Lightweight Aggregate Soil Mechanics: Properties and Applications

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Structural grade lightweight aggregates have been extensively used throughout North America for more than 70 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 lightweight aggregates, when used in backfills and over soft soils, provide geotechnical physical properties that include reduced density, high stability, high permeability, and high thermal resistance. These improved physical properties result from aggregates with a reduced specific gravity and a predictable stability that results from a consistently high angle of internal friction. The open texture available from a closely controlled manufactured aggregate gradation ensures high permeability. High thermal resistance results from porosity developed during the production process. Physical properties of structural grade lightweight aggregate and geotechnical engineering properties of lightweight aggregate backfills are illustrated, along with references to extensive testing programs that developed data on shear strength, compressibility, durability, and in-place density. Representative case studies are reported from the almost 100 projects that illustrate completed applications of structural grade lightweight aggregate fills over soft soils and behind retaining walls and bridge abutments.

For more than 70 years, shales, clays, and slates have been expanded in rotary kilns to produce structural grade lightweight aggregates for use in concrete and masonry units. Millions of tons of structural grade lightweight aggregate produced annually are used in structural concrete applications, with current availability widespread throughout North America and most of the industrially developed world. Consideration of structural grade lightweight aggregate 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 inherently high angle of internal friction, controlled open-textured gradation available from a manufactured aggregate that assures high permeability, and 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 lightweight aggregates 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 lightweight aggregate to geotechnical situations require recognition of two primary attributes: (a) the high interstitial void content typical of a 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 lightweight aggregate 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 percent in the loose state. North American rotary kiln plants producing expanded shales, clays, and slates currently supply coarse aggregates to ready-mix and precast concrete manufacturers with 20 to 5 mm (¾-#4), 13 to 5 mm (½-#4), or 10 to 2 mm (⅜-#8) gradations. With these gradations there is a minimum percentage of fines smaller than 2 mm (#8 mesh) and insignificant amounts passing the 100-mesh screen.

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 lightweight aggregate vary but commonly range from 1.25 to 1.40. Combination of this low specific gravity with high interparticle void content results in lightweight aggregate 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 1040 kg/m^3 (65 pcf).

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

Figure 2 shows the cellular pore structure of lightweight aggregates. ASTM procedures prescribe measuring the "saturated" (misnamed in the case of lightweight aggregates; "par-

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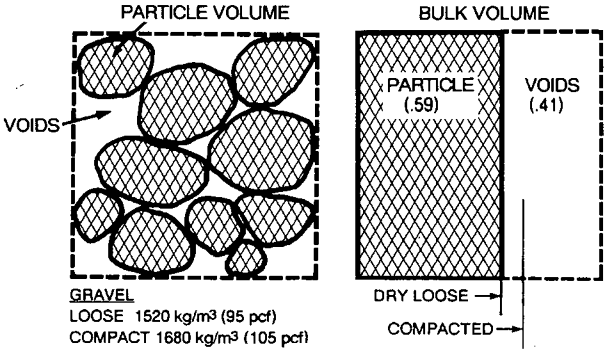


$$\text{PARTICLE VOLUME (LOOSE)} = \frac{1520\ \text{kg/m}^3}{2600\ \text{kg/m}^3} = .59 \qquad \text{PARTICLE VOLUME (COMPACTED)} = \frac{1680}{2600} = .65$$

FIGURE 1 Voids in ordinary coarse aggregates.

tially 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 hr. 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 lightweight aggregate with a measured dry loose bulk unit weight of 714 kg/m³ (44.6 pcf) and computed oven-dry specific gravity of 1.38 results in the aggregate particle occupying 52 percent of the total bulk volume, with the remaining 48 percent 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 solid specific gravities measured on several pulverized lightweight aggregate samples developed a mean value of 2.55. The representative lightweight aggregate with a dry specific gravity of 1.38 will develop a 54 percent fraction of enclosed aggregate particle ceramic solids and a remaining 46 percent pore volume (Figure 2).

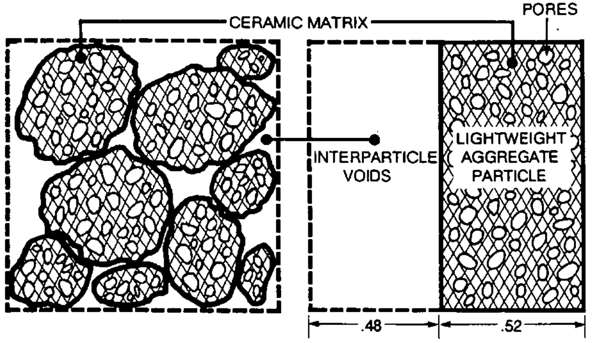
$$\gamma_D\ \text{(Dry Specific Gravity)} = \frac{\gamma_M\ \text{(Partially Saturated Surface Dry Specific Gravity)}}{(1+M)\ \text{(One Day Soak Moisture Content by Weight)}}$$

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

Measured Bulk Dry Loose Density

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

$$\begin{array}{l}\text{Fraction of bulk aggregate sample occupied} \\ \text{by interparticle voids}\end{array} = 1.00 - .52 = .48$$



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

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

FIGURE 2 Interparticle voids and within-particle pores of lightweight aggregate.

This leads to the illustration of the overall porosity in a bulk loose lightweight aggregate 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 lightweight aggregate, the dry loose bulk volume is shown to be composed of 48 percent voids, 28 percent solids, and 24 percent pores. Vacuum-saturated and submerged particle densities are also shown.

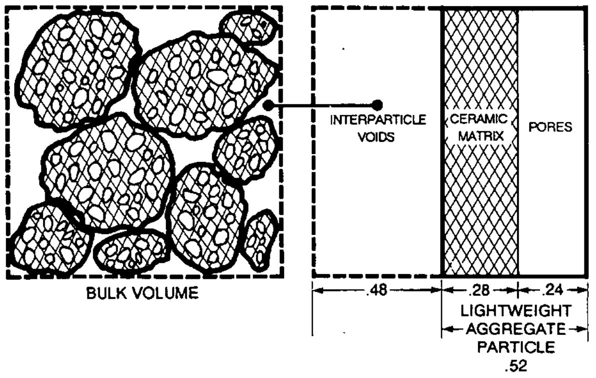
Absorption Characteristics

Lightweight aggregates 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-hr immersion and routinely associated in concrete technology with "saturated" surface-dry specific gravity is, in fact, a condition in which considerably less than 50 percent of the particle pore volume is filled.

This issue is further clarified by a schematic volumetric depiction (see Figure 4) of the degree of pore volume satu-

VOLUMETRIC FRACTIONS IN DRY LOOSE LIGHTWEIGHT AGGREGATE SAMPLE

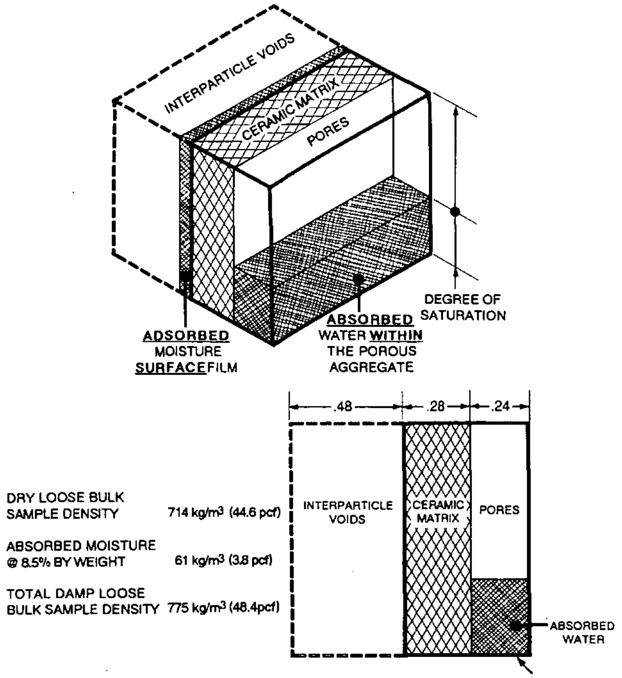
VOIDS = .48
CERAMIC SOLIDS FRACTION = .52 X .54 = .28
LIGHTWEIGHT AGGREGATE PORES = .52 X .46 = .24



LOOSE AGGREGATE CONDITION	INTERPARTICLE VOIDS	CERAMIC MATRIX	PORES	DENSITY kg/m³
DRY	—	714	—	714 (44.6 pcf)
PARTIALLY SATURATED ONE DAY SOAK	—	714	61	775 (48.4 pcf)
VACUUM SATURATION	—	714	240	954 (59.6 pcf)
LONGTIME SUBMERSION	480	714	240	1434 -1000 * 434 (27.1 pcf)

* Buoyant Unit Weight

FIGURE 3 Voids, pores, and ceramic matrix fraction in a lightweight aggregate sample.



Fraction of total bulk loose sample occupied by absorbed moisture $= \frac{61}{1000} = .06$

Degree of saturation of the lightweight aggregate pore volume by the sampled moisture content $= \frac{.06}{.24} = .25$

"Saturated", surface dry (SSD), after a one day immersion represents approximately one-quarter degree of saturation of the pores of the particular aggregate.

FIGURE 4 Degree of saturation of partially saturated lightweight aggregate.

ration of a lightweight aggregate particle that shows that the sample had a measured damp loose bulk unit weight of 785 kg/m^3 (49.1 pcf) with an 8.5 percent absorbed moisture and would, in fact, represent a condition in which approximately 25 percent of the pore volume is water filled.

Structural grade lightweight aggregate exposed to moisture in production plants and stored in open stockpiles will contain an equilibrium moisture content. Lightweight aggregates that are continuously submerged will, however, continue to absorb water with time. In one investigation, the effective specific gravity of a submerged lightweight aggregate sample was measured throughout a 1-year period to demonstrate long-term weight gain. Long-term absorption characteristics are shown in Figure 5 for a lightweight aggregate sample with a measured 1-day immersion moisture content of 8.5 percent 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 lightweight aggregate pores, it can be shown that for this particular lightweight aggregate the absorbed moisture content at infinity will approach 34 percent by weight with a totally saturated specific gravity of 1.83. Complete filling of all pores in a structural grade lightweight aggregate is unlikely because the noninterconnected pores are enveloped by a very dense ceramic matrix. However, these calculations do reveal a conservative upper limit for submerged design considerations.

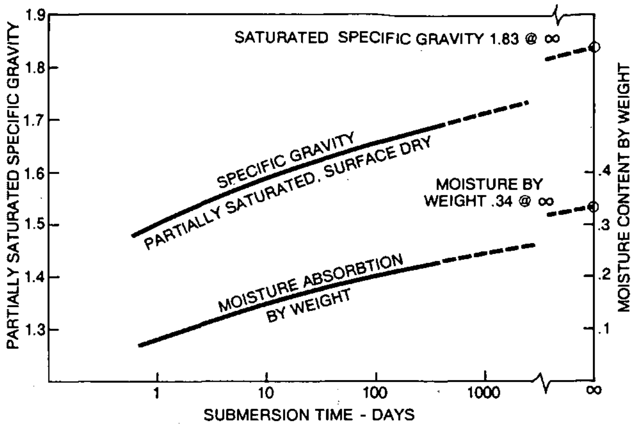


FIGURE 5 Moisture absorption (by weight) and partially saturated, surface dry specific gravity of lightweight aggregate versus time of submersion.

Durability Characteristics

The durability of lightweight aggregates used in structural concrete applications is well known. More than 400 major U.S. bridges built using structural lightweight concrete have demonstrated low maintenance and limited deterioration. Long-term durability characteristics of lightweight aggregates were demonstrated in 1991 by reclaiming and testing samples of the lightweight aggregate 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 percent (Japanese Industrial Standard J5002) or 1.0 percent (German Standard DIN 4226). The American Concrete Institute Building Code (ACI 318) mandates chloride limitation in the overall concrete mass because of concern for reinforcing bar corrosion, but no limits are specified for individual constituents. Numerous geotechnical project specifications calling for lightweight aggregates have limited water-soluble chloride content in the aggregate to be less than 100 ppm when measured by AASHTO T260.

GEOTECHNICAL PROPERTIES OF LIGHTWEIGHT AGGREGATE FILL

In-Place Compacted Moist Density

Results of compacted lightweight aggregate 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 lightweight aggregate is greater than natural soils. Part of the water added during the test 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 lightweight aggregates contain limited fines, limiting the increase in density due to packing of the fines between large particles. The objective in compacting structural grade lightweight aggregate 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 on a representative lightweight aggregate sample that contains a moisture content typical of 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 lightweight aggregates provide an essentially cohesionless, granular fill that develops stability from interparticle friction. Extensive testing on large size 250 × 600 mm (10 × 24 in. high) specimens has confirmed angles of internal friction of more than 40 degrees (*1*). Triaxial compression tests completed on lightweight aggregates 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, confirmed 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 (degrees)	
Material	*Loose*	*Compact*
Minto	40.5	48.0
Solite	40.0	45.5
Limestone	37.0	N/A
Solite (*1*)	39.5	44.5

Compressibility

Large-scale compressibility tests completed on lightweight aggregate fills demonstrated that the curvature and slope of the lightweight aggregate fill stress-strain curves in confined compression were similar to those developed for companion limestone samples (*2*). Cyclic plate-bearing tests on lightweight 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 lightweight aggregate 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 lightweight aggregates. By ASTM C330 specification, all structural grade lightweight aggregates are required to develop concrete strengths above 17.2 MPa (2500 psi). Most structural grade lightweight aggregate concrete will develop 34.4 MPa (5000 psi), and a small number can be used in concretes that develop compressive strength levels greater than 69 MPa (10,000 psi).

Thermal Resistance

For more than 7 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 lightweight concrete is considerably less than ordinary concrete, and this relationship extends to aggregates in the loose state (*4*).

Permeability

Attempts to measure permeability characteristics of unbound lightweight aggregates have not been informative because of the inability to measure the essentially unrestricted high flow rate of water moving through the open-graded structure. This characteristic has also been observed in the field, where large volumes of water have been shown to flow through lightweight aggregate drainage systems. Exfiltration applications of lightweight aggregate 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 lightweight aggregate 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 lightweight aggregate 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 lightweight aggregate or the normal weight aggregate and the geotextiles indicate that interface friction characteristics are, in general, better for lightweight than normal weight aggregates.

APPLICATIONS

During the past decade, almost 100 diverse geotechnical applications have been successfully supplied with structural grade lightweight aggregate. These 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.

Backfill Behind Waterfront Structures, Retaining Walls, and Bridge Abutments

A classic example of how an unusable riverfront was reclaimed and a large industrial site extended by the use of sheet piles and lightweight fill is demonstrated in Figure 6 (*6*). Lightweight aggregate fill specifications for this project required rotary kiln expanded shale to have a controlled coarse aggregate gradation of 20 to 5 mm (¾-#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 lightweight aggregate soil fill. Peak shipments were more

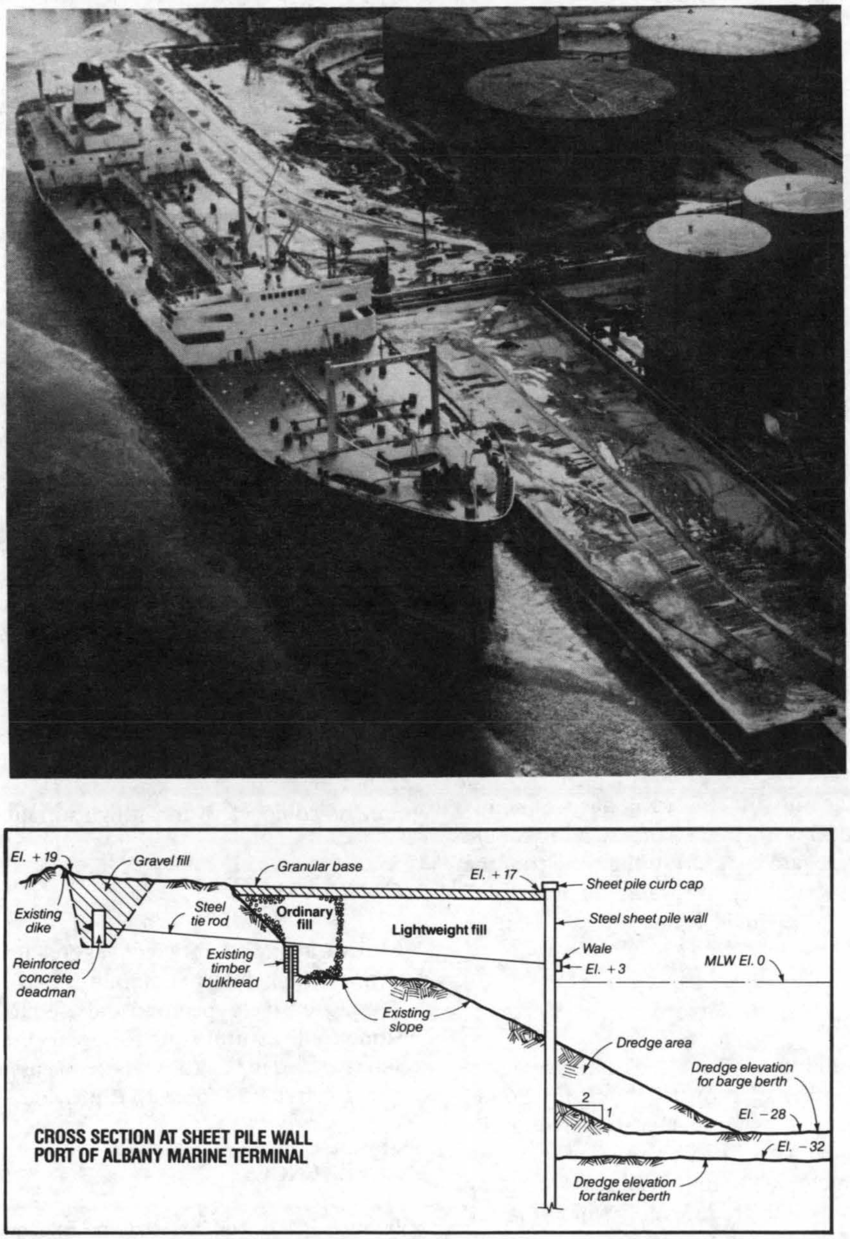


FIGURE 6 Rehabilitation of port of Albany, N.Y., marine terminal.

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 lightweight aggregate 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, lightweight aggregate 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. Lightweight 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 lightweight aggregate.

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 lightweight aggregate with low density and high stability. Replacing existing heavy soil with lightweight aggregate 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 this procedure. Soft marsh soil sections of this roadway having a low load-bearing capacity had experienced continuous settlement. The concrete roadway slabs were removed along with the soil beneath it to a depth of more than 3 ft. The normal weight soil was then replaced with structural-grade lightweight aggregate 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 lightweight aggregate 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 lightweight aggregate 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, lightweight aggregate was substituted and the railroad track bed reconstructed. Reduction of the gravitational force driving the slope failure combined with the predictable lightweight aggregate fill frictional stability provided the remedy for this problem. Troublesome subsoil conditions in other areas—including the harbors in Norfolk, Virginia, and Charleston, South Carolina—have also been similarly remedied.

High Thermal Resistance Application

Structural lightweight aggregates have 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 over 1100°C (2012°F) during the production process. Other applications have included placing lightweight aggregate 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 lightweight aggregates are sold to ready-mix, precast, and concrete masonry producers on the basis of the 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 lightweight aggregate is, for example, available at \$$X$/ton, FOB the production plant, and trucking costs to the project location call for additional \$$Y$/ton, the delivered job site cost will be a total of \$$(X + Y)$/ton. As mentioned previously, many projects have been supplied by structural lightweight aggregates delivered with a moist, loose density of about 720 kg/m^3 (45 pcf) and compacted to a moist, in-place density of approximately 960 kg/m^3 (60 pcf). This would result in an in-place, compacted moist density material cost (not including compaction costs) of

$$[\$(X + Y) \times 60 \times 27]/2{,}000$$

for the compacted, moist lightweight aggregate.

CONCLUSIONS

Structural grade lightweight aggregate 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.

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