Lightweight Aggregate Optimizes the Sustainability of Concrete, Through Weight Reduction, Internal Curing, Extended Service Life, and Lower Carbon Footprint.

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Abstract. This paper gives an overview on how lightweight aggregate (LWA) plays an important role in today’s move toward sustainable concrete. It covers how lightweight aggregate provides value in sustainable construction and includes new insights and practices that can extend the service life of concrete pavements and bridges. Even though most lightweight aggregates require energy to manufacture, when used and evaluated from a whole building perspective the overall carbon footprint of a structure is often lowered. The use of lightweight aggregate provides strategies to enhance cement hydration, improve the energy performance of structures, reduce life-cycle costs and reduce environmental impacts of material transport and construction. The latest information on internal curing, suspended floor drying rates, green roofs and how the use of lightweight aggregate contributes to LEED™ certification are addressed.

Introduction. The benefits that have made using lightweight aggregate (LWA) economical for nearly 100 years are the same characteristics that make the material what is now being called “sustainable.” The use of LWA helps designers, contractors and owners optimize the design, construction and long-term performance of concrete structures.

By definition, sustainability must be looked at with a long-term perspective. A product that is considered “green” today but lowers the durability and long-term performance of structures is not sustainable. Conversely, when the energy used to produce a product, in this case LWA, is quickly recovered both in first and ongoing life cycle costs, the material is undoubtedly sustainable. LWA has been contributing to the sustainability of the site and structure of building projects long before the current green movement came to the forefront.

Lightweight aggregate stands on a 2000 year old Foundation of Sustainability. 

*Roman period:* The first known use of lightweight concrete occurred more than 2000 years ago. There are several lightweight concrete structures in the Mediterranean region, but the three most notable structures were built during the early Roman Empire and include the Port of Cosa, the Pantheon Dome, and the Coliseum.

The Port of Cosa, built about 273 B.C., used lightweight concrete made from natural volcanic materials. These early builders learned that expanded aggregates
were better suited for marine facilities than the locally available beach sand and gravel. They went 25 miles (40 km) to the northeast to quarry volcanic aggregates at the Volcine complex for use in the harbor at Cosa. Broken shards of calcined clay vases were also used in the piers.... the first usage of manufactured aggregate. This harbor is on the west coast of Italy and consists of a series of four piers (~ 13 ft [4 m] cubes) extending out into the sea. For two millennia they have withstood the forces of nature with only surface abrasion. They only became obsolete because of siltation of the harbor.

The Pantheon, finished in 126 A.D., incorporates concrete of decreasing density from bottom to top of the dome. Roman engineers had sufficient confidence in lightweight concrete to build a dome whose diameter of 142 ft (43.3 m) was not exceeded for more than nineteen hundred years. The structure is in excellent condition and is still being used to this day for spiritual purposes.

The Coliseum, built in 75 to 80 A.D., is a gigantic amphitheater with a seating capacity of 50,000 spectators. The foundations were cast of lightweight concrete using crushed volcanic lava. The walls were made using porous, crushed-brick aggregate. The vaults and spaces between the walls were constructed using porous tufa cut stone. After the fall of the Roman Empire, lightweight concrete use was limited until the twentieth century when expanded shale, clay and slate lightweight aggregate became available for commercial use (ESCSI 1971).

Ships: While it is clearly understood that the terms high strength and high performance are not synonymous, we may consider the first modern use of high performance concrete to be when the American Emergency Fleet Corporation built lightweight concrete ships (1917-1920) in which specified compressive strengths of 5000 psi (35 MPa) were obtained with a unit weight of 110 lb/ft³ (1760 kg/m³) or less, using rotary kiln produced expanded shale, clay and slate (ESCS) lightweight aggregate. Commercial normalweight concrete strengths of that time were approximately 2500 psi (17 MPa).

Oil Platforms: In energy-related floating offshore concrete structures, great efficiencies are achieved when a lower density material is used. A 25% reduction of mass in air will result in a 50 % reduction when submerged. Because of this, the oil and gas industry recognized that lightweight concrete could be used to good advantage in its floating structures as well as structures built in a graving dock and then floated to the production site and bottom founded.

Bridges: Several hundred bridges have incorporated lightweight concrete into decks, beams, girders, or piers. Transportation engineers generally specify higher concrete strengths primarily to ensure high-quality mortar fractions (high compressive strength combined with high air content) that will minimize maintenance. Thousands of bridges in the United States are functionally obsolete with unacceptably low load capacity or an insufficient number of traffic lanes. Structural lightweight concrete has played a major roll in bringing these structures up to modern compliance in an environmentally responsible way.
Buildings: Many thousands of residential, commercial and industrial buildings, ranging from one story to multilevel high-rises, have been constructed around the world using lightweight concrete masonry and/or structural lightweight concrete.

The first major building project employing structural lightweight concrete in the United States was in 1928 and 1929, with an addition to the Southwestern Bell Telephone Company office in Kansas City. The building was originally built as a 14-story structure, and the company had found that the foundations and underpinnings would support an additional eight floors, taking into account the additional dead load of conventional normalweight concrete. Upon analysis the designers determined that by using lightweight expanded shale concrete instead of conventional concrete 14 floors could be safely added rather than eight, doubling the height of the building to a total of 28 floors. The concrete was mixed on-site (this was before the day of the ready-mix plant) with the relatively crude mixing equipment of the day. Compressive strength of the lightweight concrete was 3,500 psi at 28 days, an almost unprecedented high concrete strength at the time. The building has stood for more than 80 years as a demonstration of the practicality and economics of structural lightweight concrete.

The first structural lightweight concrete high-rise building was the Park Plaza Hotel St. Louis. Built in 1929, this 28-story building used structural lightweight concrete in both frame and floor systems, as well as for fireproofing.

Masonry: Another early “sustainable” application that is still used today is the 1923 development of lightweight concrete masonry with a higher insulation value, normal shrinkage, ease of handling and a uniform compressive strength equal to normal weight concrete masonry.

What is Lightweight Aggregate (LWA)? Structural lightweight aggregates are produced in manufacturing plants from raw materials, including suitable shales, clays, slates, fly ashes, or blast-furnace slags. Naturally occurring lightweight aggregates are mined from volcanic deposits that include pumice and scoria. Pyroprocessing methods include the rotary kiln process in which raw material is fed into a long, slowly rotating, slightly inclined cylinder where it’s fired in excess of 2000 F (1000 C). This manufacturing process, which is similar to that of portland cement, produces a uniform, high quality ceramic lightweight aggregate that is structurally strong, stable, durable and inert, yet also lightweight and insulative.

Quality lightweight aggregates contain a uniformly distributed system of pores that have a size range of approximately 5 to 300μm, developed in a continuous, relatively crack-free, high-strength vitreous phase. Pores close to the surface are readily permeable and fill with water within the first few hours to a few days of exposure to moisture. Interior pores, however, fill extremely slowly, with many months of submersion required to approach saturation. Interior pores are essentially non-interconnected and a small fraction remains unfilled after years of immersion (ACI 213R-03).
The initial cost of ESCS lightweight aggregate per unit volume is usually higher than a comparable unit of normalweight aggregate. The embodied energy unit cost to produce ESCS is also higher than a comparable unit of normalweight aggregate. However, when analyzed from an in-place use perspective, the higher initial cost and embodied energy are almost always offset and in most cases result in significant net savings. These savings come from weight reduction that results in a reduction of overall materials being used, and in construction and performance efficiencies.

**Optimize Building Design, Performance and Structural Efficiency.** Lightweight concrete is generally used for weight reduction, which often enhances the functionality, architectural expression and/or constructability of a structure. Lightweight aggregate optimizes structural efficiency by improving the strength to weight ratio as shown in the following applications:

*Buildings* - In buildings this is achieved by thinner fire resistant slabs, longer spans, expressive roof designs, taller buildings, additional floors added to existing structures and the ability to build on sites with poor soil conditions. The reduction in foundation loads may result in smaller footings, fewer piles, smaller pile caps, and less reinforcing. Reduced dead loads may result in smaller supporting members (decks, beams, girders, columns and piers). Reduced dead load will also result in reduced inertial seismic forces.

*Bridges* - In bridges, lightweight concrete may allow a wider bridge deck (additional lanes) to be placed on existing structural supports with minor or no modifications. Improved constructability may result in balanced cantilever bridge construction where lightweight concrete is used on one side of a pier and normalweight concrete used on the other to provide equal weight while accommodating a longer span on the lightweight side of the pier. This has permitted locating piers closer to land with significant reductions in cost. On bridge deck replacements or overlays, the deck may be thicker to allow more cover over reinforcing or to provide better drainage without adding additional dead load to the structure. Lightweight concrete has also been used to create longer bridge spans, thereby reducing the number of costly piers.

*Precast / Pre-stressed* - Longer or larger precast members can be manufactured without increasing overall weight. This results in fewer columns or pier elements in a system that is easier to lift or erect with fewer joints, and more elements per load when transporting. There are several documented cases in which the savings in shipping cost far exceeded the increased material cost of using lightweight concrete. At some precast plants, each element’s shipping cost is evaluated by computer to determine the optimum concrete density.

*Marine* - In marine application such as offshore oil platforms or floating bridge pontoons, lightweight concrete allows for increased topside loads and the reduced draft often permits easier movement out of dry dock and through shallow shipping channels.

*Specified Density Concrete* - Specified density concrete is becoming more frequently used to enhance design flexibility and project economics. Specified density
Concrete is defined as concrete that has been specified to a specific equilibrium density for a specific reason. The amount of lightweight aggregate used per cubic yard of concrete can range from small amounts for internal curing to 100% lightweight aggregate for very light mixtures. In the precast/prestressed concrete industry, specified density concrete ranging from 115 lb/ft³ (1920 kg/m³) to only slightly less than concrete composed entirely of normalweight aggregates are very common. The increasing usage of specified density concrete is driven by engineers’ decisions to optimize the concrete density to improve structural efficiency (strength to density ratio), to reduce concrete product transportation and construction costs, and to enhance cement hydration of concrete with very low w/cm (ACI 213R-03).

**Embodied Energy:** The embodied energy to manufacture ESCS lightweight aggregate includes mining, manufacturing, and transporting the material to the jobsite, soil blender, or building product manufacturer. The cost of this embodied energy is often paid back in a very short period of time, because less overall material is used, or due to improved thermal performance, lower transportation costs, and reduction of labor costs associated with the building elements. For example, the following embodied energy payback using ESCS aggregate in a typical lightweight concrete masonry unit, compared to using normalweight aggregate is less than one year. These calculations assume the masonry is used in single wythe integrally insulated exterior building walls, which is a typical application.

The example uses 2,300,000 Btu/Ton to manufacture ESCS lightweight aggregate or 1150 Btu/lb and 1350 lb cu yd average density, per the February 17, 2000 Life Cycle Inventory analysis of ESCS performed by CTL (Construction Technology Laboratories).

A typical mix design for 8” Lightweight cmu density (93 pcf) and strength (2500 psi) was used. The mix yielded 75 8x8x16” CMU with a cured weight of 24.0 lb. Each CMU has 15.1 lb of ESCS aggregate or 17,365 Btu per Block. The difference in wall conductivity values between a 93 pcf lightweight and a 135 pcf normalweight CMU is 0.157. This translates into an energy saving of 20,769 Btu/block/yr, or a pay back of 0.84 years.

Similarly when comparing the embodied energy of lightweight concrete (110 pcf, 3.25” thick) verse normalweight concrete (145 pcf, 4.5” thick) used in equivalent fire rated steel deck assemblies for steel frame building construction it shows about the same embodied energy for both. The additional energy to manufacture the ESCS lightweight aggregate is offset by less over all concrete and steel being used in the floor assembles itself. If the whole building is considered and the material savings for smaller columns and foundations are included, it’s most likely there will be a significant embodied energy reduction.

**Energy performance:** The use of LWA lowers the thermal conductivity of concrete and provides significantly better insulating qualities for thermally sensitive applications such as cryogenic applications or high temperature petroleum storage structures.

Reducing the concrete density increases its thermal resistance. For example, concrete at
90 lb/ft$^3$ has an R-value of 0.26/inch while the R-value for 135 lb/ft$^3$ concrete is approximately 0.10/inch. In other words, the 90 lb/ft$^3$ concrete has a 260% better insulation factor than the 135 lb/ft$^3$ concrete (National Concrete Masonry Association NCMA TEK 6-2A: R-Values for Single Wythe Concrete Masonry Walls).

Henderson Engineering, Inc., Kansas City, MO, performed an energy cost study on a “big box retail” building to determine the difference between 90 lb/ft$^3$ lightweight concrete masonry and 135 lb/ft$^3$ normalweight concrete masonry. Several locations were evaluated with results for Omaha, NE (a central location) translating into a savings of 5.5 cents per block per year. This energy cost reduction extends over the life of the structure. The life cycle cost savings are many times greater than the potential higher first cost of the block.

**Fire Resistance:** Lightweight concrete is more fire resistant than ordinary normalweight concrete because of its lower thermal conductivity, lower coefficient of thermal expansion, and the inherent thermal stability of an aggregate that has already been heated to more than 2000º F; as reported in ACI 216 Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies, when slab thickness is determined by fire resistance and not by structural criteria (joists, waffle slabs e.g.), the better thermal performance of lightweight concrete will reduce the thickness of slabs, resulting in significantly lower concrete volumes.

**Lowering the Environmental Impact of Construction.** Construction requires transportation! And there is a direct correlation between transportation, weight and environmental impact. Transportation requirements are directly related to weight and demonstrate an economic and environmental advantage when using lightweight aggregate in precast, ready-mix concrete and masonry. Table 1 includes two trucking studies conducted at a U.S. precast plant. These studies demonstrated that the transportation cost savings were seven times greater than the additional cost of lightweight aggregate used to reduce the concrete density. Fewer trucks in congested cities are not only an environmental necessity but will also generate fewer public complaints.

**Table 1. Analysis of Shipping Costs of Precast Concrete Products**

(Courtesy of Big River Industries, Inc.)

<table>
<thead>
<tr>
<th></th>
<th>Project Example Number 1</th>
<th>Project Example Number 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Shipping Cost per Truck Load</strong></td>
<td>$1,100</td>
<td>$1,339</td>
</tr>
<tr>
<td><strong>Number of Loads Required</strong></td>
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</tr>
<tr>
<td>Normalweight (145 lb/ft$^3$)</td>
<td>431</td>
<td>87</td>
</tr>
<tr>
<td>Lightweight (114 lb/ft$^3$)</td>
<td>287</td>
<td>66</td>
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<tr>
<td><strong>Total Reduction in Truck Loads:</strong></td>
<td><strong>144</strong></td>
<td><strong>21</strong></td>
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<tr>
<td><strong>Transportation Savings</strong></td>
<td></td>
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<tr>
<td>Shipping Cost per Load</td>
<td>$1,100 x 144</td>
<td>$1,339 x 21</td>
</tr>
<tr>
<td><strong>Transportation Savings:</strong></td>
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<td>$28,119</td>
</tr>
<tr>
<td>Profit Impact</td>
<td>Transportation Savings</td>
<td>$ 158,400</td>
</tr>
<tr>
<td>Less: Premium Cost of lightweight concrete</td>
<td>-17,245</td>
<td>- 3,799</td>
</tr>
<tr>
<td>Net Cost Savings by using lightweight concrete</td>
<td>$ 141,155</td>
<td>$ 24,320</td>
</tr>
</tbody>
</table>

In a similar manner Chandler Materials Inc. reported that lightweight concrete masonry units (CMU) saves truck miles. On a project requiring 100,000 8”CMUs it required 31% fewer truck loads (37 loads) to deliver lightweight units weighing 26 pounds each versus normal weight units weighing 38 pounds. This translated into 1,850 fewer truck miles traveled and savings of $3,700 in trucking cost, or $0.04 per block.

**Sustainability of the Workforce – Ergonomics.** One of the best examples of lightweight concrete and ergonomics is concrete masonry. The Center for Infrastructure Research, University of Nebraska at Lincoln reported that long-term problems stem from lifting heavy concrete masonry units. “Some masons must retire early due to the heavy lifting, and many masons experience crippling back and shoulder injuries before retirement”. This continual loss of skilled labor is expensive to replace and can hardly be considered “sustainable or green”.

At the same strength, lightweight concrete products are up to 40% lighter than traditional concrete. Lower weight reduces the physical demands on labor and equipment, resulting in fewer injuries and worker’s compensation claims, as well as extending equipment life. Repeatedly lifting less weight extends a worker’s career, and allows women and men to work efficiently. Even though mason productivity increases with lightweight CMU’s and will result in approximately 20% more wall area in a year, the mason lifts 15% less weight (about 94 less tons per year) than when placing normal weight units at lower production rates. To a similar degree, this applies to most concrete products that must be handled by labor.

**Drying Suspended Concrete Floors on Steel Decking.** The following is a brief summary of a Suspended Concrete Floor Drying Study dated October 12, 2009 by Peter A Craig FICRI, Concrete Floor Specialist.

Under laboratory conditions, lightweight concrete has been reported to take approximately twice as long as normal weight concrete to reach an acceptable level of dryness for floor coverings and coatings. On 13 June 2007 The Expanded Shale, Clay and Slate Institute (ESCSI) undertook a study to determine if similar results can be expected in an uncontrolled, “Real World” environment.

Lightweight and normal weight concretes were placed in pre-constructed 12’ x 12’ steel deck forms housed in a non-climate controlled warehouse area of Advanced Adhesive Technologies facility in Dalton, Georgia. Each of the formed sections was elevated approximately one foot above the floor to simulate actual jobsite conditions. Overhead doors to the facility remained open during the day Monday through Friday and closed over the weekend.
Three UL fire rated D 916 floor (Fig. 1) assemblies (12’ x 12’ panels) were constructed with total slab depth of, 5.25” lightweight concrete, 6.5” normal weight concrete and one 5.25” lightweight concrete on slotted steel deck.

![Fig 1. UL D 916 Fire Rated Floor Assembly](image)

Moisture Vapor Evaporation Rate (MVER) Test Results: It took 128 days after placement for normal weight concrete with a non-ground, tight-troweled finish to fall below the rate of 5 lb/24 hr/1000 sq ft acceptable for vinyl composition tile (VCT). It took 142 days for both lightweight and normal weight concrete to fall below a 5 lb emission rate with a non-ground tight troweled finish, a ground, tight troweled finish or a non-ground burnished finish. It took 170 days for burnished and ground lightweight concrete, on slotted or un-slotted metal deck, to fall below a 5 lb emission rate. For all intents and purposes, regardless of finish or surface preparation, it took all panels 226 days, and a period of very low ambient humidity, to reach an emission rate of 3 lb/24 hr/1000 sq ft, which is considered safe for most types of floor coverings and coatings.

In-Situ Concrete Relative Humidity (RH) Test Results: The industry target level of 75% RH was not reached within any of the panels one year after the start of testing. pH Test Results: After 90 days pH levels remained consistent at 10.0 for both lightweight panels and 9.5 for the normal weight panel.

Conclusions: In the “Real World” conditions of Dalton, Georgia, when measured by currently acceptable methods, there was no appreciable difference in the drying time between normal and lightweight concrete on fire rated steel deck floor assemblies.

Optimize Concrete Performance - Aggregate/Cement Interface. An essential step toward sustainability is evaluating how a given product interfaces with adjacent products and what effect this has on the performance of the combined materials. In this case how does the interface between lightweight aggregate and the hydrating cementitious mortar matrix affect the performance of structural concrete?

Contact Zone: One principal difference between lightweight concrete and normalweight concrete is the development and positive influence of the contact zone. The contact zone in lightweight concrete is the interface between two porous media: the lightweight aggregate particle and the hydrating cementitious binder and has been demonstrated to be significantly superior to that of normalweight concrete. This improvement in the quality, integrity, and microstructure stems from a number of characteristics that are unique to the interface between lightweight aggregate and surrounding cementitious mortar matrix. These characteristics include but are not limited to the following:
• The alumina and silicate rich pozzolanic surface of the fired ceramic ESCS aggregate combines with the Ca(OH2) liberated by hydration of the portland cement

• Reduced microcracking at the matrix/lightweight aggregate interface because of the similarity of the modulus of elasticity of the aggregate and the surrounding cementitious matrix.

• The modulus of elasticity of concrete depends on the relative amounts of paste and aggregate and the modulus of each constituent. In normalweight concrete there is an elastic incompatibility between the higher moduli of sand, stone, and gravel and the surrounding cementitious matrix. In contrast, the moduli of the lightweight aggregate particles are more closely matched to that of the matrix.

• Essentially, a lower modulus of elasticity (Ec) value for lightweight concrete results in a reduced stiffness, as defined by the product of modulus of elasticity and moment of inertia (EI). Reduced stiffness can be beneficial in cases requiring improved flexural response, such as bridges, structures where differential settlement may occur, etc.

• Moisture dynamics between the two porous phases (lightweight aggregate and the porous cementitious matrix is fundamentally different than the usual condition with dense aggregates, where bleed-water lenses form around the non-absorbent coarse natural aggregates that have a w/cm ratio significantly higher than the matrix. The accumulated water at the interface is subsequently lost during drying, leaving voids and a weak, low-quality aggregate/matrix interface (ACI 213R-03).

• When pozzolans are added, the high-quality microstructure of the contact zone of concrete containing lightweight aggregate is moderately enhanced. In contrast, when high-quality pozzolans are used in concretes containing normalweight aggregates, this zone of weakness is significantly improved.

**Internal Curing, Cracking, Elastic Compatibility, Permeability:** Lightweight fine aggregate batched at a high degree of saturation may be substituted for an equal volume of normalweight sand to provide internal curing in concrete (Fig 2). Field experience has shown that High Strength Concrete is not necessarily High Performance Concrete and that High Performance Concrete need not necessarily be high strength. A frequent, unintended consequence of concrete and especially high strength concrete is early-age cracking.

Over time, there is more improvement in the quality of concrete containing pre-wet lightweight aggregate than with ordinary concrete. The reason is better hydration of the cementitious fraction provided by moisture available from the slowly released reservoir of absorbed water within the pores of the lightweight aggregate. The fact that absorbed moisture in the lightweight is available for internal curing has been known for more than four decades. The first documentation of improved long term strength gains made possible by the use of saturated normalweight aggregates, was reported in 1957 by Paul Klieger, who, in addition, commented in detail on the role of absorbed water in
lightweight aggregates for extended internal curing. Campbell and Tobin documented the benefits of using pre-wet LWA at the time of batching in 1967. Their tests confirmed that availability of absorbed moisture within the LWA produced a more forgiving concrete that was less sensitive to poor field-curing conditions.

High cementitious content and low w/c concretes are vulnerable to self-desiccation and benefits significantly from the added internal moisture. Internal curing is especially helpful for concrete containing high volumes of pozzolans that are sensitive to curing procedures. While improvements in long-term strength gain have been observed, the principal contribution of internal curing rests in the reduction of early age cracking and long term permeability that develops from an extension in the time of curing. In 1959 Powers et al., showed that extending the time of curing increased the volume of hydration products formed, which caused the capillaries to become segmented and discontinuous. (ESCSI 2006)
Premature failure of concrete should not be tolerated. Whether by micro-cracks or macro-cracks, a major source of failure is initiated at cracks. Therefore, mitigating cracking becomes an essential element in sustainability. Adding lightweight aggregate to concrete mitigates crack formation, as demonstrated in the following narrative. “Core samples taken from hulls of 80-year-old lightweight concrete ships still floating in sea water, as well as 40 to 50-year-old lightweight concrete bridges, reveal that the lightweight concrete has a dense contact zone at the lightweight aggregate/cement matrix interface. This zone has very low levels of micro cracking throughout the cement mortar matrix” (Sturm 1999).

Explanation for this high resistance to weathering and corrosion involves several physical and chemical mechanisms including superior resistance to micro cracking. This excellent performance is developed by the significantly higher aggregate/matrix adhesion (contact zone) and the reduction of internal stresses due to elastic matching of the lightweight aggregate and cementitious mortar matrix phases (Holm, Bremner, and Newman 1984). This elastic matching is present regardless of the lightweight aggregate size.

High ultimate strain capacity is also provided by lightweight concrete as it has a high strength/modulus ratio. The strain at which the disruptive dilation of concrete starts is higher for lightweight concrete than for equal-strength normalweight concrete. A well-dispersed pore system provided by the surface of the lightweight fine aggregates may also assist the air-entrainment system and serve an absorption function by reducing concentration levels of deleterious materials in the matrix phase.

The following quote (Henkensiefken 2010) confirms the reduction of early age cracking. “The replacement of sand with prewetted LWA can provide a significant reduction in settlement and plastic shrinkage cracking of mortars and concretes. If a sufficient volume of prewetted LWA is provided, plastic shrinkage cracking can be reduced or eliminated under the exposure conditions employed in this study. The water movement from the LWA to the nearby cement paste, both prior to and after setting, has been verified using X-ray absorption measurements. The supply of water by the rigid but porous LWA reduces the settlement accompanying evaporation and the magnitude of the capillary stresses that are developed during drying as the water-filled pores in the LWA are generally larger than those in the hydrating cement paste. It should be noted that if self-desiccation is also a concern, the mixture needs to be properly proportioned to include enough water stored in the LWA to alleviate both of these problems.”

Permeability investigations conducted on lightweight and normalweight concrete exposed to the same testing criteria have been reported by numerous researchers, Nishi et al. (1980), Keeton (1970), Bamforth (1987), Bremner et al. (1992). It is of interest that, in every case, despite wide variations in concrete strengths, testing media (water, gas, and oil), and testing techniques (specimen size, media pressure, and equipment), lightweight concrete had equal or significantly lower permeability than its normalweight counterpart. Khokrin (1973) further reported that the lower permeability of lightweight concrete was
attributed to the elastic compatibility of the constituents and the enhanced bond (improved contact zone) between the lightweight aggregate and the mortar matrix.

There are several real world projects that have successfully used the internal hydration concept of pre-wetted lightweight aggregate (internal curing) in low-slump paving. The largest is the Union Pacific Intermodal Facility, Hutchins, Texas that began in 2005; the project used 250,000 yd\(^3\) (190,000 m\(^3\)) of concrete that required flexural strengths of 650 and 750 psi (4.5 and 5.2 MPa) at 28 days. The 7-day flexural strengths were typically in the range of 90 to 100% of the required 28-day flexural strength. In contrast to conventional paving mixtures, cracking was extremely minimal and that a visual inspection after 6 months in service only found one crack. (Villarreal, 2008)

State highway, SH- 121, Dallas, Texas used 1300 cubic yards of internally curried continuously re-enforced concrete in 2006. The concrete incorporated 300 lb/yd\(^3\) (178kg/m\(^3\)) of pre-wetted LWA. The concrete was Class P (3500 psi or 570 psi flex at 7 days). After two months the number of cracks were fewer then half that of the control normalweight concrete and the average crack width was reduced significantly.

**Internal Curing Contributes to Sustainability.** The following is quoted from *Internal Curing Improves Concrete Performance throughout its Life, Concrete In Focus* (Henkensiefken 2009).

> “Sustainability has become a major focus of various industry organizations, including NRMCA and ACI (http://www.concretesdc.org). Internal curing has the potential to contribute to a more sustainable infrastructure in a variety of ways. As shown in the results [here in], internal curing with blends of LWA and CCA [Crushed Concrete Aggregate] may provide cost-effective sustainable materials with significant reductions in autogenous shrinkage and early-age cracking, without sacrificing strength. Internal curing not only contributes to a more efficient hydration of the cement in a concrete mixture, but also promotes enhanced performance of SCMs such as fly ash and slag, both seen as major material sources for “greener” more sustainable concretes. As demonstrated by the results of the presented studies, the use of internal curing can substantially reduce transport properties such as diffusion and sorptivity, thereby increasing the service life of concrete structures. Finally, the enhanced hydration and increased strengths provided by internal curing may allow for small but significant reductions in cement content in many concrete mixtures, thereby significantly reducing the carbon footprint of each cubic yard of concrete used throughout the world.”

> “In summary, this paper has indicated that, while internal curing may have been originally developed to reduce autogenous shrinkage and mitigate early-age cracking in high performance concretes, its application has far-reaching consequences for the performance of concrete throughout its lifetime. By providing an on-demand source of extra water, internal curing can improve the slump retention, workability and finishability of fresh concrete (Villarreal 2007) (Friggle 2008) (Villarreal 2008), and reduce deformations and cracking due to plastic,
autogenous and drying shrinkage. The increased hydration and improved interfacial transition zone micro-structure provided by internal curing may increase strength while concurrently decreasing transport (and degradation).”

**Green Roof and Horticulture.** ESCS helps to reduce heat island effects by amending soils to improve landscaping and through its use in both intensive and extensive roof top gardens. LWA reduces dead load and is non-toxic, odorless, 100% inert and will not compress, degrade, decompose, or react with agricultural or horticultural chemicals. ESCS resists compaction, improves aeration and is incorporated into engineered structural soil to support healthy plant growth and improve drainage while allowing access by heavy emergency vehicles to the edges of buildings. LWA enhances soil resiliency to climate changes by reducing nutrient loss and improving moisture retention.

**LEED™.** ESCS has several benefits that contribute to projects becoming LEED™ (*Leadership in Energy and Environmental Design*) certified. It can contribute to at least 33 of the points available in 2009 LEED™ V3 as shown in Table 2.

<table>
<thead>
<tr>
<th>LEED Category</th>
<th>Available Points</th>
<th>Points Where ESCS LWA Can Contribute</th>
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</thead>
<tbody>
<tr>
<td>Sustainable Sites</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td>Water Efficiency</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Energy &amp; Atmosphere</td>
<td>35</td>
<td>1 plus*</td>
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<tr>
<td>Material &amp; Resources</td>
<td>14</td>
<td>9</td>
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<td>Indoor Environmental Quality</td>
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<tr>
<td>Innovation &amp; Design</td>
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<td>Up to 5</td>
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<td>Total Possible Points</td>
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<td>Up to 33+</td>
</tr>
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*1-19 points can be awarded for energy cost savings of 12%-48% for new buildings and 8%-44% for existing buildings. ESCS will improve the thermal performance of building materials and contribute toward obtaining these credits.*

**Regional material:** LWA is manufactured at numerous facilities in close proximity to almost every building site. The 500-mile radius from these facilities encompasses most major markets all across the United States. Lightweight products have lower transportation requirements and use fewer trucks to transport the same amount of product when compared to normal weight aggregate or concrete.

**Storm Water Management and Water Treatment.** The use of lightweight aggregate in site development has assisted designers in addressing the important issue of storm water
management with on site treatment. LWA can be used to construct vegetated filter strips, rain gardens, rain basins, constructed wetlands and bioswales to treat and reduce the amount of storm water runoff. The voids within ESCS provide an environment suitable for beneficial microbial action that will help to filter storm water and waste water with the removal of suspended solids, hydrocarbons, metals, nitrogen and phosphorous. ESCS is also used as the sub-base, underground aggregate filtering fill and water storage area beneath permeable pavements.

**Conclusion.** Lightweight aggregate concrete has been successfully used for well over two millennia. It has had widespread use for the past ninety years. This track record of proven performance has demonstrated how lightweight aggregate contributes to sustainable development by lowering transportation requirements, optimizing structural efficiency that results in a reduction in the amount of overall building materials being used, conserving energy, reducing labor demands and increasing the service life of structural concrete through internal curing and the improvement of the contact zone. These benefits all fit into the green building movement and help projects become LEED™ certified. The use of lightweight aggregate often lowers initial construction cost and the life-cycle cost of the structure.

Lightweight Aggregate can help to reduce heat island effects by amending soil to improve landscaping and promoting the use of "green roofs". Lightweight aggregate helps designers solve the issue of storm water management with on-site retention and treatment.

The sustainability process starts with a decision to create a lifestyle that respects the interdependence of all life. This requires concern for long-term performance with minimal maintenance and energy demand in our designs, as well as efficiency and responsibility in our manufacturing and construction. We believe the utilization of lightweight aggregate with all its benefits is an important element in the sustainability of the concrete industry.

**References**


