INCREASE SERVICE LIFE OF CONCRETE STRUCTURES WITH LIGHTWEIGHT AGGREGATE

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ABSTRACT

A recent study was conducted to determine the effects of lightweight coarse and fine aggregates on the transport properties and other durability related properties of structural concrete. Transport properties are used in concrete service life prediction computer software programs. The results of the study discussed in this paper show that the time to corrosion in a reinforced concrete structure will be increased by up to 94% when lightweight coarse aggregate concrete mixtures are used compared to a comparable mixture with normalweight aggregates. The study also shows that the replacement of normalweight sand with lightweight fine aggregate can result in an increase in time to corrosion by as much as 1-1/2 to three times.

INTRODUCTION

Of the 614,387 bridges in the National Bridge Inventory, almost four in 10 (39%) are over 50 years or older, and an additional 15% are between the ages of 40 and 49 years. The average bridge in the U.S. is 43 years old. Most of the country's bridges were designed for a lifespan of 50 years, so an increasing number of bridges will soon need major rehabilitation or retirement (1). New technologies are helping engineers design and build bridges better and faster while also improving maintenance for longer bridge life. Owners and designers of many new bridges and other structures exposed to weather conditions now specify a design life of 100 years or more to ensure durability and sustainability. This paper presents details and conclusions of several recent studies on the cracking tendencies of lightweight concrete and internally cured concrete and how they led to a study for the Expanded Shale, Clay, and Slate Institute (ESCSI) on how lightweight coarse and fine aggregates can impact the transport properties and other durability related properties of concrete.

EXPANDED SHALE, CLAY, AND SLATE LIGHTWEIGHT AGGREGATE

Last year, the expanded shale, clay and slate industry entered its second century on the anniversary of US Patent No. 1,255,878 being awarded to Stephen J. Hayde for his invention of the rotary kiln process for manufacturing structural lightweight aggregate. As shown by the studies which are the topic of this paper, the spirit of research and experimentation which preceded this first patent issued in 1918 is still very much alive today. The limited resources and technology available to Stephen Hayde, working as an individual, have been superseded by the improved technology and organized research possible only through the shared knowledge and shared financial support offered by a formal industry association, the Expanded Shale Clay and Slate Institute (ESCSI), founded in 1952 and now comprising an organization of manufacturers of expanded shale, clay, and slate (ESCS) lightweight aggregate (2). ESCS is a ceramic material produced by expanding and vitrifying select shale, clay, or slate in a rotary kiln. The process produces a high quality ceramic aggregate that is structurally strong, durable, environmentally inert, low in density and highly insulative. It is a natural, non-toxic, absorptive aggregate that is dimensionally stable and will not degrade over time.

Lightweight aggregate particles have a low-particle relative density because of their cellular pore system. The cellular structure within the particles is developed by heating ESCS raw materials to incipient fusion. At this temperature, gases are evolved within the pyroplastic mass, causing expansion, which is retained upon cooling. ESCS 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 10% to 30% saturation. Interior pores are essentially non-interconnected and some of the pores remain unfilled after years of immersion (3).

REDUCED CRACKING TENDENCY OF LIGHTWEIGHT CONCRETE

Early-age cracking of concrete bridge decks, typically caused by thermal effects, drying shrinkage, and autogenous shrinkage can have detrimental effects on long-term behavior and durability. Darwin and Browning (2008) reported that by controlling early age cracking, the amount of cracking at later ages should remain low, and that early-age cracking can significantly increase the rate and amount of chloride penetration (from deicing salts), which may accelerate the corrosion rate of embedded reinforcing steel (4). A survey conducted by the Federal Highway Administration (FHWA) found that more than 100,000 bridges suffer from early-age cracking (5). Given the abundance of cracking observed in bridge decks, and the impact of early-age cracking on long term performance and durability, it is imperative that bridge deck concrete be proportioned and placed to minimize early-age cracking. Cracking of hardening concrete occurs when the induced tensile stress exceeds the tensile strength of the concrete. The development of in-place stresses is affected by the shrinkage, coefficient of thermal expansion, setting characteristics, restraint conditions, stress relaxation (creep-adjusted modulus of elasticity), and temperature history of the hardening concrete. The tensile strength (and strain capacity) increases as the hydration of the cementitious system progresses. The tensile strength is impacted by the cementitious materials, the water-cementitious materials ratio, the aggregate type and gradation, the degree of curing (internal/external) provided, and the temperature history of the hardening concrete. Quantification of many of the mechanisms mentioned above is quite complicated at early ages, and many of these variables have complex interactions (6).

In 2010, ESCSI sponsored a research project at Auburn University where the effect that the use of lightweight aggregate (LWA) has on the cracking tendency of concrete was evaluated by cracking frame testing techniques. Cracking frames can measure the development of stresses due to thermal and autogenous shrinkage effects from setting until cracking. The combined effect of modulus of elasticity, creep/relaxation, coefficient of thermal expansion, thermal conductivity, autogenous shrinkage, and tensile strength on the cracking potential in a specific application is thus directly captured and quantified by this unique test setup. Since the specimen is sealed against water loss, the effect of drying shrinkage is not measured with this setup. A rigid cracking frame as developed by Dr. Rupert Springenschmid at the Technical University of Munich, Germany was utilized in this research project. The frame is designed to allow fresh concrete to be cast into temperature-controlled formwork within the frame. With this unique formwork, the concrete can be subjected to a variety of temperature profiles that simulate in-place conditions of bridge decks, elevated slabs, pavements, mass concrete structures, etc. The primary objectives of this research were:

- Develop and evaluate the cracking tendency of three types of lightweight aggregate bridge deck concretes relative to a typically used normalweight concrete mixture,

- Evaluate the effect of placement and curing temperature on the cracking tendency of concrete,
- Evaluate the modulus of elasticity, splitting tensile strength, compressive strength, coefficient of thermal expansion, and thermal diffusivity of lightweight concretes and determine their effect on the early-age cracking tendency,
- Evaluate the effect of three different source aggregates (shale, clay, and slate) on the development of mechanical properties and the cracking tendency of bridge deck concrete, and
- Determine the effectiveness of pre-wetted lightweight aggregate to provide internal curing moisture to mitigate autogenous stress development.

Three lightweight aggregate sources were evaluated by producing three different concretes with each of these lightweight aggregates and one concrete mixture with normalweight aggregate. Each concrete mixture was subjected to two types of controlled temperature histories while measuring the stress development from setting until the onset of cracking. To assess the effect of placing temperature, each mixture was placed at summer and fall placement conditions. Match-cured concrete cylinders were produced to determine the development of mechanical properties of each concrete mixture under various controlled temperature histories. The effect of the supplied internal curing water from lightweight aggregate was assessed by measuring the restrained stress development of concrete specimens cured under isothermal conditions. In addition, the coefficient of thermal expansion of the hardened concrete was assessed.

Internal Curing

Historically, lightweight aggregates (LWAs) have been used to reduce the density of concrete, thus reducing the dead load weight of slabs, girders, etc. In recent years, however, LWAs have been added to concrete to take advantage of the high absorption capacity of the aggregates to add internal curing water (in addition to batch water) for hydration. When cement hydrates, capillary pores are created. As the water in the capillary pores is consumed by continuing hydration or by atmospheric desiccation, the internal relative humidity decreases and stresses are induced. Pre-wetted high absorption particles can desorb water into the cement pore structure, thus reducing capillary stresses and providing water for hydration without increasing the initial water/cementitious material ratio. The process of providing additional water for capillary pore stress reduction and additional cement hydration through pre-wetted particles is called internal curing. Lightweight fine aggregates are generally used for internal curing purposes due to their greater dispersion compared to coarse aggregates. It has been shown that water from LWA can move 0.07 inches into paste around the aggregate particle (7).

Conclusions – Auburn University Research on Cracking Tendency of Lightweight Concrete

The following bullet points are some of conclusions from this research that were made about the effect of using lightweight aggregate on the cracking tendency and autogenous shrinkage of concrete (6):

- The use of pre-wetted lightweight aggregates in concrete can reduce or eliminate the stress development caused by autogenous shrinkage. The decrease in autogenous stresses is due to internal curing, because water is desorbed from the lightweight aggregates to fill capillary voids formed by chemical shrinkage.
- Internal curing concrete made with pre-wetted lightweight aggregate experienced *reduced* stress development due to autogenous shrinkage effects when compared to the normalweight concrete. Since the sand-lightweight and all-lightweight concretes can supply more internal curing water, they cause a greater reduction in tensile stresses due to autogenous shrinkage effects than the

internal curing concretes. The sand-lightweight and all-lightweight concretes used in this study completely prevented the development of tensile stresses due to autogenous shrinkage effects.
- The use of lightweight aggregates to produce internal curing concretes delays the occurrence of cracking at early ages in bridge deck concrete applications when compared to the normalweight control concrete. This improvement in cracking behavior is attributed to the increased tensile strength and decrease in modulus of elasticity, coefficient of thermal expansion, and autogenous shrinkage of the internal curing concretes when compared to the normalweight control concrete.
- The use of sand-lightweight and all-lightweight concretes significantly delays the occurrence of cracking at early ages in bridge deck concrete applications when compared to the normalweight control concrete. Although the sand-lightweight and all lightweight concretes experience greater peak temperatures, the significant reduction in coefficient of thermal expansion and modulus of elasticity lead to a significant overall delay in early-age cracking in bridge deck concrete applications.
- When compared to a normalweight control concrete, the introduction of lightweight aggregates in concrete effectively delays the occurrence of cracking at early ages in bridge deck applications.

BENEFITS OF INTERNAL CURING ON CONCRETE SERVICE LIFE

Over a decade ago, Cusson, Lounis and Daigle (8) investigated the impact of internal curing on the service life of high-performance concrete (HPC) bridge decks by using analytical models to predict the times to onset of corrosion, onset of corrosion-induced damage, and failure of decks. Three bridge deck design options were compared: (i) normal concrete deck; (ii) HPC deck with supplementary cementing materials (SCM); and (iii) HPC deck with SCM and internal curing. It was found that the use of internal curing can extend the service life of high-performance concrete bridge decks by more than 20 years, which is mainly due to a significant reduction in the rate of penetration of chlorides in concrete as a result of reduced early-age shrinkage cracking and reduced chloride diffusion. Compared to normal concrete, HPC with SCM and internal curing was predicted to add more than 40 years to the service life of bridge decks in severe environmental conditions. (8)

Also in 2009 – 2010, students at Purdue University under the direction of Professor Dr. Jason Weiss in cooperation with Tommy Nantung, Indiana DOT conducted a study of various aggregates for *"Development of Internally Cured Concrete for Increased Service Life"* (9). The goal of this study was to provide an improved understanding of the timing and distance of water movement from prewetted lightweight aggregates into the paste in concrete mixtures with internal curing. Through the use of x-ray absorption measurements and other testing, the results of this investigation indicated that internally cured concrete has great potential for use in transportation structures, specifically due to the reduced potential for shrinkage and thermal cracking, the reduced fluid transport, and the increased densification of the cementitious matrix.

Based on the conclusions of this Purdue University study, in 2013 the Indiana Department of Transportation (INDOT) commissioned the construction of four bridge decks to be made with a new class of internally cured, higher performance concrete (IC HPC). The IC HPC bridge decks that were cast were made by four separate producers, located in four different regions of Indiana. Dr. Weiss supervised another group of graduate students at Purdue University as they conducted an experimental investigation of these four internally cured bridge deck concretes. In addition, these same mixtures were reproduced at the local production facilities, except without the lightweight fine aggregate for internal curing. The service life was then estimated for these 8 bridge deck concretes using SIMCO's STADIUM® software. STADIUM® is a sophisticated finite element analysis software which predicts concrete degradation kinetics and time before the initiation of reinforcing steel corrosion. The service life of each of these mixtures was then compared to the service life of the traditional bridge deck concrete mixture in Indiana. It was shown that for the service life model presented based on these four bridge decks, the IC HPC concretes achieved an estimated service life improvement of 3 to 4.5 times that of the conventional bridge deck concrete specified (10).

ESCSI STUDY – DETERMINATION OF TRANSPORT PROPERTIES OF LIGHTWEIGHT AGGRGATE CONCRETE FOR SERVICE LIFE MODELING

Owners and designers of many new structures currently specify a design life of 100 years or more to ensure durability and sustainability. In 2016, the Expanded Shale, Clay and Slate Institute (ESCSI) contracted with Tourney Consulting Group, LLC (TCG), Kalamazoo, MI, to conduct a study to determine the effects of lightweight coarse and fine aggregates on the transport properties and other durability related properties of concrete. Transport properties of concrete are measurements of the ability of ions and fluids to move through the material. Transport properties are used in several service life programs including STADIUM® and Life 365™.

Expanded shale, clay and slate (ESCS) lightweight (LW) coarse aggregates from ten different ESCS manufacturing plants across the United States were delivered to TCG for use in batching concrete mixtures ("sand lightweight concrete") that were compared to a normalweight (NW) concrete with respect to transport properties. In addition, one mixture with normalweight coarse aggregate and lightweight fine aggregate (an "inverted mixture"); one mixture with lightweight coarse aggregate and lightweight fine aggregate ("all lightweight concrete"); and one mixture with normalweight aggregate with a partial replacement of normalweight sand with lightweight fine aggregate (an "internally cured mixture") were batched and evaluated for transport properties. Each of the thirteen lightweight concrete mixtures and the normalweight control mixture used 658 pounds of Type I Portland cement per cubic yard of concrete. No supplementary cementitious materials, corrosion inhibitors, or corrosion resistant reinforcing bars were used so that the effect of lightweight aggregates alone on the transport properties could be demonstrated. The concrete mixtures were air-entrained to be representative of applications where freezing and thawing are a concern.

Table 1 – MIXTURES PRODUCED

Mix Description:	LW1			LW2							ALW	LWF	IC	C
	Ltwt C.A. Nat. C.A. Nat F.A.	Ltwt C.A. Nat. C.A. Nat F.A.	Ltwt C.A. Nat. C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Nat F.A.	Ltwt C.A. Ltwt F.A.	Nat. C.A. Ltwt F.A.	Nat C.A. Nat F.A. Ltwt FA	Control Nat C.A. Nat F.A.
Lafarge Alpena Type I lb/yd^3	658	658	658	658	658	658	658	658	658	658	658	658	658	658
Agg.Resource Midway Pit **Natural Fine Agg** SSD lb/yd^3	1360	1342	1320	1119	1119	1074	1568	1346	990	1465	------	------	846	1294
Bay Aggregates Cedarville Pit **Limestone Coarse Agg.** #67 SSD lb/yd^3	450	350	150	------	------	------	------	------	------	------	------	1800	1800	1800
Lightweight Coarse SSD lb/yd^3	500	650	862	1215	1209	1209	862	1038	1273	875	1115	------	------	------
Lightweight Fine SSD lb/yd^3	------	------	------	------	------	------	------	------	------	------	917	833	304	------
Total Water lb/yd^3	250	250	244	243	243	243	242	243	243	246	243	243	243	243
Designed Air %	6.5	6.5	6.0	7.0	7.0	7.0	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Designed Plastic Density lbs/ft^3	120.5	120.4	118.9	119.7	119.5	117.8	123.3	121.7	117.2	120.1	108.7	130.9	142.6	148.0
Water/Cement Ratio	0.38	0.38	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Admixtures														
BASF Master Air AE100 oz/cwt	0.15	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.4	0.5
BASF Glenuim 7500 (HRWR) oz/cwt	3.2	3.6	3.7	3.9	4.3	3.9	5.2	5.8	3.5	5.0	4.3	5.3	5.0	4.4
Physical Properties														
Slump, in.	4.00	5.00	3.50	3.00	8.75	5.00	2.75	5.25	3.00	4.00	3.00	5.00	7.50	4.00
Air % as tested (Volumetric)	6.75	8.00	7.50	7.25	6.50	6.50	7.00	6.25	6.25	7.00	6.25	6.00	7.00	7.10
Water Sat. Bulk Density lb/ft3	37.4	65.2	49.3	60.8	60.7	57.1	56.1	56.9	59.8	54.1	57.6	53.3	53.3	
Density lb/ft3 Plastic (Concrete)	120.5	123.0	118.5	119.1	122.6	122.2	125.7	123.5	121.4	120.7	109.8	133.3	141.6	146.2
Density lb/ft3 Oven Dry (Concrete)	111.9	113.8	108.9	109.2	109.8	108.2	115.7	114.0	109.1	114.1	95.6	130.1	137.2	142.1
Density lb/ft3 Equilibrium Air Dry (Concrete)	118.6	119.9	115.4	117.3	117.7	115.9	122.3	120.7	117.1	120.3	104.8	136.5	142.9	147.3
No. of Days to Reach Equilibrium (avg. 2)	112	84	84	140	140	140	112	112	112	56	140	84	84	67

Mixes:

LW1 – Average of three mixes with LW coarse aggregate with some NW coarse and all NW fine aggregate

LW2 – Average of seven mixes with LW coarse aggregate and NW fine aggregate

ALW – One mix with LW coarse aggregate and LW fine aggregate

C – One “control” mix with NW coarse aggregate and NW fine aggregate

IC – One internally cured mix with NW coarse and fine aggregates, plus LW fines

LWF – One “reverse mix” with NW coarse aggregates and LW fine aggregates

Table 2 – MIXTURE PROPERTIES

Mix Description:	LW1		LW2		ALW	LWF	IC	C
	Average	Standard Dev.	Average	Standard Dev.				
Lafarge Alpena Type I lb/yd^3	658	0	658	0	658	658	658	658
Agg.Resource Midway Pit **Natural Fine** Agg SSD lb/yd^3	1341	16	1240	203	------	------	846	1294
Bay Aggregates Cedarville Pit **Limestone Coarse** Agg. #67 SSD lb/yd^3	317	125			------	1800	1800	1800
Lightweight Coarse SSD lb/yd^3	671	149	1097	159	1115	------	------	------
Lightweight Fine SSD lb/yd^3					917	833	304	------
Total Water lb/yd^3	248	3	243	1	243	243	243	243
Designed Air %	6.33	0.24	6.50	0.46	6.0	6.0	6.0	6.0
Designed Plastic Density lbs/ft^3	119.9	0.7	119.9	2.0	108.7	130.9	142.6	148.0
Water/Cement Ratio	0.38	0.00	0.37	0.00	0.37	0.37	0.37	0.37
Admixtures								
BASF Master Air AE100 oz/cwt	0.2	0.0	0.2	0.0	0.2	0.2	0.4	0.5
BASF Glenuim 7500 (HRWR) oz/cwt	3.5	0.2	4.5	0.8	4.3	5.3	5.0	4.4
Physical Properties								
Slump, in.	4.2	0.6	4.5	2.0	3.00	5.00	7.50	4.00
Air % as tested (Volumetric)	7.4	0.5	6.7	0.4	6.25	6.00	7.00	7.10
Water Sat. Bulk Density lb/ft3	50.6	11.4	57.9	2.4	57.6	53.3	53.3	
Density lb/ft3 Plastic (Concrete)	120.7	1.8	122.2	1.9	109.8	133.3	141.6	146.2
Density lb/ft3 Oven Dry (Concrete)	111.5	2.0	111.4	2.8	95.6	130.1	137.2	142.1
Density lb/ft3 Equilibrium Air Dry (Concrete)	118.0	1.9	118.8	2.2	104.8	136.5	142.9	147.3
Compressive Strength								
1 Day Strength psi (3 each)	2870	210	3370	420	2700	3500	3570	3310
28 Day Strength psi (3 each)	5650	280	6540	540	6160	7120	6760	5470
90 Day Strength psi (3 each)	6260	410	7240	640	7140	8040	7743	5950

Table 3 – TESTS ON EACH MIXTURE PRODUCED

Tests	Per Mix	Notes
Plastic Properties (Slump, Air, Setting Time)	1	For each mix
Compressive Strength	3	1, 28, 90 days
STADIUM Transp. (IDC, MTC, ASTM C642 porosity)	2	28 and 90 days
ASTM C1760 Bulk Conductivity	2	28, 90 days
NT Build 492 Non Steady State Diffusion Coefficient	1	28 days
ASTM C1556 Bulk Diffusion	1	28 days
ASTM C1585 Capillary Absorption	1	28 and 90 days LWA
ASTM C1581 Restrained Shrinkage	1	Only for IC mix and control

All the tests listed in Table 3 were performed in the TCG lab. Using the results from these tests, a bridge deck subjected to deicing salts in Detroit, MI, was modeled using Life 365™ and STADIUM® software. The STADIUM® software results showed that the concrete bridge deck service life would be increased compared to the normalweight concrete control mixture as follows:

- By approximately 22% average for the ten mixtures with lightweight coarse aggregate and normalweight sand ("sand lightweight concrete"). It was observed, however, that the service life prediction would be increased by as much as 94% for one individual sand lightweight concrete mixture.
- By approximately 88% for mixtures with normalweight coarse aggregate and lightweight fine aggregate ("inverted mixture")
- By approximately 35% for mixtures with lightweight coarse aggregate and lightweight fine aggregate ("all lightweight concrete")
- By approximately 32% for mixtures with normalweight coarse aggregate and a partial replacement of normalweight sand with lightweight fine aggregate ("internally cured mixture")

The Life 365™ analysis showed equivalent performance between the sand lightweight mixes and the control mix. As with the STADIUM® analysis, significant improvements were shown with the lightweight fines, up to a three times improvement with lightweight fine aggregate replacing normalweight sand.

While the results of the TCG study are encouraging, other studies as mentioned in this paper have shown even greater improvements in properties related to durability for different types of lightweight and internally cured concrete. Such results would indicate even greater increases in expected service life than are presented in the findings of this study.

These service life predictions are estimates for uncracked concrete. As part of their testing program, Tourney Consulting Group also evaluated properties of lightweight concrete related to cracking potential. The addition of a small quantity of lightweight fines for internal curing was shown to reduce restrained shrinkage cracking and to increase compressive strength and service life. Tourney's findings agree with studies by others (including the previously mentioned References) that find that lightweight concrete also has reduced potential for cracking compared to the control concrete, providing further benefit for increasing the service life of concrete structures that is not considered in the Life 365™ and STADIUM® analyses . For complete information on the tests performed to determine the transport and durability properties of concrete, as well as the assumptions for the service life analyses, see the full report "Determination of Transport Properties of Lightweight Aggregate Concrete for Service Life Modeling" dated August 23, 2018, which can be downloaded from www.escsi.org.

Lightweight aggregate concrete made with ESCS has been used in concrete structures for over 100 years, demonstrating its superior durability and service life. Structural lightweight concrete has compressive strengths comparable to normalweight concrete, yet it is typically 20% to 25% lighter (and in some cases up to 33% lighter), offering design flexibility and substantial cost savings by reducing dead load, improving seismic structural response, allowing longer spans, providing better fire ratings, and by permitting thinner sections, decreased story heights, smaller size structural members, reduced reinforcing steel and lower foundation costs. These savings generally result in additional reductions of cost, energy, and emissions associated with the transportation of materials, and thus, less environmental impacts. The excellent durability performance of structural lightweight concrete and internally cured concrete is a result of a number of factors such as increased cement hydration (including supplementary cementitious materials reaction), and reduced autogenous shrinkage, early age cracking, modulus of elasticity and coefficient of thermal expansion.

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