ENGINEERING PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE

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SUMMARY

This paper discusses the unique physical characteristics of rotary kiln expanded slate lightweight aggregate for producing high performance and high strength lightweight concrete. The compressive strength, elastic modulus, splitting tensile strength, specific creep, and other properties of lightweight concrete are significantly affected by the structural properties of the lightweight aggregate used. Concrete production, transportation, pumping and placing are also affected. Raw materials and rotary kiln processing is discussed. Data from academic and laboratory studies is presented as well as data from actual projects such as the Raftsundet Bridge in Norway and the Hibernia Offshore Oil Platform Gravity Base Structure.

INTRODUCTION

Structural lightweight aggregate concrete is an important and versatile material in modern construction. It has many and varied applications including multistory building frames and floors, bridges, offshore oil platforms, and prestressed or precast elements of all types. Many architects, engineers, and contractors recognize the inherent economies and advantages offered by this material, as evidenced by the many impressive lightweight concrete structures found today throughout the world [1]. Structural lightweight aggregate concrete solves weight and durability problems in buildings and exposed structures. Lightweight concrete has strengths comparable to normal weight concrete, yet is typically 25% to 35% lighter. Structural lightweight concrete offers design flexibility and substantial cost savings by providing: less dead load, improved seismic structural response, longer spans, better fire ratings, thinner sections, decreased story height, smaller size structural members, less reinforcing steel, and lower foundation costs. Lightweight concrete precast elements offer reduced transportation and placement costs [2].

There are many types of aggregates available that are classed as lightweight, and their properties cover wide ranges. Elastic properties, compressive and tensile strength, time-dependent properties, durability, fire resistance, and other properties of structural lightweight aggregate concrete are dependent on the type of lightweight aggregate utilized in the concrete [1]. Structural lightweight aggregate concrete is defined as concrete which: (a) is made with lightweight aggregates conforming to ASTM C 330, (b) has a compressive strength in excess of 2,500 psi (17.25 MPa) at 28 days of age when tested in accordance with methods stated in ASTM C 330, and (c) has an air dry density not exceeding 115 pcf (1,840 kg/m^3) as determined by ASTM C 567 [3]. Job specifications often allow unit weights up to 120 pcf (1,920 kg/m^3) or more. High performance lightweight concretes are typically produced using rotary kiln expanded clay, shale or slate. These lightweight aggregates are relatively “light” in weight (density) due to the cellular structure of the individual aggregate particles. This cellular structure within the particles is formed at high temperatures, generally 2,000° F (1,100° C) or higher, by the rotary kiln process. This paper focuses on the unique physical characteristics of rotary kiln expanded slate aggregate and the structural lightweight concrete that it can be used to produce.

RAW MATERIALS

Currently, the foothills region of North Carolina, east of Charlotte, is the only source of slate that is being used as a raw material for rotary kiln expanded slate lightweight aggregate. This argillite slate is found in a geologic formation known as the Tillery Formation. It is a thinly laminated, gray, fine-grained siltstone, composed of clastic (transported) rock fragments. The geologic history of the Tillery Formation began 550 million years ago in the Cambrian Period, approximately 330 million years before dinosaurs. Rock fragments of volcanic ash origin were deposited in a water environment (sedimentation) and later solidified into solid rock (lithification). Consequent burial and tectonic pressure then changed (metamorphosed) the rock into argillite slate.

Along with the deposition of the volcanic ash was an occasional ash (debris) flow or gravitational mud-type flow into the same deposition basin. Additional layers, consisting of volcanic tuff with high calcite concentrations, formed within the system. Subsequent millions of years of geologic forces caused the alternating layers of material to fold and fault, causing disorder to the once ordered, layered system. Along with this disorder came diabase dike rock intrusion of Triassic-Jurassic age (about 180-220 million years ago), which caused additional rock structures of vertical emplacement that further complicated the system.

The Tillery Formation is a complex system and must be selectively mined in order to separate the desirable product from the non-desirable to manufacture a high quality expanded slate aggregate. The calcareous tuff impedes the bloating process of lightweight aggregate production. At 2,000° F (1,100° C), the calcite simply calcines. At high temperatures of over 2,200° F (1,200° C), diabase rock (specific gravity of 3.0) begins to melt to a glassy type of rock with no specific gravity change. Because this high specific gravity creates havoc on a desired lightweight specific gravity material, it should be avoided totally. The only way to avoid this material is through a process of selective mining. Extensive core drilling must be performed along with microscopic, chemical, and laboratory test bloating of the core in order to “map” the subsurface material and identify desirable versus non-desirable aggregate. Computer software must then be used to identify high-quality cross-sections of desirable versus non-desirable rock zones. Mining computer software can then be used to design the selective mining sequence. A modern fractionating plant with controllable radial stackers and feed systems then crushes the high-quality bloatable material to optimum size for processing and separates it to be conveyed to the raw feed storage silos [4].

ROTARY KILN PROCESS

Expanded slate aggregate is produced by the rotary kiln method. This discussion describes one specific lightweight aggregate manufacturing plant. Other rotary kiln process facilities are similar, but may have variations from the process described herein.

The rotary kiln is a long tube that rotates on large bearings. Typical kilns are approximately 11 feet (3.4 meters) in diameter and 160 feet (49 meters) long constructed on a slight incline. The kiln is lined with insulation and refractory materials. Raw slate is fed from the storage silos into patented pre-heaters that allow the rock to heat up at a moderate rate. It then enters the upper end of the kiln where it slowly revolves and moves toward the "burn zone" near the lower end of the kiln. The "burn zone" reaches temperatures in excess of 2200° F (1200° C). The plant being described uses high BTU, low sulfur coal for its heat source. Some lightweight aggregate production facilities use natural gas, while others supplement these traditional energy sources by burning hazardous wastes. In the "burn zone" of the rotary kiln, the slate becomes sufficiently plastic to allow expanding gases to form masses of small, unconnected cells. As the expanded slate cools, these cells remain, giving the aggregate its low unit weight and low absorption. The expanded material, called clinker at this point, leaves the lower end of the kiln and enters a forced-air cooling system. This cooling process reduces the chance that the aggregate will crystallize as can happen in water-cooled systems where the very hot expanded material is dropped directly into a pit filled with cold water.

From the cooler, the clinker is conveyed to a classification area. In the classification area the material is crushed and screened to various size fractions. These different size fractions are kept separate until, by means of an automaticly controlled blending system, specified gradations are produced for various applications. After blending, actual moisture content is automatically adjusted to a predetermined level. The expanded slate aggregate is then tested for proper gradation, moisture content, specific gravity and unit weight. After testing is completed, the expanded slate aggregate is stored or conveyed directly to trucks or railcars for shipment. Two procedures are used to minimize segregation during storage: 1) Coarse grades are stored in low-elevation stockpiles that feature a moisture control system. 2) Fine grades are stored in low-height silos that feature a perimeter port feeding design to minimize segregation. Prior to loading, trucks and railcars must be inspected for cleanliness and washed when needed. A particular procedure is carefully followed when loading material from either the storage silos or the stockpiles to insure that material consistency is maintained. A rigid quality control and testing program confirms compliance with the customer's specified needs.

PHYSICAL CHARACTERISTICS OF EXPANDED SLATE AGGREGATE

<u>1/2" (12.5mm) Structural Aggregate</u>

Density

- Dry Loose (ASTM C29) 50 lbs/cf 805 kg/m^3
- Saturated Surface Dry Loose (ASTM C29) 52 lbs/cf 833 kg/m^3

Specific Gravity

- Dry (ASTM C127) 1.45
- Saturated Surface Dry (ASTM C127) 1.52

Absorption

- Saturated Surface Dry (ASTM C127) 6%
- Under High Pumping Pressure of 150 psi (1033 kPa) 9.4%

Soundness

- Magnesium Sulfate (ASTM C88) 0.01%
- Sodium Sulfate (ASTM C88) 0.23%
- After 25 Cycles Freezing & Thawing (AASHTO T103) 0.22%

Toughness

- Los Angeles Abrasion (AASHTO T-96-B) 25%

ENGINEERING PROPERTIES OF STRUCTURAL LIGHTWEIGHT CONCRETE

The use of lightweight aggregate to reduce concrete densities is a well-established procedure where properties such as increased fire resistance, ease of handling and transportation, or reduced structure dead load is desired. Lightweight concrete with compressive strengths of up to 5,000 psi (34.5 MPa) has been used in commercial construction routinely since the early 1930's. During the last two decades, however, much higher strengths have been specified.

Aggregates normally constitute 60–70% of a concrete mix, and the physical characteristics of the aggregate will, therefore, have a pronounced influence on the physical property of the concrete [5]. High strength concrete relies more heavily on the quality of the aggregate than does low or even medium strength concrete. The function of the aggregate, to a large extent, is to act as an inexpensive filler material. The cement paste matrix takes up most of the load imposed on the concrete. As design loads approach and exceed the strength limits of the cement paste matrix, the load carrying capacity of the aggregate and the interplay between aggregate and cement paste become the limiting factors in strength development. For all practical purposes, this limit appears to be in the region of 15,000 to 16,000 psi (100 to 110 MPa) for concrete using normal weight aggregate, approximately 80% of this for concrete using expanded slate lightweight aggregate and probably less than 70% of this for concrete using expanded clay or shale aggregate. This limitation is more pronounced for lightweight concrete because the mechanical characteristics of the lightweight aggregate are more similar to those of the cement paste matrix than to the normal weight aggregate, and variations in aggregate quality will be more directly reflected in the concrete characteristics.

Low absorption lightweight aggregates are most desirable for developing a concrete mixture of high strength and durability [6]. The following table lists typical properties of various lightweight aggregate materials [5]:

Type	Dry Loose Unit Weight (pcf)	Dry Loose Unit Weight (Kg/m^3)	Bulk Specific Gravity (Kg/m^3)	1 Hour Water Absorption (% Weight)	24 Hour Water Absorption (% Weight)
Expanded Clay	37	600	1300	25	30
Expanded Clay	47	750	1300	8	11
Expanded Clay	50	800	1450	8	11
Expanded Clay	45	700	1250	7	not available
Expanded Clay	50	800	1500	7	10
Expanded Clay	50	800	1500	12	20
Expanded Shale	45	700	1400	9	10
Expanded Slate	47	750	1500	4	5

In the mid 1980's, the North Carolina Department of Transportation sponsored a two-year study investigating the properties of high strength concrete using materials from North Carolina, including expanded slate aggregate. This study was conducted at North Carolina State University. One of the primary goals was to provide basic "round figure" data on certain "specialty" concretes such as lightweight concrete. "The purpose of this research was not so much to produce the absolute highest strengths attainable as it was to produce the highest strength which could reasonably be attained in practice with more or less conventional materials and methods." Lightweight concrete was produced with a compressive strength greater than 11,000 psi (76 MPa). The elastic modulus of high strength lightweight concrete was found to be less than the elastic modulus of normal weight concrete of comparable strength, but the equation recommended in ACI 318, based on unit weight and compressive strength, provided a good estimate of the elastic modulus of the high strength lightweight concrete in this study. The following table presents results from the lightweight concrete mixes investigated in this study [7].

Summary Data: Lightweight High Strength Concrete[7]

Mix	D-1	D-2	D-8	D-10	D-11
Cement (pcy)	742	711	795	797	862
Silica Fume (pcy)		213	239	239	157
1/2" LW Coarse Aggregate (pcy)	950	890	900	830	760
Natural Aggregate (pcy)				410	
Slump (inches)	6	6-3/4	6	6	4
Total Air Content (%)	5.4	9.1	7	6.1	3.3
Unit Weight, Plastic (pcf)	114.4	110	113.6	122.4	126.8
Unit Weight, 28-day air dry (pcf)	105.3	107.3	111.7	119.2	122
Strength					
Compressive (psi)	6,920	8,360	8,170	10,980	11,850
Compressive (MPa)	47.7	57.6	56.3	75.7	81.7
Age (days)	49	49	35	35	35
Splitting Tensile (psi)	not tested	not tested	520	505	615
Splitting Tensile (MPa)			3.6	3.5	4.2
Age (days)			35	35	35
Elastic Modulus (million psi)	not tested	not tested	3.27	3.95	4.56
Elastic Modulus (GPa)			22.6	27.2	31.4
Age (days)			35	35	35
Specific Creep (millionths/psi)					0.25
Specific Creep (millionths/MPa)					36.25
Age (days)					365

Specified Density Concrete (MNDC) for Offshore Oil Platforms

Prior to the 1980's, very little research had been performed concerning the use of lightweight aggregate in high strength concrete. Development of oil fields in Arctic locations prompted construction of large offshore platforms that were constructed in accessible locations and then "floated" to the oil fields. These huge floating structures required reduced density concrete for improved buoyancy. Other properties required included: workability, pumpability, impermeability, and high strength for structural integrity, durability and the ability to withstand iceberg impact. A major, 3-1/2 year study was funded by a consortium of oil companies on high strength lightweight aggregate concrete for arctic applications [8]. This study indicated that not all lightweight aggregates could be used for offshore structures because of limiting strength of the aggregate or because of high water absorptions that adversely affected freezing and thawing durability and constructability. Testing for the Hibernia Platform indicated that replacing 50% of the normal weight aggregate (by volume) with expanded slate aggregate most closely approximated the project criteria for the modified normal density concrete (MNDC). The following table presents results from this testing [9]:

Summary of Test Results for Full Size Field Batches
Modified Normal Density Concrete

Mixture	Quantities	
Cement	450 kg/m^3	
Fine Aggregate	920 kg/m^3	
Coarse Aggregate, NW	430 kg/m^3	
Coarse Aggregate, LWA	255 kg/m^3	
Mix Water	150 kg/m^3	
W/C Ratio	0.33	
Compressive Strength	79.3 MPa	(11,500 psi)
Unhardened Density	2193 kg/m^3	(136.8 pcf)
Slump	216 mm	(8.5 inches)
Splitting Tensile Strength	5.87 MPa	(851 psi)
Modulus of Elasticity	30.5 GPa	(4.4 x 10^6 psi)
Poisson's Ratio	0.22	

Creep and Shrinkage of Lightweight Concrete

In 1989-1990 a study was conducted at North Carolina State University to determine the shrinkage and creep potential of concrete made with expanded slate aggregate [10]. As part of this study, elastic modulus and other standard plastic concrete characteristics were also determined. Four separate concrete mixes were produced for this study. One mix was a conventional concrete using normal weight coarse aggregate for comparison. Two mixes were "standard lightweight" mixes, and the fourth mix was a relatively high strength mix. The author (Leming) noted that values of creep and shrinkage strain for these lightweight concretes were low compared to national (United States) averages. He also noted that values of the elastic modulus were significantly higher than predicted by American Concrete Institute equations based on compressive strength and unit weight. He noted that "this is almost certainly due to the superior stiffness of the expanded slate aggregate compared to many other commercially available lightweight aggregates The following table summarizes the results of the "high strength" mix in this study.

Quantities		Mix S-4
Cement (pcy)		536
Ground Blast Furnace Slag (pcy)		342
Water (pcy)		323
3/4" (19 mm) Expanded Slate LWA (pcy)		940
Unit Weight Plastic	1948 kg/m^3	121.6 pcf
Unit Weight Dry	1865 kg/m^3	116.4 pcf
Slump	171.5 mm	6-3/4 in
Air		1.50%
Compressive Strength:		
7 days	36.8 MPa	5340 psi
28 days	49.5 MPa	7180 psi
365 days	57.2 MPa	8290 psi
Splitting Tensile Strength:		
7 days	2.6 MPa	370 psi
28 days	3.4 MPa	495 psi
365 days	3.6 MPa	520 psi
Elastic Modulus:		
7 days	23.3 GPa	3.38×10^6 psi
28 days	24.7 GPa	3.58×10^6 psi
365 days	26.5 GPa	3.84×10^6 psi
Creep Data:		
Specific Creep		0.29
Creep Coefficient		1.2
Shrinkage Data (at 365 days):		
Microstrain		310

High Performance Lightweight Concrete for the Raftsundet Bridge [11]

The recently completed Raftsundet Bridge is a 711 meter (2,333 feet), free cantilever, box girder bridge spanning the Raftsundet Sound in Northern Norway. The main span has a total length of 298 meters (978 feet) with a sailing height of 46 meters (151 feet), and is mainly constructed of high performance lightweight concrete with a hardened density of 19.75 kN (125 pcf) and a 28 days compressive strength of 60 MPa (8,700 psi). The bridge contains a total of 10,700 m^3 (14,000 cy) normal weight concrete and 2,400 m^3 (3,140 cy) lightweight concrete, with all the concrete having been distributed by standard concrete pumps. The pumpable lightweight concrete was based on expanded slate aggregate from North Carolina, USA. Prior to this project, lightweight concrete placement by pumping had not been allowed on Norwegian Public Road Department bridges. An extensive testing program was conducted to compare the performance of the lightweight concrete with the normal weight concrete produced and placed on this project. The results show that a high performance lightweight concrete utilizing an expanded slate aggregate can be produced and placed under the same general procedures using the same equipment as for normal weight concrete. Quality control documentation from the general production testing, both at the batch plant, and at the site, demonstrated that the lightweight concrete used at the Raftsundet Bridge showed equal or less variation in most parameters compared to the normal weight concrete used at the same project [11]. The following table presents a summary of these test results.

Mix Properties and Test Results LC60, Raftsundet Bridge Norway

Materials	Quantities	
Cement	430 kg/m^3	
Silica Fume	25 kg/m^3	
Water	175 kg/m^3	
1/2" (12.5 mm) Expanded Slate LWA	550 kg/m^3	
Air	3-6%	
Hardened Density, Average	19.32 kN/m^3	122.8 pcf
Compressive Strength, 28 d, Average	65.9 MPa	9,555 psi
Elastic Modulus:	23.5 GPa	3.4×10^6 psi

Sand Key Condominiums – Phase II

High strength lightweight concrete is increasingly utilized in office buildings and residential buildings in order to achieve long clear spans. The Sand Key Condominiums were recently constructed in the Sand Key Beach resort area near Tampa, Florida, USA. This 14 story project is a post-tensioned concrete frame building. The project specifications called for 9,000 psi (62 MPa) 28 day compressive strength with a maximum calculated equilibrium unit weight (ASTM C567) of 110 pcf (1,760 kg/m^3) for the elevated floor slabs. All of this lightweight concrete was placed by pumping through a 5 inch (125 mm) line. As shown in the following data, average 28 day compressive strengths were over 12,000 psi (82.75 MPa).

Mix Design
Sand Key – Phase II

Materials	Quantities
Cement, Type I	780 lbs.
Fly Ash, Class F	250 lbs.
Normal Weight Sand Fine Aggregate	725 lbs.
½" (12.5 mm) Expanded Slate Coarse Aggregate	980 lbs.
Water	325 lbs.
Total Air (%)	4.0 +/- 1.5
Water/Cement Ratio	0.32
Theoretical Plastic Weight	113.4 pcf (1817 kg/m^3)

Frequency Distribution: 28 Day Compressive Strength
Sand Key – Phase II

Sequence Number	Sample ID	Sample Date	Slump	28 Day Compressive Strength
1	1	6/08/99	8.00 in (205 mm)	11,340 psi (78.2 MPa)
2	2	6/10/99	7.75 in (195 mm)	12,540 psi (86.5 MPa)
3	4	8/06/99	7.75 in (195 mm)	12,105 psi (83.5 MPa)
4	7	9/01/99	8.25 in (210 mm)	12,945 psi (89.3 MPa)
5	11	10/06/99	7.75 in (195 mm)	11,295 psi (77.9 MPa)
6	12	10/07/99	7.50 in (190 mm)	12,775 psi (88.1 MPa)
7	15	11/03/99	7.50 in (190 mm)	12,490 psi (86.1 MPa)
8	16	11/12/99	8.25 in (210 mm)	12,100 psi (83.5 MPa)
9	17	11/12/99	8.50 in (215 mm)	12,495 psi (86.2 MPa)

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Argillite – a compact argillaceous rock differing from shale in being cemented by silica and from slate in having no slaty cleavage.

Slate – a dense fine-grained metamorphic rock produced by the compression of various sediments (as clay or shale) so as to develop a characterist cleavage.

Clastic – made up of fragments of preexisting rocks.

Shale – a fissile rock that is formed by the consolidation of clay, mud or silt, has a finely stratified or laminated structure, and is composed of minerals essentially unaltered since deposition.

Fissile – capable of being split or divided in the direction of the grain or along natural planes of cleavage.

Cambrian – of, relating to, or being the earliest geologic period of the Paleozoic era or the corresponding system of rocks marked by fossils of every great animal type except the vertebrate and by scarcely recognizable plant fossils.

Tectonic – of or relating to the deformation of the crust of a planet, the forces involved in or producing such deformation, and the resulting forms.

Calcite – a mineral $CaCO_3$ consisting of calcium carbonate crystallized in hexagonal form and including common limestone, chalk, and marble.

Calcine – to heat to a high temperature (as inorganic materials) but without fusing in order to drive off volatile matter or to effect changes.

Diabase – an altered basalt (a dark gray to black, dense to fine-grained igneous rock - different from argillite slate).

Tuff – a rock composed of the finer kinds of volcanic detritus usually fused together by heat.