Foamed Glass Aggregate Lightweight Fill Over Compressible Soils

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ABSTRACT
Ultra-lightweight foamed glass aggregate (UL-FGA) may now be considered as a lightweight and insulating fill material for use in the construction of retaining structures, embankments, bridge abutments, and foundation slabs in North America. This granular material has dry bulk densities ranging from 130 – 240 kg/m^3 (8 – 15 lb/ft^3) and a closed cell structure which provides good insulation properties and minimal water absorption. UL-FGA is made from 100% recycled glass and is a sustainable, closed-loop product that has a favorable energy footprint when compared to other lightweight fill options. This paper covers the history and development of foamed glass aggregate and the physical and engineering properties of the material that are needed for design. Additionally, three projects where UL-FGA has been used over soft, compressible soils are described.

RÉSUMÉ
L'agrégat de verre expansé ultra-léger (UL-FGA) peut maintenant être considéré comme un matériau de remplissage léger et isolant pour la construction de structures de soutènement, de digues, de culées de ponts et de dalles de fondation en Amérique du Nord. Ce matériau granulaire a des densités apparentes sèches allant de 130 – 240 kg/m^3 (8 à 15 lb/ft^3) et une structure à alvéoles fermées qui offre de bonnes propriétés d'isolation et une absorption minimale de l'eau. UL-FGA est composé à 100% de verre recyclé. Il s'agit d'un produit durable, en boucle fermée qui présente une empreinte énergétique favorable par rapport aux autres options de remblais légers. Ce l'histoire et le développement des agrégats de verre expansé et. les propriétés physiques et techniques du matériau essentielles à la conception. En outre, trois projets où UL-FGA a été utilisé sur des sols mous et compressibles sont présentés.

1 INTRODUCTION

Lightweight fill is a commonly-used approach to mitigate the presence of soft, compressible soils or utilities that are sensitive to additional load. Often, lightweight fill will replace traditional soil or aggregate on these projects so that settlements are reduced, utilities are protected from damage, or driving forces on walls or slopes are reduced. Various types of lightweight fill are available in today's North American marketplace and these fill materials include geofoam, expanded shale, clay, or slate lightweight aggregate, foamed concrete, shredded tires, and now, ultra-lightweight foamed glass aggregate (UL-FGA). These lightweight materials span a range of unit weights and have strengths and weaknesses related to recycled content and sustainability factors, durability, chemical compatibility, flammability, buoyancy, permeability, installation difficulty and duration, availability, and economics.

Foamed glass aggregate was first produced and utilized on a commercial scale in Norway in the early 1990s driven by a cold climate a geology that has soils susceptible to frost-heave and quick clays. Currently, there are over a dozen sites producing UL-FGA in Scandinavia and central Europe.

2 UL-FGA PRODUCTION AND INSTALLATION

The production of UL-FGA begins with obtaining glass or glass cullet (see Figure 1), typically from a materials recovery facility (MRF) or a glass processor. The glass must be dried and cleaned to remove impurities and then very finely ground. Once it is a fine powder, it is then mixed with a foaming agent such as silica carbide (Aabøe and Øiseth, 2004). This glass powder and foaming agent mixture travels through a high-temperature furnace on a steel belt whereby it expands (Aabøe et al., 2005). After leaving the furnace, the foam glass cake cracks into small fragments due to temperature shock (Zegowitz, 2010).

Figure 1. Cleaned recycled glass cullet used in the production of UL-FGA.

Some of the foamed glass aggregate production in Europe was initiated to address waste glass from contaminated and toxic sources such as light bulbs, mercury lamps, windowpanes, car windshields, computer and television monitors, and industrial slag and fly ash. During the grinding process, the heavy metals are removed from the cullet and likewise recycled (Aabøe and Øiseth, 2004). Foamed glass aggregate production in the U.S. does not use contaminated waste glass; rather, the feedstock is sourced from curbside-collected (thus, post-consumer) container glass.

Foamed glass aggregate has been manufactured in North America since early 2017. Figure 2 shows a standard product marketed for geotechnical applications. To manufacture one cubic meter (1.31 cubic yards) of foamed glass aggregate, the equivalent of approximately 1,000 standard-sized glass bottles are used. Delivered costs to Canada are anticipated to be \$100 USD/m^3 and higher and will be greatly influenced by the project location.

Figure 2. Foamed glass aggregate manufactured by AeroAggregates of North America. Note the permanent marker in the photo for scale.

Standard compaction procedures for soils and traditional aggregates should not be applied to UL-FGA. The compaction procedures recommended by manufacturers are intended to limit the potential for over-crushing of the UL-FGA. Over-crushing would negatively impact the in-place unit weight. Standard installation procedures from various manufacturers of UL-FGA cite large maximum lift thicknesses (between 0.6 to 1.0 m) [2 and 3.3 ft]. For standard load-bearing applications (i.e. under roadways) a compression ratio of between 1.15 and 1.25 is typically recommended. A compression ratio of 1.25 corresponds to 20% compaction of each (uncompacted) lift.

The equipment that is typically used to compact UL-FGA is tracked equipment with ground pressures between 30 - 50 kPa (625 - 1,025 psf). This equipment, typically an excavator or dozer, will complete two to four passes over the UL-FGA layer to reach a compression ratio of 1.25. Compaction occurs by the static and dynamic forces imparted by the tracked equipment and will produce slight particle breakage but good particle interlock. In areas not accessible to tracked equipment, thinner lifts of 0.3 to 0.6 m (12 to 24 inches) can be compacted using a 50-100 kg (110-220 lbs) plate compactor. Unless higher degrees of compaction are required, static or vibratory rollers are not recommended to be used for the compaction of UL-FGA.

Because UL-FGA is an open-graded aggregate, typical CQA procedures for soil compaction (i.e., nuclear density gauge testing) are not applicable. Instead, observance and verification of the method based-specification for UL-FGA compaction is required.

A non-woven geotextile should be used as a separator where UL-FGA is in contact with other granular materials to prevent the migration of smaller particles into the UL-FGA layer over time. UL-FGA is stable and easily installed at a 1H:1V slope; however, the cover material must also be stable at this angle for a durable design (e.g. rip rap). Otherwise, a slope stabilization system may be used or cover soil may be graded out at flatter slope.

3 UL-FGA PROPERTIES

3.1 Unit Weight, Buoyancy, Moisture Content, Gradation

The design unit weights associated with UL-FGA encompasses a relatively small range and the design value for a particular project should be selected based on the intended application and site conditions. Dry unit weights for foamed glass aggregate varies between 130 – 240 kg/m^3 (8 – 15 lb/ft^3), although UL-FGA for infrastructure uses tends to be at the upper end of this range. Design unit weights should also account for residual adsorbed moisture, typically on the order of 6% by volume if material is stockpiled outside.

For closed-cell UL-FGA, the individual particles are composed of a glass matrix that surrounds trapped air bubbles, making the material buoyant even under long-term conditions. As such, care should be taken during design and construction to provide proper ballast (overburden weight from soils and concrete or asphalt above the UL-FGA) in the event of a flood.

The nominal particle size for UL-FGA is 10 to 60 mm (0.375 to 2.5 inches) with up to 15 percent by weight finer and coarser than these limits. Prior to and after compaction, UL-FGA classifies as a poorly graded gravel (GP) based on the Unified Soil Classification System. Figure 3 depicts the grain size distribution curves for samples collected during active UL-FGA installation. The porosity of uncompacted material has been shown to be approximately 0.5, but even after compaction, the porosity remains high enough (>0.35) to provide a very free-draining, highly permeable layer on the order of k > 1 cm/s (k > 0.03 ft/s).

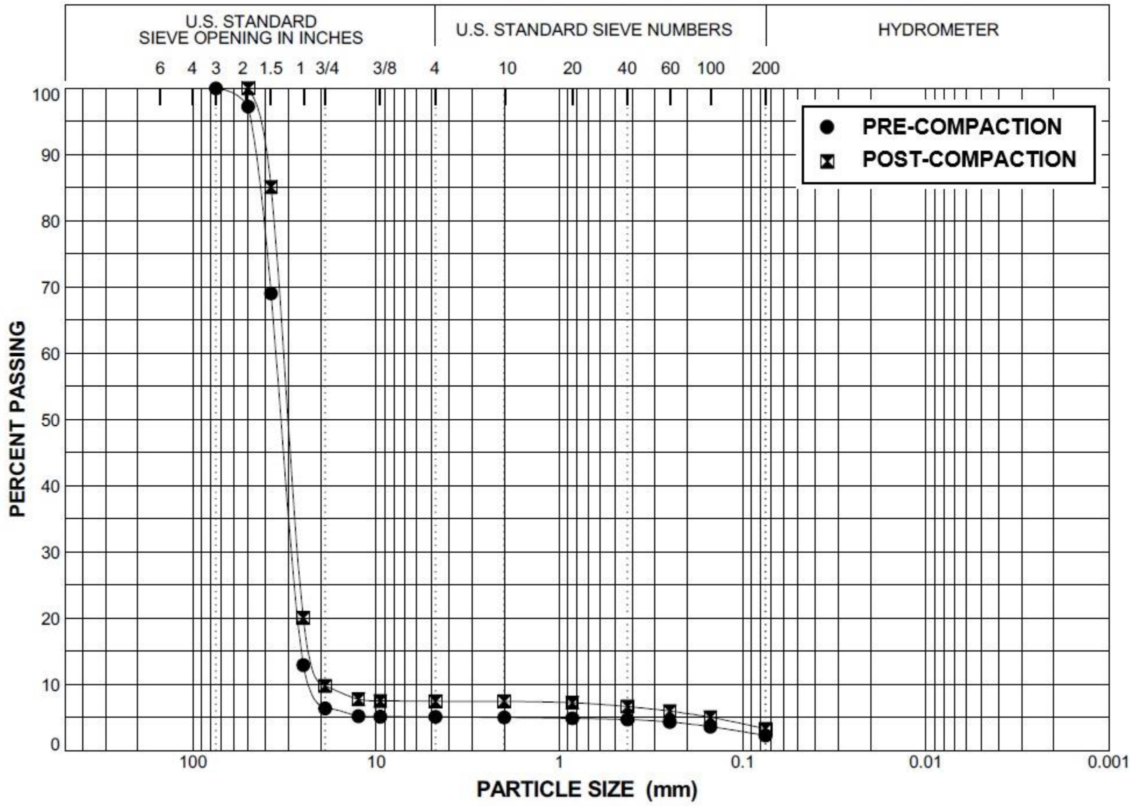


Figure 3. UL-FGA grain size distribution curves pre- and post-in field compaction from the Route 7 project in Kearny, NJ.

3.2 Shear Strength and Pullout Testing

The highly frictional surface of UL-FGA and the angularity of the particles produces a very high internal friction angle (55°) at confining stresses of 57.5 kPa (1,200 psf) and lower (Arulrajah et al., 2015b). This angle will decrease to approximately 40° at higher normal stresses (144 kPa [3,000 psf]) and thus, has a similar or higher friction angle compared to typical natural aggregate materials.

Since a popular application area for lightweight fill has been use as a backfill material in retaining structures, including all types of mechanically stabilized earth (MSE) designs, full-scale pullout testing per ASTM D6706, Standard Test Method for Measuring Geosynthetic Pullout Resistance in Soil has been completed to evaluate the interaction of UL-FGA with various types of reinforcement. To date, UL-FGA, in combination with metal and synthetic straps and uniaxial and biaxial geogrids, has been investigated (Loux et al., 2019). This testing yielded results within normal ranges for the reinforcement types and aggregate with similarly-sized particles to UL-FGA. An MSE structure can be designed using the pullout testing results for any of the reinforcement materials that were evaluated.

3.3 Modulus and Creep

The elastic modulus for UL-FGA will vary based on the overlying, adjacent, and underlying layers, but is estimated to range from 50 to 70 MPa (525 to 725 tons per square foot [tsf]) or possibly greater from plate load or lightweight deflectometer (LWD) testing (Betti et al., 2014). The resilient modulus of UL-FGA will vary based on the confining stress conditions. Values are reported between 75-150 MPa (775 and 1,550 tsf).

Creep of UL-FGA is possible if static and dynamic loads are not properly considered. In practical terms, flexible pavement systems will require a certain distance between the top of pavement and top of UL-FGA layer to stay within the dynamic load threshold. As a result, UL-FGA is not a suitable replacement for natural stone subbase in flexible pavement systems.

A linear-elastic analysis can be completed using a project-specific cross section, loading conditions, and the material properties for the asphalt and subgrade layers present. These analyses may result in an increased thickness of stone subbase, inclusion of a geogrid or geocell reinforcement layer, or a concrete load distribution slab on top of the UL-FGA layer to minimize dynamic loads.

Also, because of similar concerns, UL-FGA is typically not recommended for use directly under footings for highway structures or building foundations.

3.4 Durability, Compatibility, and Thermal Conductivity

The resistance of aggregates to weathering via wetting/drying and freezing/thawing cycles is evaluated for aggregates in various applications including roadway subbase and retaining wall backfill and is especially critical for moderate climates. Closed-cell, foamed glass aggregate has been tested for durability via magnesium sulfate and sodium sulfate testing and freeze/thaw testing (Zegowitz, 2010, Aabøe et al., 2005, Skogstad et al., 2005). UL-FGA meets the durability requirements for MSE backfill per AASHTO's Standard Specifications for Highway Bridges (Loux et al., 2019). The first infrastructure projects utilizing UL-FGA were completed in Scandinavia in the mid-1990s, and no known performance issues have been reported.

UL-FGA is considered fireproof and does not react to fire (Zegowitz, 2010). Because UL-FGA was developed using contaminated recycled glass, there has been extensive testing regarding the leachability of contaminants from the finished product. Several papers report that leaching products from the material are well below the allowable limits for clean fill (Frydenlund and Aabøe, 2003, and Arulrajah et al., 2015a).

UL-FGA is often utilized as an insulator under foundation slabs and in green roof systems, or to protect against frost-heave in roadway embankments. In the design of these applications, the thermal conductivity of compacted UL-FGA can be used or converted to a R-value or U-value based upon a compacted thickness. The reported thermal conductivity for foamed glass aggregate from various manufacturers varies between 0.075-0.11 W/mK (0.044-0.064 Btu/[hr·ft·°F]) for dry material and 0.11-0.14 W/mK (0.064-0.081 Btu/[hr·ft·°F]) for moist material.

4 APPLICATION AREAS

UL-FGA may provide a lightweight or insulating fill solution in many applications within infrastructure, and commercial and residential building construction. In all application areas, it will be necessary to provide a proper drainage design to outlet any water away from the UL-FGA layer and avoid forming water-collecting depressions

4.1 Infrastructure

Application areas for UL-FGA within infrastructure projects are shown in Figure 4. These areas include settlement mitigation; load reduction over sensitive utilities; free-draining and highly frictional backfill in retaining wall systems to reduce lateral loads; and frost-heave prevention. A typical asphalt pavement section is shown in Figure 5. UL-FGA has further advantages for infrastructure projects that utilize the EnvisionTM (Institute for Sustainable Infrastructure) or similar rating systems.

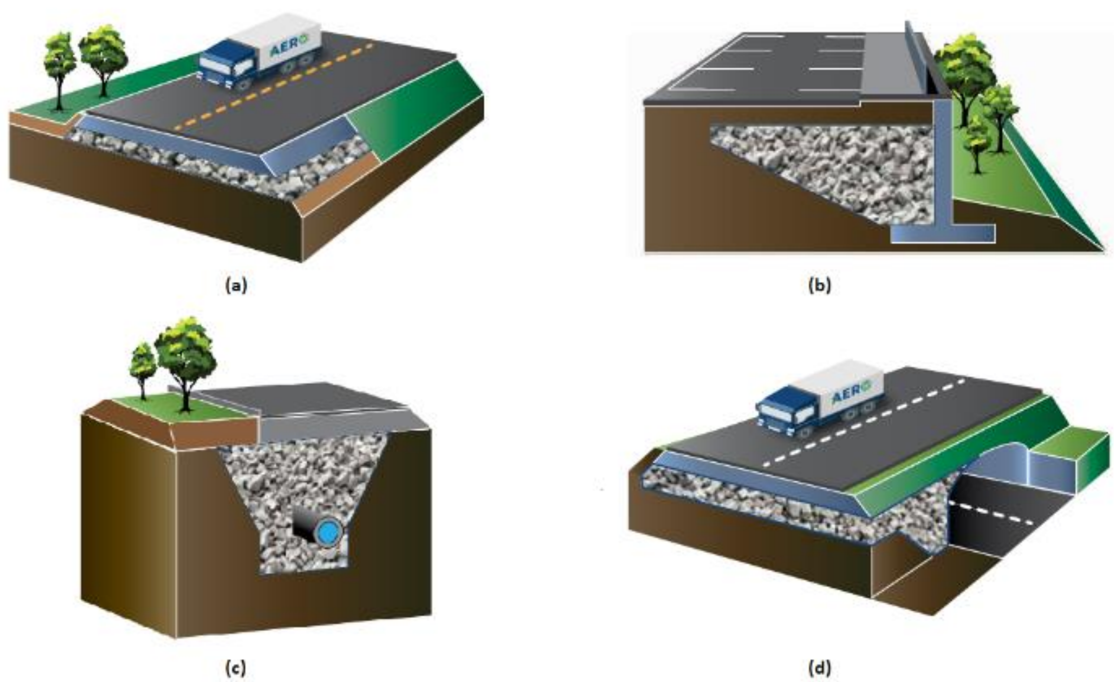


Figure 4. UL-FGA application areas on infrastructure projects include (a) in embankments, (b) retaining walls, (c) around and over utilities, and (d) around and over culverts and tunnels.

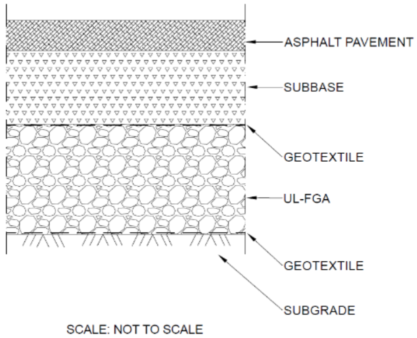


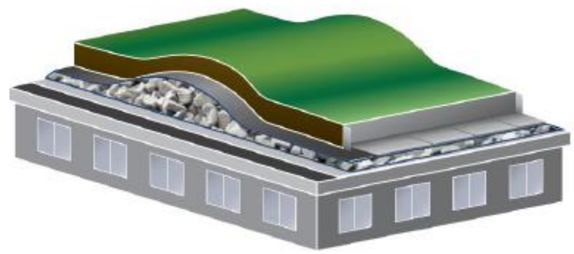
Figure 5. Typical Asphalt Pavement Section

4.2 Building Construction

Application areas for UL-FGA within residential and commercial building projects can be seen on Figure 6 and include settlement mitigation under slabs; rodent- and insect-resistant insulation and drainage under concrete slabs or around basement walls; insulation and drainage in green roof or elevated patio systems, and frost-heave prevention under slabs or footings. Figure 7 shows a typical cross section for under a concrete slab. In addition, most buildings that use a sustainable construction rating system such as LEED (U.S. Green Building Council) during the design process will benefit from the inclusion of UL-FGA manufacturers from 100% post-consumer recycled glass.

Another potential aspect of UL-FGA utilization in building construction can be seen in relation to the design of ice walls. Typically, the footing depth for structures must extend beyond the frost depth; for structures on grade, this can result in a sizeable and expensive ice wall (see Figure 8(a). The alternative system using UL-FGA is shown in Figure 8(b). UL-FGA will extend beyond the footprint of the building to provide protection against freezing of the subsoil and thus, prevent any instability and damage of the structure. The length that the insulation must extend beyond the building footprint will be related to climatic conditions.


(a)


(b)


(c)

Figure 6. UL-FGA for building construction as lightweight, insulating, and free-draining fill (a) under foundation slabs or around basement walls, (b) in green roof systems, (c) in elevated plaza deck systems.

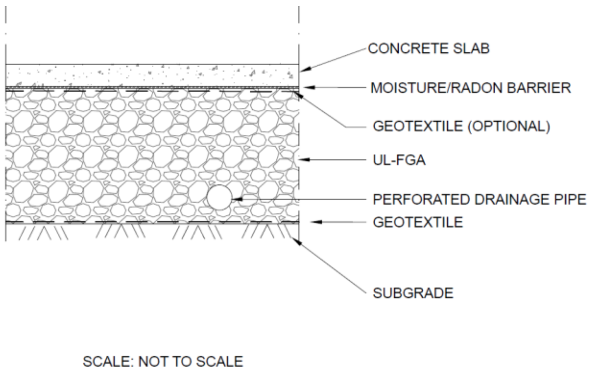


Figure 7. UL-FGA under slab insulation detail

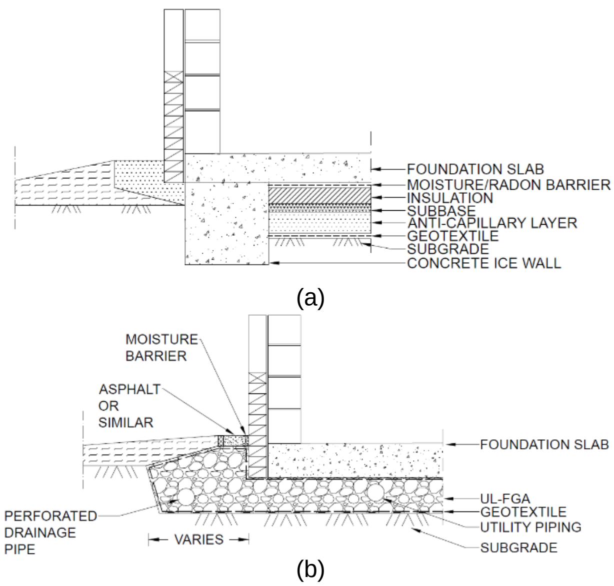


Figure 8. Ice wall detail (a) without UL-FGA, and (b) with UL-FGA

5 CASE STUDIES

5.1 Langley Avenue

The Philadelphia Navy Yard has undergone a significant transformation since the U.S. Navy gave up ownership of the yard in 2000. The Philadelphia Industrial Development Corporation (PIDC) acts as the master developer for the Site which encompasses 485 ha (1,200 acres) and provides commercial workspace to over 150 companies and 13,500 employees. Committed to smart energy innovation and sustainability including LEED certified development, the area has been undergoing improvements for more than a decade, except for one road. Langley Avenue is the main corridor between the Navy Yard's main entrance on South Broad Street and the Girard Point Commerce Center on South 26th Street. Enhancing the Langley Avenue corridor promotes the redevelopment of the existing buildings and the development of new structures in this area of the Navy Yard.

The Navy Yard is located at the confluence of the Delaware and Schuylkill Rivers and is partially within the 100-year floodplain. Newly-completed flood plain delineations have considered recent extreme weather events including Hurricane Sandy which severely impacted the Northeast U.S. As a result, the flood elevations have been increased in many areas, and subsequent design and construction projects must consider these higher elevations to provide more resilient infrastructure in the wake of more frequent and extreme weather.

UL-FGA was used as roadway fill along a portion of the Langley Avenue roadway alignment to minimize settlement of the existing weak soil and to maintain vehicular traffic along the existing roadway while the new road was constructed. The maximum thickness of UL-FGA was approximately 0.91 m (3 feet). This was the first usage of UL-FGA for an infrastructure project in the United States.

This Philadelphia Industrial Development Corporation (PIDC)-sponsored project received federal funding and proceeded through the PennDOT design and construction process. The project was designed in accordance with City of Philadelphia and PennDOT standards by Pennoni Associates and was developed to reflect the history and context of the Navy Yard in accordance with the Programmatic Agreement in place between the US Navy and the Pennsylvania Historic Preservation Office.

Construction of the new roadway commenced in Fall 2017. Reports of roadway performance to date have been favorable as anticipated. Figure 9 shows the site during construction.

Figure 9. Construction of Langley Avenue in Philadelphia, PA during placement and compaction of UL-FGA

5.2 Route 7 Wittpenn Bridge

The Route 7 Wittpenn Bridge project is located within Jersey City, NJ, and Kearny, NJ. This route crosses over the Hackensack River and is a major connector for New York City and the surrounding area. The existing bridge is a vertical lift bridge built in 1930 and is structurally deficient. The new vertical lift structure will have improvements including an auxiliary lane, right shoulders in each direction, a sidewalk to accommodate pedestrian and bicycle traffic, a left shoulder and median to separate opposing traffic, and an increased vertical clearance above the mean high water elevation.

The New Jersey Department of Transportation (NJDOT) divided construction into five separate contracts. Contract 4, awarded in 2017 to George Harms Construction Company Inc. (GHCCI), includes the construction of the final bridge and approach roadway segments of the new vertical lift bridge as well as various interchange improvements and utility relocations. With the proximity of this project to the Hackensack River, Contract 4 included both lightweight aggregate (expanded shale) and geofoam in sections of the improved roadway because of poor subsoil conditions, the likelihood of settlement, and time and space constraints. GHCCI submitted a value engineering proposal to NJDOT to substitute UL-FGA for a majority of the lightweight fill specified in the design of Contract 4. For the expanded shale areas, the cost-savings to the owner and contractor was primarily due to reduced excavation and a net decrease in the amount of lightweight fill required. For the geofoam areas, the cost-savings was primarily due to the substitution of geofoam with UL-FGA, the elimination of the fuel-resistant geomembrane and load-distribution slab. Figure 10 shows a picture of the UL-FGA construction for this project. The total anticipated quantity of UL-FGA is approximately 21,500 m^3 (28,000 cubic yards).

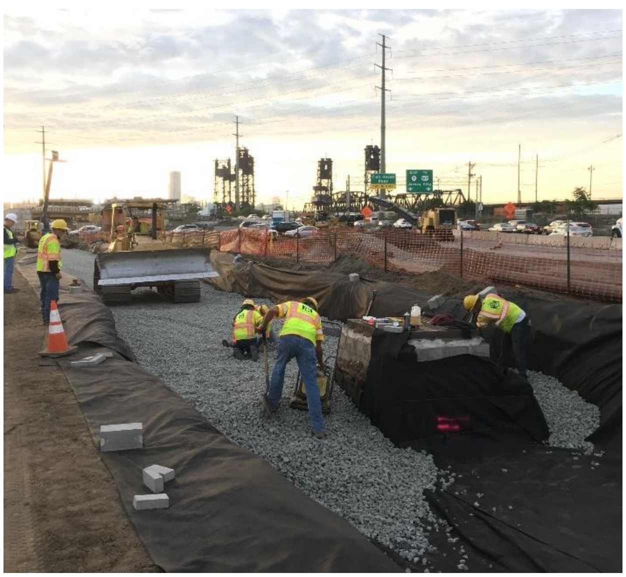


Figure 10. Construction of Route 7 in Kearny, NJ. Note the reduced lift thickness and plate compactor around the inlet.

5.3 Starrett-Lehigh Building

The Starrett-Lehigh Building encompasses a fill city block between 11th and 12th Avenues and 26th and 27th Streets on the lower west side of Manhattan in New York City. The building was originally completed in 1931 and is considered to be an example of International Style in architecture with its vast size, curtainwall construction, and strong lines created by red brick, concrete, and glass surfaces. The Starrett-Lehigh was designated a New York City landmark in 1986.

Today, the Starrett-Lehigh is part of the West Chelsea Historic District and the workplace of more than 5,000 people each day.

RXR Reality, the owner and operator of the Starrett-Lehigh, undertook a project to renovate first floor parking areas into new commercial space. Part of this design involved demolition of the existing concrete and the placement of fill to raise the slab elevation by approximately 0.6 to 0.9 m (2 to 3 feet). Because of the proximity of the building to the Hudson River, the subsoil had significant potential for settlement under the increased load of the fill and new slab. UL-FGA lightweight fill was selected primarily because of its cost and ease of placement and was installed in stages over approximately six months in 2018. Figure 11 depicts UL-FGA construction at this site.

Figure 11. Construction of UL-FGA at the Starrett-Lehigh Building in Manhattan. The area to the right is compacted and ready for slab construction.

6 CONCLUSION

Foamed glass aggregate for use as lightweight fill has been approved by multiple transportation authorities in the U.S., including many State DOTs, buoyed by greater than 20 years of successful use of the product in Europe. While the low unit weight of UL-FGA was the primary beneficial characteristic in the three case studies described, UL-FGA is also a good insulator, highly frictional, non-leaching, volume stable, and free-draining. As a material made from 100% post-consumer recycled glass, UL-FGA is a sustainable material that is also technically-sound and economically-feasible and is now an available lightweight and insulating fill option for engineers and contractors in North America.

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