B-16. Does your agency specify any special drainage systems when designing with FGA that differ from those typically used with conventional fills?

- Yes (please specify)
- No

B-17. Does your agency specify any practices to limit crushing of FGA fill particles during construction?

- Yes (please specify)
- No

B-18. Does your agency specify a minimum thickness between FGA fills and roadway structures?

- Yes (please specify)
- No

B-19. Does your agency require separation between FGA fills when placed adjacent to other soils?

- Yes (please specify)
- No

B-20. How does the construction time compare between FGA fills and conventional fills?

B-21. How does the number of truckloads compare between FGA fills and conventional fills?

B-22. How does the transportation cost compare between FGA fills and conventional fills?

Section 2(C): Design and Construction Practices of TDA Fills at your Agency

11. Has TDA been used by your agency? If yes, answer the following questions regarding design and construction with TDA. If not, skip this section and move to Section 2(D).
    - o Yes
    - o No

C-1. Does your state have specific design and/or construction guidelines for TDA fill applications?
- o Yes (please attach)
- o No
- o Under development.

C-2. If you answered yes to the previous question, check any of the following that address new design with lightweight fills within your agency? (Choose all that apply)
- o Design manuals
- o Standard drawings
- o Specifications
- o Inspection and maintenance
- o Recommended analysis methods and/or software
- o Other (please specify): _________

C-3. Does your agency require that TDA follow any standards or specifications developed by your agency or other parties, such as other agencies?
- o Yes (please specify)
- o No

C-4. Does your agency specify a range for target unit weight for TDA fills?
- o Yes (please specify)
- o No

C-5. Does your agency consider buoyancy/uplift when designing with TDA fills?
- o Yes (please specify)
- o No

C-6. What are the target ranges for the following properties of TDA fills (if different from traditional fills)?
- o Shear strength (specify design parameters and their ranges): __________
- o Compressibility (specify design parameters and their ranges): __________
- o Creep (specify design parameters and their ranges): __________
- o Permeability (specify design parameters and their ranges): __________

C-7. Does your agency have specific design considerations for lateral earth pressure when using TDA fills in retaining structures and abutments that differ from those for traditional fills?
- o Yes (please specify)
- o No

C-8. How does foundation soil type affect TDA fill designs?

C-9. How do you evaluate the following properties of TDA fills?
- o Mechanical properties in the short and long terms (specify properties and their evaluation methods): _________
- o Hydraulic properties in the short and long terms (specify properties and their evaluation methods): ________
- o Electrochemical properties in the short and long terms (specify properties and their evaluation methods): _________

C-10. What challenges have you encountered when using TDA fills? (Choose all that apply)
- o High costs
- o Limited availability of materials
- o Lack of expertise
- o Design/implementation issues
- o Other (please specify): _________

C-11. Does your agency specify a minimum slope at which TDA fills have to be constructed?
- o Yes (please specify)
- o No

C-12. Does your agency specify a minimum cover thickness (if any) above TDA fills?
- o Yes (please specify)
- o No

C-13. Does your agency specify compaction practices for TDA fills that differ from those for conventional fills? If yes, please explain (include information about compaction lifts, equipment, compaction energy and passes, field compaction evaluation).
- o Yes (please specify)
- o No

C-14. Does your agency specify any special drainage systems when designing with TDA that differ from those typically used with conventional fills?
- o Yes (please specify)
- o No

C-15. Does your agency require preloading of TDA fills to minimize post-construction settlement due to TDA compressibility?
- o Yes (please specify)
- o No

C-16. Does your agency have a limitation on construction with TDA below groundwater table?

- Yes (please specify)
- No

C-17. Does your agency specify a minimum thickness between TDA fills and roadway structures?
- Yes (please specify)
- No

C-18. Does your agency require separation between TDA fills when placed adjacent to other soils?
- Yes (please specify)
- No

C-19. How does the construction time compare between TDA fills and conventional fills?

C-20. How does the number of truckloads compare between TDA fills and conventional fills?

C-21. How does the transportation cost compare between TDA fills and conventional fills?

Section 2(D): Design and Construction Practices of LCC Fills at your Agency

12. Has LCC been used by your agency? If yes, answer the following questions regarding design and construction with LCC. If not, skip this section and move to Section 2(E).
    - o Yes
    - o No

D-1. Does your state have specific design and/or construction guidelines for LCC fill applications?
- o Yes (please attach)
- o No
- o Under development.

D-2. If you answered yes to the previous question, check any of the following that address new design with lightweight fills within your agency? (Choose all that apply)
- o Design manuals
- o Standard drawings
- o Specifications
- o Inspection and maintenance
- o Recommended analysis methods and/or software
- o Other (please specify): _________

D-3. Does your agency require that LCC follow any standards or specifications developed by your agency or other parties, such as other agencies of providers?
- o Yes (please specify)
- o No

D-4. Does your agency specify a range for target unit weight for LCC fills?
- o Yes (please specify)
- o No

D-5. Does your agency consider buoyancy/uplift when designing with LCC fills?
- o Yes (please specify)
- o No

D-6. What are the target ranges for the following properties of LCC fills (if different from traditional fills)?
- o Compressive strength (specify design parameters and their ranges): __________
- o Compressibility (specify design parameters and their ranges): __________
- o Creep (specify design parameters and their ranges): __________
- o Permeability (specify design parameters and their ranges): __________

D-7. Does your agency have specific design considerations for lateral earth pressure when using LCC fills in retaining structures and abutments that differ from those for traditional fills?

- o Yes (please specify)
- o No

D-8. How does foundation soil type affect LCC fill designs?

D-9. How do you evaluate the following properties of LCC fills?

- o Mechanical properties in the short and long terms (specify properties and their evaluation methods): _________
- o Hydraulic properties in the short and long terms (specify properties and their evaluation methods): ________
- o Electrochemical properties in the short and long terms (specify properties and their evaluation methods): _________

D-10. What challenges have you encountered when using LCC fills? (Choose all that apply)

- o High costs
- o Limited availability of materials
- o Lack of expertise
- o Design/implementation issues
- o Other (please specify): _________

D-11. Does your agency specify a minimum cover thickness (if any) above LCC fills?

- o Yes (please specify)
- o No

D-12. Does your agency specify placement practices for LCC fills? If yes, please explain (include information about lift thickness, wait time between lifts, compaction energy and passes, field placement evaluation).

- o Yes (please specify)
- o No

D-13. Does your agency specify any special drainage systems when designing with LCC that differ from those typically used with conventional fills?

- o Yes (please specify)
- o No

D-14. Does your agency limit LCC fills placement in rainy, snowy, or high temperature conditions?

- o Yes (please specify)
- o No

D-15. Does your agency limit the use of LCC within frost zones?

- o Yes (please specify)
- o No

D-16. Does your agency allow the use of both premixed LCC and mixed on site LCC?

- o Yes (please specify)

- No

D-17. Does your agency specify a minimum thickness between LCC fills and roadway structures?
- Yes (please specify)
- No

D-18. Does your agency require separation between LCC fills when placed adjacent to other soils?
- Yes (please specify)
- No

D-19. How does the construction time compare between LCC fills and conventional fills?

D-20. How does the transportation cost compare between LCC fills and conventional fills?

Section 2(E): Design and Construction Practices of EPS Fills at your Agency

13. Has EPS been used by your agency? If yes, answer the following questions regarding design and construction with EPS. If not, skip this section.
    - o Yes
    - o No

E-1. Does your state have specific design and/or construction guidelines for EPS fill applications?
- o Yes (please attach)
- o No
- o Under development.

E-2. If you answered yes to the previous question, check any of the following that address new design with lightweight fills within your agency? (Choose all that apply)
- o Design manuals
- o Standard drawings
- o Specifications
- o Inspection and maintenance
- o Recommended analysis methods and/or software
- o Other (please specify): _________

E-3. Does your agency require that EPS follow any standards or specifications developed by your agency or other parties, such as other agencies of manufacturers?
- o Yes (please specify)
- o No

E-4. Does your agency specify a range for target unit weight for EPS fills?
- o Yes (please specify)
- o No

E-5. Does your agency consider buoyancy/uplift when designing with EPS fills?
- o Yes (please specify)
- o No

E-6. What are the target ranges for the following properties of EPS fills (if different from traditional fills)?
- o Compressive strength (specify design parameters and their ranges): __________
- o Compressibility (specify design parameters and their ranges): __________
- o Creep (specify design parameters and their ranges): __________
- o Permeability (specify design parameters and their ranges): __________

E-7. Does your agency have specific design considerations for lateral earth pressure when using EPS fills in retaining structures and

abutments that differ from those for traditional fills?
- Yes (please specify)
- No

E-8. How does foundation soil type affect EPS fill designs?

E-9. How do you evaluate the following properties of EPS fills?
- Mechanical properties in the short and long terms (specify properties and their evaluation methods): _________
- Hydraulic properties in the short and long terms (specify properties and their evaluation methods): ________
- Electrochemical properties in the short and long terms (specify properties and their evaluation methods): _________

E-10. What challenges have you encountered when using EPS fills? (Choose all that apply)
- High costs
- Limited availability of materials
- Lack of expertise
- Design/implementation issues
- Other (please specify): _________

E-11. Does your agency specify a minimum cover thickness (if any) above EPS fills?
- Yes (please specify)
- No

E-12. Does your agency specify placement practices for EPS fills? If yes, please explain (include information about operating equipment above EPS, UV exposure time, block orientation and layout)
- Yes (please specify)
- No

E-13. Does your agency specify any special drainage systems when designing with EPS that differ from those typically used with conventional fills?
- Yes (please specify)
- No

E-14. Does your agency limit the use of EPS within frost zones?
- Yes (please specify)
- No

E-15. Does your agency specify a minimum thickness between EPS fills and roadway structures?
- Yes (please specify)
- No

E-16. Does your agency specify design requirements to protect EPS against fire?
- Yes (please specify)
- No

E-17. Does your agency specify design requirements to protect EPS against gasoline spills?

- Yes (please specify)
- No

E-18. Does your agency consider long-term water absorption of EPS fills in design?
- Yes (please specify)
- No

E-19. Does your agency require separation between EPS fills when placed adjacent to other soils?
- Yes (please specify)
- No

E-20. How does the construction time compare between EPS fills and conventional fills?

E-21. How does the number of truckloads compare between EPS fills and conventional fills?

E-22. How does the transportation cost compare between EPS fills and conventional fills?

Appendix B. Construction Specification Guides for Lightweight Fills

Construction Specification Guide for ESCS Fills

ITEM ###
Expanded Shale, Clay, and Slate (ESCS) Lightweight Fill

1. DESCRIPTION

Furnish, place, and compact expanded shale, clay, or slate (ESCS) lightweight aggregate as engineered fill for embankments, structural excavation backfills, and earth retaining systems as shown on the project plans.

2. MATERIALS

2.1. Expanded Shale, Clay, or Slate (ESCS) aggregate
Provide ESCS aggregate manufactured by the rotary kiln process conforming to ASTM C330 and meeting the requirements in Table 1. Ensure the material is durable, with uniform density and free from deleterious matter.

Table 1
Physical Requirements for ESCS Lightweight Fill

Property	Test Method	Specification Limit
Soundness Loss ($MgSO_4$)	AASHTO T 104 or Tex-411-A	< 6%
Abrasion Resistance	ASTM C131 or Tex-410-A	< 40%
Durability Index	AASHTO T 210	> 35
Chloride Content	AASHTO T 291 or Tex-620-J	< 100 ppm (if applicable)
Sulfate Content	AASHTO T 290 or Tex-620-J	< 200 ppm (if applicable)
Organic Content	AASHTO T267 or Tex-148-E	< 1% (if applicable)
Resistivity	AASHTO T288 or Tex-129-E	> 3,000 ohm-cm (if applicable)
pH	AASHTO T 289 or Tex-128-E	5–10 (if applicable)
Gradation	ASTM C136 or Tex-401-A	100% passing 3/8 in.
Compacted In-Place Unit Weight (moist)	ASTM D698 or Tex-115-E*	≤ 70 pcf or accepted by the Engineer

*Note: Due to the cohesionless nature of coarse lightweight aggregates, the standard shall be modified as follows: The aggregate sample shall be placed in a 0.5 ft^3 bucket at the moisture content that the aggregate will be delivered to the jobsite. The sample shall be placed in three equal layers and compacted by dropping a 5.5-lb hammer from a drop height of 12 in., 25 times on each layer.

2.2. Geotextile Separator

Provide Type 1 filter fabric in accordance with DMS-6200, “Filter Fabric.” Install to fully encapsulate the engineered fill.

3. CONSTRUCTION

Provide a designated stockpile of engineered fill at the producer’s site and maintain it until accepted by the Engineer. The Engineer reserves the right to sample at any time. Stockpile fill, when necessary, in windrows or other configurations at designated locations. Keep the stockpile areas drained during the period of engineered fill removal and leave them in a neat condition when removal is complete.

Place the engineered fill in uniform lifts as shown on the project plans. Use suitable equipment to water and compact the material. Take all necessary precautions when working adjacent to the lightweight fill to ensure that the material is not over compacted. Do not operate construction equipment on exposed ESCS fill other than placement and compaction equipment.

Protect existing and previously installed elements including waterproofing, irrigation and drainage systems, and utilities during construction.

Install a minimum 6 in. layer of approved capping material (granular fill, concrete slab, or subbase). Place additional layers per project plan requirements to minimize long-term material degradation under live loads and to protect the fill from buoyancy/uplift during flood events. Protect the ESCS fill from stormwater inundation until overburden is placed.

4. MEASUREMENT

This Item will be measured by the cubic yard complete in place. This is a plans quantity measurement item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments of quantities are required.

5. **PAYMENT**

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for “Expanded Shale, Clay, or Slate Aggregate (Lightweight Fill).” This price is full compensation for testing, certification, loading, hauling, stockpiling, placing, rolling, labor, materials, tools, and incidentals.

Construction Specification Guide for FGA Fills

ITEM ###
Foamed Glass Aggregate (FGA) Lightweight Fill

1. DESCRIPTION

Furnish and place foamed glass aggregate (FGA) lightweight fill as engineered fill for embankments, structural excavation backfills, and earth retaining systems as shown on the project plans.

2. MATERIALS

2.1. Foamed Glass Aggregate (FGA)
Provide lightweight aggregate manufactured from a minimum of 98% recycled glass with a closed-cell structure and meeting the requirements in Table 1. Ensure the material is durable, with uniform density and free from deleterious matter.

Table 1
Physical Requirements for FGA Lightweight Fill

Property	Test Method	Specification Limit
Compacted In-Place Unit Weight (moist)	ASTM C29/C29M Method C	< 25 pcf or accepted by the Engineer
Compressive Strength	EN 1097-11	> 7,000 psf at 10% strain; > 15,000 psf at 20% strain
Friction Angle (ϕ)	AASHTO T236 or ASTM D3080	> 45° for normal stresses up to 1200 psf; > 38° for normal stresses up to 3000 psf
Gradation	ASTM C136 or Tex-401-A	100% passing 4"; 85–100% passing 2½"; 0–15% passing 3/8" or accepted by the Engineer
Soundness Loss ($MgSO_4$)	AASHTO T 104 or Tex-411-A	< 7% loss
pH	AASHTO T 289 or Tex-128-E	5–10

2.2. Geotextile Separator
Provide Type 1 filter fabric in accordance with DMS-6200, "Filter Fabric." Install to fully encapsulate the engineered fill.

3. CONSTRUCTION

Deliver material in bulk or super sacks. Minimize handling to reduce particle degradation. The Engineer reserves the right to sample at any time. Store fill, when necessary, at designated locations. Keep the storage areas drained during the period of engineered fill removal and leave them in a neat condition when removal is complete.

Place the engineered fill in uniform lifts, as shown on the project plans, not exceeding 24 in. for tracked equipment or 12 in. for plate compactors. Apply four full passes with tracked equipment exerting ground pressure 625–1025 psf. For confined areas, apply four full passes with a plate compactor weighing 110–220 lb. Take all necessary precautions when working adjacent to the lightweight fill to ensure that the material is not over compacted. Maintain uniformity and minimize material breakdown. Do not operate construction equipment on exposed FGA fill other than placement and compaction equipment.

Protect existing and previously installed elements including waterproofing, irrigation and drainage systems, and utilities during construction.

Install a minimum 6 in. layer of approved capping material (granular fill, concrete slab, or subbase). Place additional layers per project plan requirements to minimize long-term material degradation under live loads and to protect the fill from buoyancy/uplift during flood events. Protect the FGA fill from stormwater inundation until overburden is placed.

4. MEASUREMENT

This Item will be measured by the cubic yard complete in place. This is a plans quantity measurement item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments of quantities are required.

5. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for “Foamed Glass Aggregate (Lightweight Fill).” This price is full compensation for testing, certification, loading, hauling, stockpiling, placing, rolling, labor, materials, tools, and incidentals.

Construction Specification Guide for TDA Fills

ITEM ###
Tire-Derived Aggregate (TDA) Lightweight Fill

1. DESCRIPTION

Furnish and place tire-derived aggregate (TDA) lightweight fill as engineered fill for embankments, structural excavation backfills, and earth retaining systems as shown on the project plans.

2. MATERIALS

2.1. Tire-Derived Aggregate (TDA)
Provide TDA produced by shredding whole scrap tires. Hammer-milled tires are not permitted. Ensure material meets the grading requirements of Type A or B in Table 1 and complies with ASTM D6270. Use tires that have not been exposed to fire. Ensure the material is free of any deleterious materials or loose metal particles that are not firmly attached to the rubber shreds. Residual wire must be partially encased in rubber and must not pose a safety hazard. All TDA shreds must have at least one sidewall severed from the face of the tires.

Table 1
Physical Requirements for TDA Lightweight Fill

Property	Specification Limit	
	Type A	Type B
% passing 12 in. sieve	100%	100%
% passing 8 in. sieve	100%	75–100%
% passing 4 in. sieve	100%	–
% passing 3 in. sieve	95–100%	0–85%
% passing 1½ in. sieve	0–70%	0–25%
% passing No. 4 sieve	0–5%	0–1%
Free steel fragments	< 1% by weight	< 1% by weight
Longest shred	10 in.	18 in.
Wire protrusions (>2 in.)	< 10% by weight	< 10% by weight
Wire protrusions (>1 in.)	< 25% by weight	< 25% by weight

2.2. Geotextile Separator
Provide Type 1 filter fabric in accordance with DMS-6200, "Filter Fabric." Install to fully encapsulate the engineered fill.

3. CONSTRUCTION

Deliver and stockpile engineered fill, when necessary, at designated locations approved by the Engineer. The Engineer reserves the right to sample at any time. Keep the stockpile areas drained during the period of engineered fill removal and leave them in a neat condition when removal is complete.

Place the engineered fill in uniform lifts, as shown on the project plans, not exceeding 12 in. (loose thickness). Limit vertical TDA fill thickness to 10 ft between intermediate soil layers. For thicker embankments, alternate with minimum 2 ft compacted soil layers. Avoid segregation during placement. Compact each lift using a minimum of six passes of tracked dozer or smooth drum roller (min. 20,000 lb. static weight). Avoid direct exposure to heavy equipment or excessive compression. Do not compact TDA with pneumatic or vibratory plate compactors.

Avoid placement below the water table. Do not place adjacent to open drains or structures unless approved. Prevent infiltration of water and air with geomembrane or geotextile, as necessary. If left exposed during construction, place a temporary soil cover.

Protect existing and previously installed elements including waterproofing, irrigation and drainage systems, and utilities during construction.

TDA fill shall be covered with a minimum 3 ft encasement material. Install a minimum 5 ft layer of approved capping material above the TDA fill and a minimum of 3 ft layers on the sides. Place additional layers per project plan requirements to minimize long-term material degradation under live loads and to protect the fill from buoyancy/uplift during flood events. Protect the TDA fill from stormwater inundation until overburden is placed.

4. MEASUREMENT

This Item will be measured by the cubic yard complete in place. This is a plans quantity measurement item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments of quantities are required.

5. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for “Tire-Derived Aggregate (Lightweight Fill).” This price is full compensation for testing, certification, loading, hauling, stockpiling, placing, rolling, labor, materials, tools, and incidentals.

Construction Specification Guide for LCC Fills

ITEM ###
Lightweight Cellular Concrete (LCC) Lightweight Fill

1. DESCRIPTION

Furnish and place lightweight cellular concrete (LCC) lightweight fill as engineered fill for embankments, structural excavation backfills, and earth retaining systems as shown on the project plans.

2. MATERIALS

Produce LCC as a homogeneous mixture of Portland cement, water, and preformed foam, with or without supplementary cementitious materials and admixtures. Do not include coarse aggregates. Use only equipment and processes approved by the foam manufacturer. LCC shall meet the density and compressive strength ranges in Table 1, unless otherwise shown on the plans.

2.1. Cementitious Components
Provide Portland Cement Type I, II, or IL per ASTM C150.
Provide Fly Ash (if used) Class C or F per ASTM C618.
Provide Slag Cement (if used) per ASTM C989.
Provide clean, potable water free of deleterious substances.

2.2. Foam and Admixtures
Provide foaming agent per ASTM C869, tested per ASTM C796.
Provide admixtures per ASTM C494 and only if compatible with foam system and approved by the foam and LCC manufacturer.

Table 1
Physical Requirements for LCC Lightweight Fill

Class	As-Cast Density (pcf)	Min. 28-Day Compressive Strength (psi)
I	30 ± 2	40
II	36 ± 2	80
III	42 ± 2	120
IV	50 ± 2	150

3. EQUIPMENT

Use specialized mobile batch plants capable of proportioning, mixing, and pumping cellular concrete. Equipment must be calibrated and approved by the foam manufacturer. Do not use transit mixers for blending foam and slurry.

4. CONSTRUCTION

Prepare the subgrade free of debris, soft soil, standing water, ice, or snow. Do not place on frozen ground or in active precipitation. Place LCC in lifts no more than 2.5 ft thick, unless otherwise directed. Avoid segregation. Do not vibrate or rod the material. Stagger vertical joints a minimum of 10 ft. Final surface shall be within ±0.1 ft of plan elevation. Do not place more than 3 lifts in a 96-hour period without Engineer approval. Do not allow construction traffic on LCC until compressive strength meets specified requirements. Protect LCC from excessive moisture loss. Do not apply load, backfill, or surcharge until the LCC has achieved a minimum compressive strength of 16 psi, or as shown on the plans.

5. QUALITY CONTROL

Test first batch each day and every 2 hours thereafter per ASTM C796. Use average of two measurements. Sample per ASTM C495. Mold a minimum of four 3"x6" cylinders per 200 cu yd or once every 4 hours. Test at 7 and 28 days. Do not oven dry prior to testing. Average of two strength tests per lot must meet minimum 28-day strength. Wet density results must fall within class-specified range. Failure to meet either criterion may result in removal or price adjustment at Engineer discretion.

6. MEASUREMENT

This Item will be measured by the cubic yard complete in place. This is a plans quantity measurement item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments of quantities are required.

7. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for “Lightweight Cellular Concrete.” This price is full compensation for material, mixing, transporting, placing, testing, protection, and all labor, equipment, tools, and incidentals.

Construction Specification Guide for EPS Fills

ITEM ###
Expanded Polystyrene (EPS) Lightweight Fill

1. DESCRIPTION

Furnish and place Expanded Polystyrene (EPS) geofoam blocks as lightweight fill for embankments, structural excavation backfills, and earth retaining systems as shown on the project plans.

2. MATERIALS

2.1. EPS Geofoam
Provide EPS in accordance with ASTM D6817 and with physical properties as shown in Table 1. Ensure that EPS meet the following:

- Fabricated from virgin feedstock with ≤5% regrind.
- Fabricated with required flame-retardant additive (UL fire certification required).
- Cured at least 24 hours before delivery.
- Treated for termite resistance per ICC AC239.
- Each block must be labeled with manufacturer, date, type, density, and compliance signature.

Table 1
Physical Requirements for EPS Lightweight Fill

Property	Test Method	Minimum Requirement
Density	ASTM D1622	1.8 – 2.4 pcf
Compressive Resistance at 1% Strain	ASTM D1621	≥ 10.9 – 15.0 psi
Flexural Strength	ASTM C203	≥ 50 – 60 psi
Oxygen Index	ASTM D2863	≥ 24%
Water Absorption (by Volume)	ASTM C272	≤ 2%
Elastic Modulus	ASTM D1621	≥ 1090 – 1500 psi

2.2. Connectors
Use galvanized or stainless-steel multi-barbed plates. Each plate must provide >60 lb. lateral strength with a safety factor of 2. Place minimum 2–3 connectors per 4' × 8' panel.

2.3. Geomembrane
Install hydrocarbon-resistant, flexible geomembrane over all EPS surfaces, with properties shown in Table 2.

Table 2
Requirements for Geomembrane

Property	Test Method	Requirement
Thickness	ASTM D751	> 28 mils
Gasoline Vapor Transmission	ASTM D814	< 0.4 oz/ft²/24 hr.
Grab Tensile Strength	ASTM D751	> 600 lb. (both machine and cross directions)
Elongation at Break	ASTM D751	> 20%
Puncture Resistance	ASTM D751 (ball tip)	> 800 lb.
Cold Crack Resistance	ASTM D2136 (1 in. mandrel, 4 hr.)	Pass -30°F
Factory Seam Bond Width	–	> 2 in.
Shear	ASTM D751 (modified per National Sanitation Foundation Std. No. 54)	> 320 lb., fail in sheet

3. CONSTRUCTION

Clear debris, dewater area, and prepare subgrade to ±0.5% tolerance. Install drainage systems and utilities before placing EPS. Place EPS tightly with staggered joints; rotate alternate layers by 90°. Do not allow more than 0.07 ft vertical gaps; surface flatness ≤0.05 ft over 10 ft. Trim blocks as needed using hot-wire tools. Protect blocks from UV, solvents, and vehicle traffic. Use sand bedding. Use a minimum of 2–3 connectors per 4' x 8' panel, or as shown on the plans. Press connector flush into EPS before placing the next layer. Correct damage to EPS as follows:

- Slight Damage (<0.12 ft^3 with no linear dimension greater than 1 ft): Leave in place.
- Moderate Damage (<0.35 ft^3 with no linear dimension greater than 3.3 ft): Fill with sand.
- Excessive Damage: Replace or cut to remove damaged portion.

Drape geomembrane over all exposed EPS surfaces. Cover with 3 in. of protective sand layer before placing overlying fill. Do not allow construction equipment to contact geomembrane directly.

4. MEASUREMENT

This Item will be measured by the cubic foot quantity of expanded polystyrene. This is a plans quantity measurement item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments of quantities are required.

5. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under "Measurement" will be paid for at the unit price bid for “Geofoam Fill.” This price is full compensation for material, mixing, transporting, placing, testing, protection, and all labor, equipment, tools, and incidentals.