GEOTECH

Expanded Shale, Clay and Slate (ESCS) Lightweight Aggregate Soil Mechanics

Properties and Applications

Equal Weights (25 Tons / 1Truckload) of Ordinary Granular Aggregate (*left)* and ESCS Lightweight Aggregate (*Right*)

Expanded Shale, Clay and Slate (ESCS) compacted geotechnical fills are approximately half the weight of ordinary aggregate fills. This advantage, coupled with the high angle of internal friction of ESCS, can also reduce lateral forces by more than one-half. ESCS has been effectively used to solve numerous geotechnical engineering problems and to convert unstable soil into usable land. ESCS is a reliable, economical geotechnical solution.

ABSTRACT of the following paper: *Structural grade lightweight aggregates (LWA) have been extensively used throughout North America for more than [80] years in cast-in-place structural lightweight concretes for high-rise buildings and bridges, and are now being widely used for geotechnical applications. Structural grade LWA, when used in backfills and over soft soils, provides geotechnical physical properties that include reduced density, high stability, high permeability, and high thermal resistance. These improved physical properties are found in aggregates with a reduced specific gravity and a predictable stability resulting from a consistently high angle of internal friction. The open texture available from a closely controlled manufactured aggregate gradation ensure high permeability. High thermal resistance results from porosity developed during the production process. In this publication, the physical properties of structural grade LWA and geotechnical engineering properties of LWA backfills are illustrated. Additionally, references to extensive testing programs that developed data on shear strength, compressibility, durability, and in-place density are given. Representative case studies are reported from [several hundred] projects that illustrate completed applications of structural grade LWA fills over soft soils and behind retaining walls and bridge abutments.*

Lightweight Aggregate Soil Mechanics: *Properties and Applications*

T.A. Holm and A.J. Valsangkar

For more than [80] years, shales, clays, and slates have been expanded in rotary kilns to produce structural grade LWA for use in concrete and masonry units. Millions of tons of structural grade LWA produced annually are used in structural concrete applications. Its availability is currently widespread throughout most of the industrially developed world. Consideration of structural grade LWA as a remedy to geotechnical problems stems primarily from the improved physical properties of reduced dead weight, high internal stability, high permeability, and high thermal resistance. These significant advantages arise from the reduction in particle specific gravity, stability that results from the inherent high angle of internal friction, the controlled open-textured gradation available from a manufactured aggregate which assures high permeability, and the high thermal resistance developed because of the high particle porosity.

PHYSICAL PROPERTIES OF STRUCTURAL LIGHTWEIGHT AGGREGATES

Particle Shape and Gradation

As with naturally occurring granular materials, manufactured LWA's have particle shapes that vary from round to angular with a characteristically high interstitial void content that results from a narrow range of particle sizes. Applications of LWA to geotechnical situations require recognition of two primary attributes: (a) the high interstitial void content typical of closely controlled manufactured granular coarse aggregate that closely resembles a clean, crushed stone, and (b) the high volume of pores enclosed within the cellular particle.

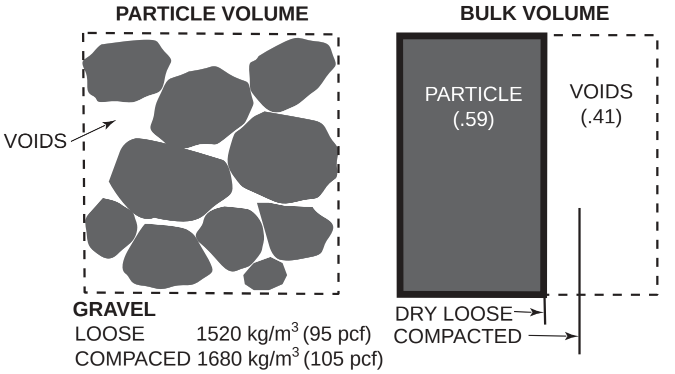
Structural grade LWA gradations commonly used in high-rise concrete buildings and long-span concrete bridge decks conform to the requirements of ASTM C330. The narrow range of particle sizes ensures a high interstitial void content that approaches 50% in the loose state. North American rotary kiln plants producing expanded shales, clays, and slates currently supply coarse [and fine] aggregates to ready-mix and precast concrete manufacturers with 20 to 5 mm (3/4 - #4), 13 to 5 mm (1/2 - #4), or 10 to 2 mm (3/8 - #8) gradations [and various fine aggregate gradings]. With [coarse] gradations there is a minimum percentage of fines smaller than 2 mm (#8 mesh) and insignificant amounts passing the 100 mesh screen.

Retaining wall backfill, Providence, Rhode Island

Particle Porosity and Bulk Density

When suitable shales, clays, and slates are heated in rotary kilns to temperatures in excess of 1100° C (2012°F), a cellular structure is formed of essentially noninterconnected spherical pores surrounded by a strong, durable ceramic matrix that has characteristics similar to those of vitrified clay brick. Oven-dry specific gravities of LWA vary but commonly range from 1.25 to 1.40. Combination of this low specific gravity with high interparticle void content results in LWA bulk dry densities commonly in the range of 720 kg/m^3 (45 pcf). Compaction of expanded aggregates in a manner similar to that used with crushed stone provides a highly stable interlocking network that will develop in-place moist densities of less than [960 kg/m^3 (60 pcf)].

Differences in porosity and bulk density between LWA's and ordinary soils may be illustrated by a series of schematic depictions. For comparative purposes, Figure 1 shows the interparticle voids in ordinary coarse aggregate. Although normal weight aggregates commonly have porosities of 1-2%, the schematic assumes ordinary aggregates to be 100% solid. For illustrative purposes, the bulk volume is shown to be broken into one entirely solid part with the remaining fraction being interparticle voids.



$$\text{PARTICLE VOLUME (LOOSE)} = \frac{1520\text{ kg/m}^3}{2600\text{ kg/m}^3} = .59 \qquad \text{PARTICLE VOLUME (COMPACTED)} = \frac{1680\text{ kg/m}^3}{2600\text{ kg/m}^3} = .65$$

[2600 kg/m^3 is the particle density of ordinary aggregate, SG = 2.60 x 1000 kg/m^3.]

FIGURE 1 Voids in ordinary coarse aggregates

Figure 2 shows the cellular pore structure of a typical LWA. ASTM procedures prescribe measuring the "saturated" (*misnamed in the case of LWA's; partially saturated after a 1-day soak is more accurate*) specific gravity in a pycnometer and then determining the moisture content on the sample that had been immersed in water for 24 hours. After a 1-day immersion in water, the rate of moisture absorption into the lightweight aggregate will be so low that the partially saturated specific gravity will be essentially unchanged during the time necessary to take weight measurements in the pycnometer. When the moisture content is known, the oven-dry specific gravity may be directly computed. This representative coarse LWA with a measured dry loose bulk unit weight of 714 kg/m^3 (44.6 pcf) and computed oven-dry specific gravity of 1.38 results in the aggregate particle occupying 52% of the total bulk volume, with the remaining 48% composed of interparticle voids.

The specific gravity of the pore-free ceramic solid fraction of a lightweight aggregate may be determined by standard procedures after porous particles have been thoroughly pulverized in a jaw mill. Pore-free ceramic solids specific gravities measured on several pulverized LWA samples developed a mean value of 2.55. The representative LWA with a dry specific gravity of 1.38 will develop a 54% fraction of enclosed aggregate particle ceramic solids and a remaining 46% pore volume (Figure 2).

This leads to the illustration of the overall porosity in a bulk loose LWA sample as shown in Figure 3. Interparticle voids of the overall bulk sample are shown within the enclosed dotted area, and the solid pore-free ceramic and the internal pores are shown within the solid particle lines. For this representative LWA, the dry loose bulk volume is shown to be composed of 48% voids, 28% solids, and 24% pores.

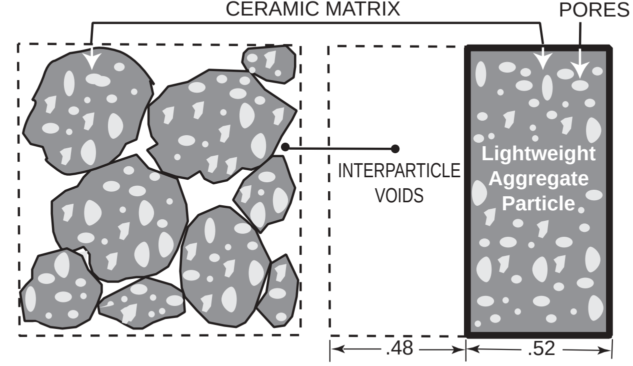
$$\gamma_D \text{ (Dry Specific Gravity)} = \frac{\gamma_M \text{ (Partially Saturated Surface Dry Specific Gravity)}}{(1 - M)\text{ (1-Day Soak Moisture Content by Weight)}}$$

$$\gamma_D = \frac{1.50}{(1 + .085)} = 1.38$$

Measured Bulk Dry Loose Density

Fraction of bulk aggregate sample occupied by lightweight aggregate particles $= \frac{714\text{ kg/m}^3}{1380\text{ kg/m}^3} = .52$

Fraction of bulk aggregate sample occupied by interparticle voids $= 1.00 - .52 = .48$



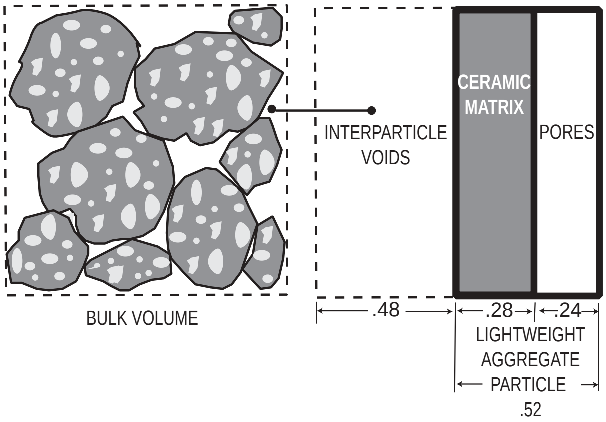
$$V_s \left(\begin{array}{c}\text{Fractional Part of Lightweight Aggregate}\\ \text{Particle Occupied by Ceramic Matrix}\end{array}\right) = \frac{\gamma_D \text{ Dry Specific Gravity}}{\gamma_D \text{ Dry Specific Gravity of Pore-Free Ceramic Mix}}$$

$$V_s = \frac{1380\text{ kg/m}^3}{2550\text{ kg/m}^3} = .54\text{, then } V_{pores} = 1 - .54 = .46$$

FIGURE 2 Interparticle voids and within-particle pores of lightweight aggregate (LWA)

VOLUMETRIC FRACTIONS IN DRY LOOSE LIGHTWEIGHT AGGREGATE SAMPLE

VOIDS	.48
CERAMIC SOLIDS FRACTION	= .52 X .54 = .28
LIGHTWEIGHT AGGREGATE PORES	= .52 X .46 = .24



LOOSE AGGREGATE CONDITION	INTERPARTICLE VOIDS	CERAMIC MATRIX	PORES	DENSITY kg/m^3
DRY	–	714	–	714 (44.6 pcf)
PARTIALLY SATURATED ONE-DAY DRY SOAK	–	714	61	775 (48.4 pcf)
VACUUM SATURATION	–	714	240	954 (59.6 pcf)
LONG TIME SATURATION [Submerged]	480	714	240	1434 -1000 = *434 (27.1 pcf)

*Buoyant Unit Weight

FIGURE 3 Voids, pores, and ceramic matrix fraction in a lightweight aggregate (LWA) sample

Absorption Characteristics

LWA's stored in exposed stockpiles in a manner similar to crushed stone will have some internal pores partially filled and may also carry an adsorbed moisture film on the surface of the particles. The moisture content that is defined in ASTM procedures as "absorption" based on a 24-hour immersion and routinely associated in concrete technology with "saturated" surface-dry specific gravity is, in fact, a condition in which considerably less than 50% of the particle pore volume is filled.

The issue is further clarified by a schematic volumetric depiction (see Figure 4) of the degree of pore volume saturation of a LWA particle that shows that the sample had a measured damp loose bulk unit weight of 775 kg/m^3 (48.4 pcf) with an 8.5% absorbed moisture and would, in fact, represent a condition in which approximately 25% of the pore volume is water filled.

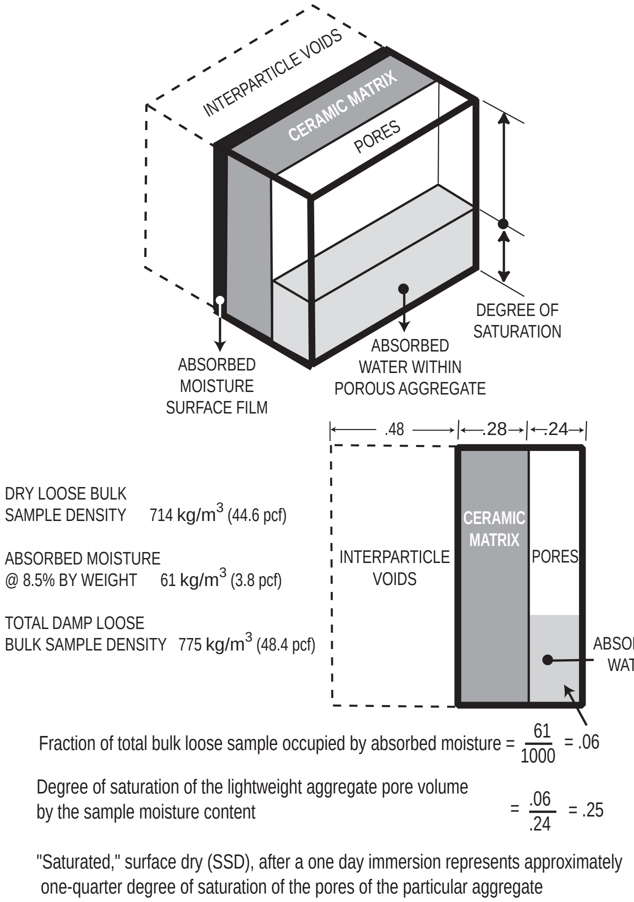


FIGURE 4 Degree of saturation of partially saturated lightweight aggregate (LWA)

Structural grade LWA exposed to moisture in production plants and stored in open stockpiles will contain an equilibrium moisture content. LWA's that are continuously submerged will, however, continue to absorb water over time. In one investigation, the effective specific gravity of a submerged LWA sample was measured throughout a one-year period to demonstrate long-term weight gain. Long-term absorption characteristics are shown in Figure 5 for a LWA sample with a measured 1-day immersion moisture content of 8.5% associated with a partially saturated surface-dry specific gravity of 1.5. When moisture absorption-versus-time relationships are extrapolated or theoretical calculations used to estimate the total filling of all the LWA pores, it can be shown that for this particular LWA the absorbed moisture content at infinity will approach 34% by weight with a totally saturated specific gravity of 1.83. Complete filling of all pores in a structural grade LWA is unlikely because the non-interconnected pores are enveloped by a very dense ceramic matrix. However, these calculations do reveal a conservative upper limit for submerged design considerations.

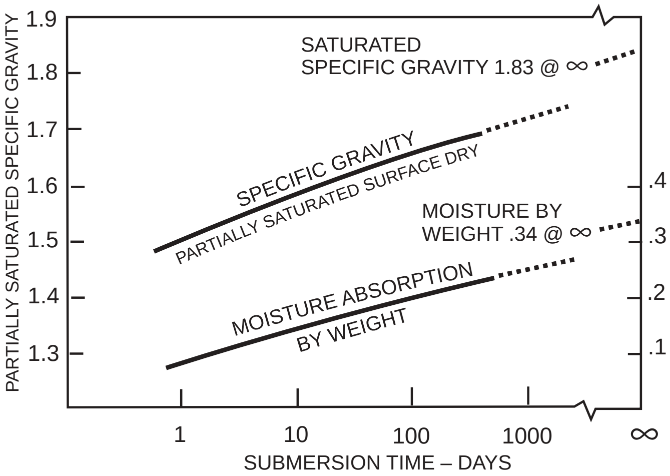


FIGURE 5 Moisture absorption (by weight) and partially saturated, surface dry specific gravity of lightweight aggregate (LWA) versus time of submersion

Durability Characteristics

The durability of LWA's used in structural concrete applications is well known. More than 400 major U.S. bridges built using structural lightweight concrete (LWC) have demonstrated low maintenance and limited deterioration. Long-term durability characteristics of LWA's were demonstrated in 1991 by reclaiming and testing samples of the LWA fill supplied in 1968 to a Hudson River site. Magnesium soundness tests conducted on the reclaimed aggregate sample exposed to long-term weathering resulted in soundness loss values comparable to those measured and reported in routine quality control testing procedures 23 years earlier, indicating little long-term deterioration due to continuous submersion and freeze-thaw cycling at the waterline.

Although ASTM standard specifications C330 and C331 for lightweight aggregate make no mention of corrosive chemicals limitations, foreign specifications strictly limit SO_3 equivalents to 0.5% (*Japanese Industrial Standard J5002*) or 1.0% (*German Standard DIN 4226*). The American Concrete Institute Building Code (ACI 318) mandates chloride limitations in the overall concrete mass because of concern for reinforcing bar corrosion, but no limits are specified for individual constituents. Numerous geotechnical projects specifications calling for lightweight aggregates have limited water-soluble chloride content in the aggregate to be less than 100 ppm when measured by AASHTO T291.

GEOTECHNICAL PROPERTIES OF LIGHTWEIGHT FILL

In-Place Compacted Moist Density

Results of compacted LWA density tests conducted in accordance with laboratory procedures (Proctor tests) should be interpreted differently from those for natural soils. Two fundamental aspects of lightweight aggregate soil fill will modify the usual interpretation soils engineers place on Proctor test data. The first is that the absorption of LWA is greater than natural soils. Part of the water added during tests will be absorbed within the aggregate particle and will not affect interparticle physics (bulking, lubrication of the surfaces, etc.). Second, unlike cohesive natural soils, structural grade LWA contains limited fines, limiting the increase in density due to packing of the fines between large particles. The objective in compacting structural grade LWA fill is not to aim for maximum in-place density, but to strive for an optimum density that provides high stability without unduly increasing compacted density. Optimum field density is commonly achieved by two to four passes of rubber tire equipment. Excessive particle degradation developed by steel-tracked rolling equipment should be avoided. Field density may be approximated in the laboratory by conducting a one-point ASTM D698, AASHTO T99 Proctor test [using a 0.5 $ft.^3$ bucket] on a representative LWA sample that contains a moisture content typical of the field delivery. Many projects have been successfully supplied where specifications called for an in-place, compacted, moist density not to exceed 960 kg/m^3 (60 pcf).

Shear Strength

Structural grade LWA's provide an essentially cohesionless, granular fill that develops stability from inter-particle friction. Extensive testing on large 250 x 600 mm (10 x 24 in. high) specimens has confirmed angles of internal friction of more than 40 degrees (*1*). Triaxial compression tests completed on LWA from six production plants, which included variations in gradations, moisture content, and compaction levels, revealed consistently high angles of internal friction. With a commonly specified in-place moist compacted unit weight less than 960 kg/m^3 (60 pcf), it may be seen from a simplistic analysis that lateral pressures, overturning moments, and gravitational forces approach one-half of those generally associated with ordinary soils.

A summary of the extensive direct shear testing program conducted by Valsangkar and Holm (*2*), presented in the following table, confirm the high angle of internal friction measured on large-scale triaxial compression testing procedures as reported earlier by Stoll and Holm (*1*).

	Angle of Internal Friction (degree)	
Material	***Loose***	***Compacted***
Minto [LWA]	40.5	48.0
Solite [LWA]	40.0	45.5
Limestone	37.0	N/A
Solite (*1*) [LWA]	39.5	44.5

Compressibility

Large-scale compressibility tests completed on lightweight aggregate fills demonstrated that the curvature and slope of the LWA fill stress-strain curves in confined compression were similar to those developed for companion limestone samples (*2*). Cyclic plate-bearing tests on LWA fills indicated vertical subgrade reaction responses that were essentially similar for the lightweight and normal weight aggregate samples tested (*3*).

Attempts by concrete technologists to estimate aggregate strength characteristics by subjecting unbound LWA samples to piston ram pressures in a confined steel cylinder have provided inconsistent and essentially unusable data for determination of the strength making characteristics of concretes that incorporate structural grade LWA. By ASTM C330 specifications, all structural grade LWA's are required to develop concrete strengths above 17.2 MPa (2500 psi). Most structural grade LWA concrete will develop 34.4 MPa (5000 psi), and a small number can be used in concretes that develop compressive strengths greater than 69 MPa (10,000 psi).

Thermal Resistance

For more than [8] decades, design professionals have used lightweight concrete masonry and lightweight structural concrete on building facades to reduce energy losses through exterior walls. It is well demonstrated that the thermal resistance of LWC is considerably less than that of ordinary concrete, and this relationship extends to aggregates in the loose state (4).

Permeability

Attempts to measure permeability characteristics of unbound LWA have not been informative because of the inability to measure the essentially unrestricted high flow rate of water moving through open-graded structure. This characteristic has also been observed in the field, where large volumes of water have been shown to flow through LWA drainage systems. Exfiltration applications of LWA have demonstrated a proven capacity to effectively handle high volumes of storm water runoff. Subterranean exfiltration systems have provided competitive alternatives to infiltration ponds by not using valuable property areas as well as eliminating the long-term maintenance problems associated with open storage of water.

Interaction Between Lightweight Aggregate Fills and Geotextiles

Valsangkar and Holm (5) reported results of testing programs on the interaction between geotextiles and LWA fills that included the variables of differing aggregate types and densities, thickness of aggregate layer, and geotextile types. The results indicated that the overall roadbed stiffness is unaffected when LWA is used instead of normal weight aggregate for small deflections and initial load applications. These tests were followed by a large-scale test (2), which reported that the comparison of the friction angles between the LWA or the normal weight aggregate and the geotextiles indicate that interface friction characteristics are, in general, better for LWA than normal weight aggregates.

APPLICATIONS

During the past decade several hundred diverse geotechnical applications have been successfully supplied with structural grade LWA. The applications primarily fit into the following major categories:

- **Backfill behind waterfront structures, retaining walls, and bridge abutments;**
- **Load compensation and buried pipe applications on soft soils;**
- **Improved slope stability situations; and**
- **High thermal resistance applications.**

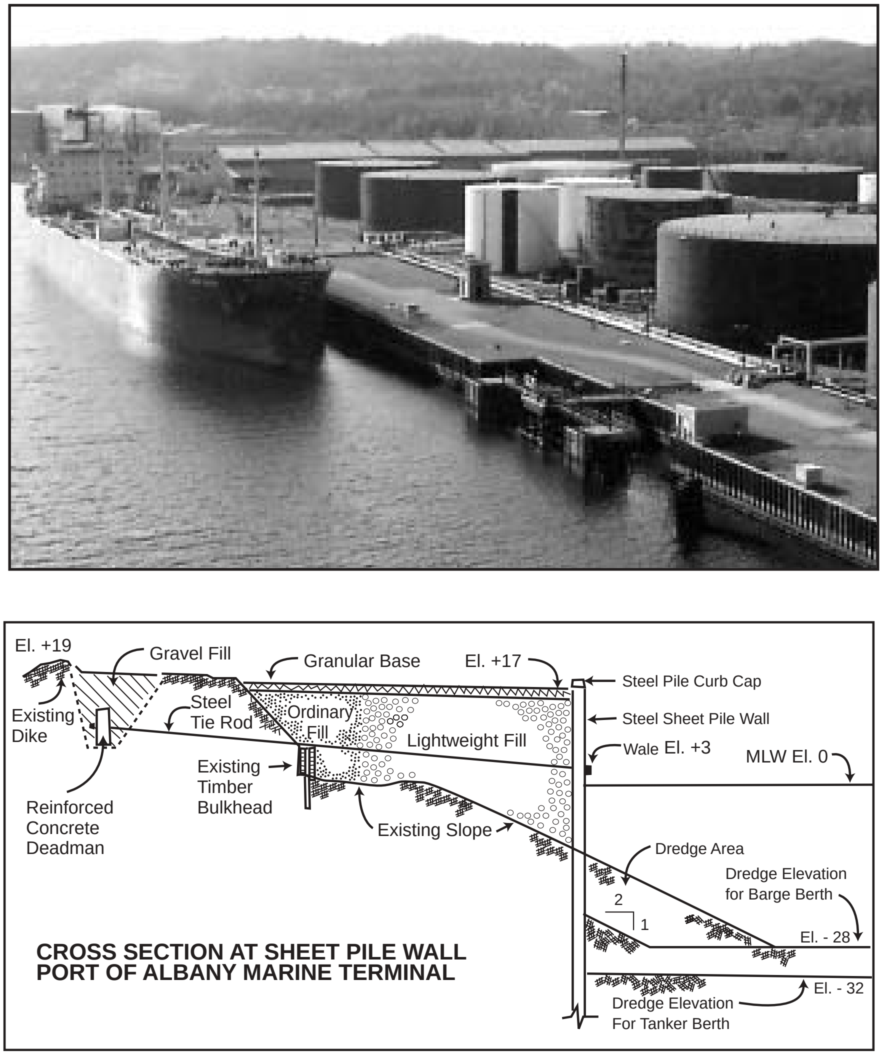


FIGURE 6 Rehabilitation of Port of Albany, New York [1981]

Backfill Behind Waterfront Structures, Retaining Walls and Bridge Abutments

A classic example of how unusable river front was reclaimed and large industrial site extended by the use of sheet piles and lightweight fill is demonstrated in Figure 6 (*6*). LWA fill specifications for this project required rotary kiln expanded shale to have a controlled coarse aggregate gradation of 20 to 5 mm (3/4 - #4) and laboratory test certification of an angle of internal friction greater than 40 degrees. No constructability problems were experienced by the contractor while transporting, placing, and compacting the LWA soil fill. Peak shipment were more than 1,000 tons per day without any logistical difficulties. The material was trucked to the point of deposit at the job site and distributed by front-end loaders. This project used approximately 20,000 m^3 (27,000 yd^3) of compacted LWA and resulted in overall savings by reducing sizes of sheet piling and lowering costs associated with the anchor system.

On the Charter Oak Bridge project, Hartford, Connecticut, constructed in 1989 to 1990, LWA fill was placed in the east abutment area to avoid placing a berm that would have been necessary to stabilize an earth fill embankment. According to the designer, construction of a berm would have required relocating a tributary river. LWA fill was also used in other areas to avoid increasing stresses and settlements in an old brick sewer (*7*). When all applications were totaled, this project incorporated more than 100,000 tons of structural grade LWA.

Load Compensation and Buried Pipe Applications on Soft Soils

In numerous locations throughout North America, design of pavements resting on soft soils has been facilitated by a “load compensation” replacement of heavy soils with a free-draining structural grade LWA with low density and high stability. Replacing existing heavy soil with LWA permits raising elevations to necessary levels without providing any further surcharge loads to the lower-level soft soils. Rehabilitation of Colonial Parkway near Williamsburg, Virginia, built alongside the James and York rivers, provides a representative example of the procedure. Soft marsh soil sections of this roadway had a low load-bearing capacity, and had experienced continuous settlement. The concrete roadway slabs were removed along with the soil beneath to a depth of more than 3 ft. The normal weight soil was then replaced with structural-grade LWA with a compacted moist density of less than 960 kg/m^3 (60 pcf), providing effective distribution of load to the soft soil layer, load compensation, and side slope stability. Reconstruction was completed in two stages by first completely rehabilitating in one direction, followed by excavation of the opposing lane with delivery, compaction, and slab construction routinely repeated.

Construction of pipelines in soft soil areas has frequently been facilitated by equalizing the new construction weight (pipe plus LWA backfill) to the weight of the excavated natural soil. Supporting substrates do not “see” any increased loading and settlement forces are minimized.

Improved Slope Stability

Improvement of slope stability has been facilitated by LWA in a number of projects prone to sliding. Waterside railroad tracks paralleling the Hudson River in the vicinity of West Point, New York, had on several occasions suffered serious misalignment due to major subsurface sliding because of soft clay seams close to grade level. After riverbank soil was excavated by a barge-mounted derrick, LWA was substituted and the railroad track bed reconstructed. Reduction of the gravitational force driving the slope failure combined with the predictable LWA fill frictional stability provided the remedy for this problem. Troublesome subsoil conditions in other area, including the harbors in Norfolk, VA, and Charleston, SC, have also been similarly remedied.

High Thermal Resistance Applications

Structural LWA has been effectively used to surround high-temperature pipelines to lower heat loss. Long-term, high-temperature stability characteristics can be maintained by aggregates that have already been exposed to temperatures of 1100° C (2012° F) during the production process. Other applications have included placing LWA beneath heated oil processing plants to reduce heat flow to the supporting soils.

ECONOMICS

An economic solution provided by a design that calls for an expensive aggregate requires brief elaboration. In many geographical areas, structural-grade LWA's are sold to ready-mix, precast, and concrete masonry producers on the basis of a price per ton, FOB the plant. On the other hand, the contractor responsible for the construction of the project bases costs on the compacted material necessary to fill a prescribed volume. Because of the significantly lower bulk density, a fixed weight of this material will obviously provide a greater volume. To illustrate that point, one may presume that if a LWA is available at \$X/ton, FOB the production plant, and trucking costs to the project location call for additional \$Y/ton, the delivered job site cost will be \$(X+Y)/ton. As mentioned previously, many projects have been supplied with structural LWA aggregates delivered with a moist, loose density of about [770 kg/m^3 (48 pcf)] and compacted to a moist, in-place density [less than the typically specified 960 kg/m^3 (60 pcf)]. This would result in an in-place, compacted moist density material cost (*not including compaction cost*) of

$$\{\$(X + Y) \text{ x } 60 \text{ x } 27\}/2{,}000$$

for the compacted, moist lightweight aggregate.

[*Additional Economic Benefits* - April 2001]

- Approximately twice as much volume of LWA can be transported per load as compared to normal weight.
- In restricted or commercial areas, cutting the number of trucks by half is environmentally significant.
- Loader or crane bucket volume can be increased to allow faster placement and longer reaches.
- In tight spaces where hand placement and compaction is required, LWA is much easier to handle and offers considerable labor savings.

CONCLUSIONS

Structural grade LWA fills possessing reduced density, high internal stability, and high permeability have been extensively specified and used to replace gravel, crushed stone, and natural soils for geotechnical applications at soft soil sites and in backfills where the assured reduction in lateral and gravitational forces has provided economical solutions.

REFERENCES

1. Stoll, R.D., and T.A. Holm; Expanded Shale Lightweight Fill: Geotechnical Properties, *Journal of Geotechnical Engineering*, ASCE, Vol. 111, No. 8, Aug. 1985

2. Valsangkar, A.J., and T.A. Holm; Geotechnical Properties of Expanded Shale Lightweight Aggregate, *Geotechnical Testing Journal*, ASTM, Vol. 13, No.1, March 1990, pp 10-15

3. Valsangkar, A.J., and T.A. Holm; *Cyclic Plate Load Tests on Lightweight Aggregate Beds*, Presented at the 72nd Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1993

4. Valore, R.C.; *The Thermophysical Properties of Masonry and Its Constituents*, International Masonry Institute, Washington D.C., 1988

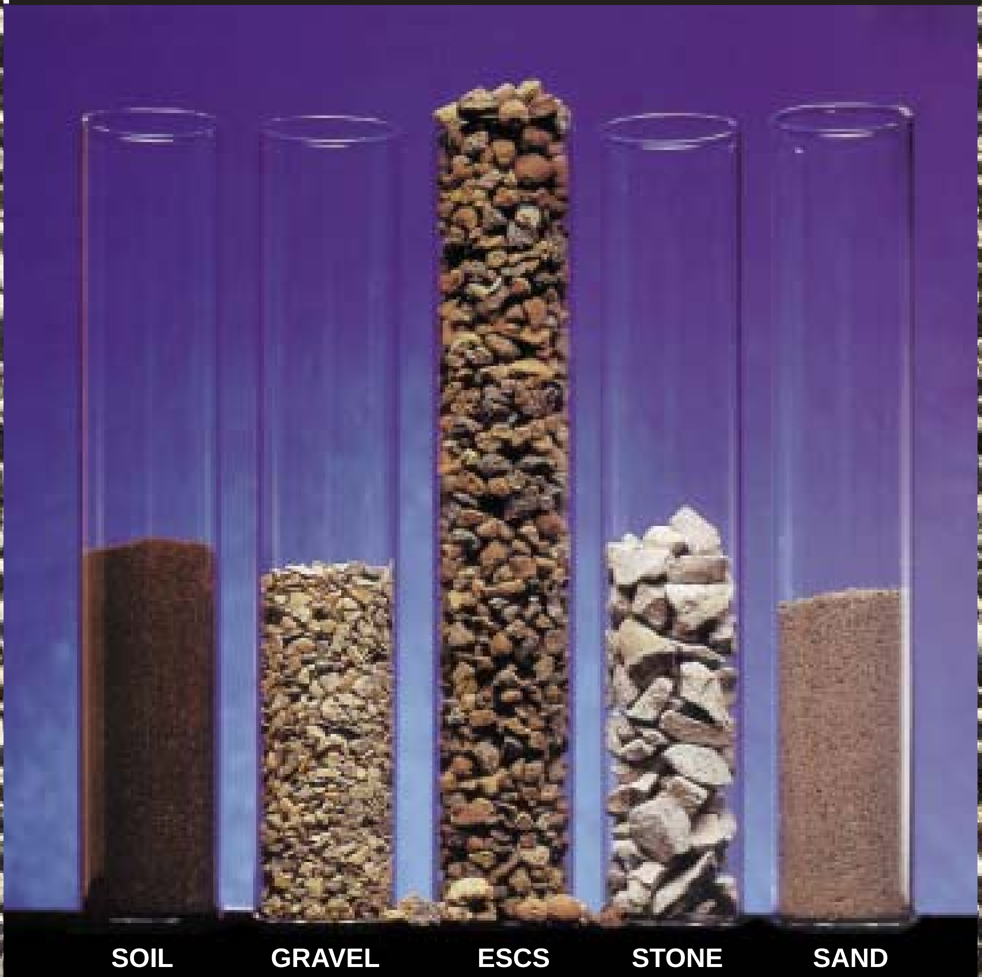
5. Valsangkar, A.J., and T.A. Holm; Model Tests on Peat-Geotextile-Lightweight Aggregate System, *Geotextiles and Geomembranes*, Elsevier Science Publishers, Ltd., England, 1987

6. Childs, K., D.L. Porter, and T.A. Holm; Lightweight Fill Helps Albany Port Expand, *Civil Engineering*, ASCE, April 1983

7. Dugan, J.P., Jr.; *Engineering News Record*, Haley and Aldrich, Inc., ENR Letters, New York, Aug. 23, 1990

Reprinted with permission of the Transportation Research Board, National Research Council, Washington, D.C., *Transportation Research Record 1422; Soils Geology and Foundations; Lightweight Artificial and Waste Materials for Embankments Over Soft Soils*, T.A. Holm and A.J. Valsangkar, January 1993
Reprinted March 2001
The principal author, Thomas Holm, has supervised this reprinting by the Expanded Shale, Clay and Slate Institute. Under his direction, Figures 1, 2, and 3 have been modified for clarity. Other updated information is indicated by brackets [ ].

ESCS Structural Lightweight Aggregate Is Approximately Half the Weight of Ordinary Aggregates



Equal Weights of Aggregates

(Note: ESCS is approximately twice the volume)

Expanded Shale, Clay and Slate Institute
2225 Murray-Holladay Road • Suite 102
Salt Lake City, Utah 84117 • 801-272-7070 • Fax 801-272-3377
www.escsi.org

Publication No. 6610 • April 2001
Printed in U.S.A.