THERMAL PROPERTIES OF LIGHTWEIGHT CONCRETE AND THEIR IMPACT ON BRIDGE DESIGN

Reid W. Castrodale, PhD, PE, Castrodale Engineering Consultants, PC, Concord, NC
Tara L. Cavalline, PhD, PE, University of North Carolina at Charlotte, Charlotte, NC

ABSTRACT

Lightweight concrete has long been recognized has having different thermal properties from normal weight concrete. However, the effect of these properties has not been studied or utilized for bridge design.

Important thermal properties of concrete include the coefficient of thermal expansion, thermal conductivity, thermal diffusivity, specific heat and heat capacity. The early-age thermal behavior of lightweight concrete is also important because it typically has higher initial concrete temperatures than a similar normal weight concrete.

This paper begins by discussing the thermal properties of concrete. Test data for thermal properties of lightweight concrete are presented including the heat capacity and thermal conductivity of two types of lightweight concrete and a normal weight concrete. The modulus of elasticity and tensile strength of the concrete are also presented because these properties interact with thermal properties to affect potential stress development and cracking tendency in concrete. Test results for lightweight concrete from a similar study are presented for comparison.

To conclude, the potential effects of thermal properties of lightweight concrete on bridge behavior are discussed briefly for early age behavior, temperature change in decks, superstructure movements, moments in substructure elements, positive moment development in continuous girders, and mass concrete.

Keywords: Lightweight concrete, Coefficient of thermal expansion, Thermal conductivity, Thermal diffusivity, Specific heat, Heat capacity, Test results

INTRODUCTION

Lightweight concrete has long been recognized has having significantly different thermal properties from normal weight concrete. In fact, its beneficial thermal properties have been recognized in building construction for years. For example, lightweight concrete provides the required fire resistance for floors with a reduced thickness of concrete.

Recently, significant effort has been focused on studying the influence of concrete thermal properties on concrete pavement performance. These studies support development and implementation of the mechanistic-empirical pavement design guide (MEPDG) which recognizes thermal properties as significant design parameters. However, the effect of these properties has not been studied or utilized for bridge design.

Important thermal properties of concrete include the coefficient of thermal expansion, thermal conductivity, thermal diffusivity, specific heat and heat capacity. The early-age thermal behavior of lightweight concrete is also important because the insulating properties of lightweight aggregate typically result in higher initial concrete temperatures when compared to a similar normal weight concrete mixture.

This paper begins by discussing the thermal properties of concrete mentioned above. Test data on thermal properties of lightweight concrete are presented from a study by Cavalline at the University of North Carolina at Charlotte (UNC Charlotte)[1] including measurements of heat capacity and thermal conductivity of two types of lightweight and a normal weight concrete at known moisture states. The modulus of elasticity and tensile strength of the concrete are also presented because these properties interact with thermal properties to affect potential stress development and cracking tendency in concrete. Test results for lightweight concrete from a study by Byard and Schindler at Auburn University[2] are presented for comparison.

To conclude the paper, the potential effects of thermal properties of lightweight concrete on bridge behavior are discussed briefly for early age behavior, temperature change in decks, superstructure movements, moments in substructure elements, positive moment development in continuous girders, and mass concrete. Further study of the impacts of thermal properties of lightweight concrete on bridge performance is needed.

INTRODUCTION TO THERMAL PROPERTIES

Many bridge engineers are not very familiar with the thermal properties of materials, other than the coefficient of thermal expansion. In this section, each of the relevant thermal properties will be discussed, including generally accepted methods for estimating the quantities and test methods used to determine them. Much of this information in this section is taken from the American Concrete Institute (ACI) "Guide to Thermal Properties of Concrete and Masonry Systems (ACI 122R-14)."[3] Typical values for thermal properties of normal weight and lightweight concrete reported in the literature are presented to give context to the test results presented later in the paper.

THERMAL CONDUCTIVITY

ACI 122R-14[3] defines thermal conductivity, *k*, as "a measure of the rate at which heat (energy) passes perpendicularly through a unit area of thermally homogeneous gas, liquid, or solid of unit thickness for a temperature difference of one degree under steady-state conditions." The quantity is expressed as Btu · in./(hr · ft^2 · °F).

An equation was developed by Valore[4] based on evaluation of data for oven dry concrete. He found that the variation of the thermal conductivity of dry concrete could be related to its density using the following equation:

$$k = 0.5e^{0.02\rho} \qquad \text{(in.-lb units)} \qquad (1)$$

This equation demonstrates that thermal conductivity of concrete is dependent on the density of the concrete. Therefore, for a given moisture state, lightweight concrete will have a lower thermal conductivity than normal weight concrete. This means that lightweight concrete has a greater resistance to conducting heat, which is reflected by its use as an insulating material and its ability to provide the required fire resistance in buildings with a reduced thickness.

As a measure of heat transmission, thermal conductivity is relevant in both structural and pavement applications. Thermal conductivity is an input for portland cement concrete for rigid pavement analysis and design performed in accordance with the American Association of State Highway and Transportation Officials (AASHTO) Mechanistic-Empirical Pavement Design Guide (M-EPDG).[5,6,7] In pavement applications, sensitivity analyses for jointed plain concrete pavement design indicate that higher thermal conductivity values are associated with better predicted performance characteristics such as reduced cracking, joint faulting, and ride quality[8].

Lee et al.[9] reported that published values of thermal conductivity of concrete range from 0.70 to 1.4 BTU/(hr · ft · ºF). The typical range of values of thermal conductivity suggested for use in M-EPDG for conventional concrete pavement is 1.0 to 1.5 BTU/(hr · ft · ºF), with a global default value of 1.25 BTU/hr · ft · °F.[10] Values from both of these sources are for normal weight concrete. ACI 122R-14[3] provides a range of thermal conductivity values for oven-dry lightweight concrete with different types of lightweight aggregates and different densities. These values were obtained from a linear regression analysis of test data published from 1949 to 1988. These values show a significant range of variation from the values of thermal conductivity predicted using Eq. (1).

One shortcoming for applying these published (oven-dry) thermal conductivity values to bridge and pavement applications is that these structures are exposed to moisture, and different locations in the structure may have widely varying moisture states throughout a typical day or season in service. A review of the literature indicates that very little information is available regarding the moisture states of specimens tested to obtain recommended values used for pavement design. ACI 122-14[3] includes a table with thermal conductivity moisture correction factors that can be used to adjust oven-dry conductivity values to “practical design values.” The factor given in the table for expanded shale, clay and slate is a 5% increase per 1% of moisture content, which can be a significant adjustment. A table published in an ASTM document[11] demonstrates the possible variation in thermal conductivity values for lightweight concrete made with expanded shale for three moisture conditions:

Moist	5.9 BTU · in./(hr · ft^2 · ºF)
50% relative humidity	5.5 BTU · in./(hr · ft^2 · ºF)
Dry	4.3 BTU · in./(hr · ft^2 · ºF)

Density also has a significant effect on the thermal conductivity of concrete. A table in ACI 122-R14[3] indicates that the thermal conductivity for oven-dry lightweight concrete ranges from 1.70 to 7.60 BTU · in./(hr · ft^2 · ºF) for densities ranging from 50 to 120 lb/ft^3.

The thermal conductivity of a material is usually measured in accordance with ASTM C177[12] or C1363[13]. These methods require the powdering of the specimen, which destroys the void structure in the lightweight aggregate and therefore significantly alters its thermal behavior. A method of measuring the bulk thermal conductivity of intact concrete specimens was used by Cavalline in the UNC Charlotte study[1] to obtain more realistic values for the material. Tests were performed at approximately 120 days after the concrete was mixed using the Fox50 Heat Flow Meter Instrument by Laser Comp in accordance to ASTM C518[14]. Three specimens were prepared for each mixture by cutting three representative rectangular prisms (approximately 1.5 in. x 1.5 in. x 1 in. thick) from a 4 in. x 8 in. cylinder seven days before the test date. Care was taken during sample preparation to ensure that each of the three specimens did not contain large entrapped air voids and represented the mixture composition (aggregates were well distributed within the paste). Test specimens are shown in Figure 1.

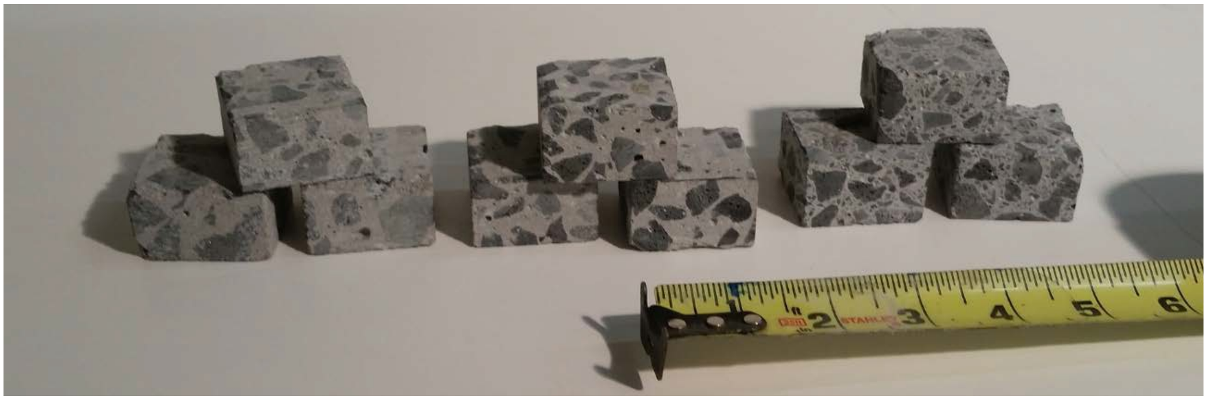

Figure 1: Test specimens utilized for thermal conductivity and heat capacity testing: normal weight concrete (left), sand-lightweight concrete (center), all-lightweight concrete (right)[1]

To ensure a consistent moisture content in each specimen, the three specimens were placed into an environmental chamber set at 72°F and 50% relative humidity for seven days prior to testing. The Fox50 test apparatus utilizes software called WinTherm32 to control calibration and testing. The calibration sequence was performed using a manufacturer-supplied reference sample prior to the testing. The thickness of each specimen was computed by the Fox50 apparatus, and the test results provided by the equipment include an adjustment for specimen height. Cushions provided by the manufacturer were used to ensure optimal contact between the heating elements and sensors and the specimens in the test chamber. Test values were obtained for both thermal conductivity and heat capacity at 25°C. Values were adjusted to account for the thermal characteristics for the cushioning pads and parchment paper used to protect the sensor coatings per the equipment manufacturer's instructions. Test results appear in a later section of this paper.

HEAT CAPACITY AND SPECIFIC HEAT

Heat capacity and specific heat are closely related quantities. Heat capacity is an indication of the amount of heat needed to raise the temperature of a *given sample* of a substance by 1°C or K, while specific heat is an indication of the amount of heat required to raise the temperature of a *kilogram* of a substance by 1°C or K. ACI 122R-14[3] defines specific heat, c_p, as the "measure of the amount of heat required to change by one degree a specified unit of mass of a gas, liquid, [or] solid," while heat capacity, h_c, a more general term, is defined as the "measure of the amount of heat required to change by one degree a specified object." In ACI 122R-14, typical values for specific heat of concrete, masonry, and related materials are presented on a mass basis in BTU/(lb · ºF), while values for heat capacity of wall systems are presented in terms of area - BTU/(ft^2 · ºF). When considering a solid material, the heat capacity can also be expressed in terms of volume - BTU/(ft^3 · ºF). ACI 122R-14 indicates that the specific heat (expressed on a weight basis) for concretes with densities ranging from 80 lb/ft^3 to 140 lb/ft^3 (covering the range from lightweight concrete to normal weight concrete) is a constant 0.21 BTU/(lb · ºF). Since the specific heat for concrete expressed on a weight basis is constant, the value expressed as a volume basis will be directly proportional to the density of the concrete, so lightweight concrete will have a lower specific heat based on volume than normal weight concrete. The ACI report also indicates that concrete absorbs heat more slowly than many other common building materials because it has a higher heat capacity.

In building applications, values of heat capacity are of interest in evaluating how a building material stores heat, preventing temperature fluctuations[15]. The same behavior associated with heat capacity can be reasonably applied to infrastructure such as pavements and bridges. A reasonable range for heat capacity for conventional concrete for use in M-EPDG design of conventional concrete pavement is 0.20 to 0.40 BTU/(lb · ºF) with 0.28 BTU/(lb · ºF) recommended as the default value.[10] Heat capacity was shown to have a lesser effect on predicted performance of pavements than some other thermal factors, but evaluation of material-specific inputs is still recommended.[8]

The heat capacity of the concrete specimens was obtained at UNC Charlotte using the Fox50 Heat Flow Meter Instrument by Laser Comp in accordance with ASTM C518[14] using the same bulk concrete test specimens tested for thermal conductivity. Test values were obtained for volumetric heat capacity at 25°C, using two temperature steps (20°C and 30°C). Values were adjusted to account for the thermal characteristics for the cushioning pads and parchment paper used to protect the sensor coatings per the equipment manufacturer's instructions. The adjusted values of volumetric heat capacity were then converted to weight basis using the concrete density of cylinder specimens conditioned to 50% relative humidity (same as test specimens). Test results appear in a later section of this paper.

THERMAL DIFFUSIVITY

ACI 122R-14[3] defines thermal diffusivity, α, as the "measure of the time rate of change of temperature at any point within a gas, liquid, or solid; thermal diffusivity is thermal conductivity divided by the product of density and specific heat." This relationship is expressed using the following equation:

$$\alpha = k/(\rho \text{ x } c_p) \tag{2}$$

Since this quantity can be derived from other quantities, it is typically not measured directly.

COEFFICIENT OF THERMAL EXPANSION

The coefficient of thermal expansion is generally defined as the "change in linear dimension per unit length per degree to temperature change."[16] The coefficient of thermal expansion for lightweight concrete is generally accepted to be less than values for normal weight concrete, although this depends on the type of normal weight aggregate. The *AASHTO LRFD Bridge Design Specifications*[17] give values of the coefficient of thermal expansion for use in the absence of more precise data. Article 5.4.2.2 gives the following values for normal weight and lightweight concretes:

For normal weight concrete:	6.0 x 10-6 / deg. F
For lightweight concrete:	5.0 x 10^{-6} / deg. F

The coefficient of thermal expansion (CTE) is a measure of deformation in response to a change in temperature, and is relevant to the design of both bridges and pavements, as well as other types of structures. Lower CTE values are typically desirable in both structure and pavement construction. There has been a significant amount of research on the influence of the CTE on concrete performance because higher CTE values have been associated with increased cracking and joint deterioration distress in concrete pavements.[18] Sensitivity analyses indicate that CTE is a key input to the Pavement ME software[8,18] that is currently utilized many state highway agencies for pavement design and analysis. It has been shown that since aggregates comprise the bulk of concrete by volume, the CTE of concrete is greatly influenced by aggregate type and origin. Concrete CTE values published in various literature sources range from 3 to 8×10^{-6} in/(in·°F) as shown in Table 1.[10]

Coefficient of thermal expansion testing at UNC Charlotte was performed in accordance with AASHTO T336-11.[19] Specimens were cut from cylinders using the bottom 7.0±0.1-in. portion of the cylinder. Prior to testing, specimens were conditioned by submersion in limewater at 73±4°F (23±2.0°C) for not less than 48 hours or until successive weights (24-hour interval) of surface-dry specimens differed by less than 0.5%. Testing was performed using AFCT2 test equipment manufactured by Pine Instrument Company. Each specimen was tested three times (three successive days), one time in each of the three frames used in the test equipment. For each of these tests, the average value for the three cylinders was computed and reported. In accordance with AASHTO T336-11, specimens were cycled between 50±2°F (10±1°C) and 122±2°F (50±1°C). When computing the coefficient of thermal expansion from the test results, the requirements of Section 7.2.9 of AASHTO T336-11 were met.

Table 1 Typical ranges for coefficients of thermal expansion (CTE) for common components of concrete and of concrete made using these materials [10].

Type of Material	CTE of Aggregate 10^{-6} in/in/°F	CTE of Concrete made with Aggregate 10^{-6} in/in/°F
Marbles	2.2 – 3.9	2.3
Limestones	2.0 – 3.6	3.4 – 5.1
Granites & Gneisses	3.2 – 5.3	3.8 – 5.3
Syenites, Diorites, Andesite, Basalt, Gabbros, Diabase	3.0 – 4.5	4.4 – 5.3
Dolomites	3.9 – 5.5	5.1 – 6.4
Blast Furnace Slag	Not reported	5.1 – 5.9
Sandstones	5.6 – 6.7	5.6 – 6.5
Quartz Sands & Gravels	5.5 – 7.1	6.0 – 8.7
Quartzite, Cherts	6.1 – 7.0	6.6 – 7.1
Cement Paste - w/c = 0.4 to 0.6 (saturated)	10-11	N/A
Concrete cores from Long-Term Pavement Performance (LTPP) Program	N/A	4.0 (min.), 5.5 (mean), 7.2 (max.)

CONCRETE TESTING PROGRAMS

This paper presents the findings from a recently completed testing program conducted at UNC Charlotte that was conducted solely for the purpose of determining thermal properties of lightweight concrete made using an expanded slate lightweight aggregate.[1] For comparison, findings from a second study in which thermal properties of lightweight concrete were determined are also presented. This study was performed for the Expanded Shale Clay and Slate Institute (ESCSI) by Byard and Schindler at Auburn University.[2] In this section, mixture proportions and fresh properties of the concrete mixtures tested at UNC Charlotte are presented, as well as the mixture proportions for the mixes tested at Auburn University. As can be seen from the data presented, the mixtures tested are very similar.

TESTING PROGRAM AT UNC CHARLOTTE

The testing program conducted at UNC Charlotte[1] evaluated three types of concrete: a normal weight concrete (NWC); a "sand lightweight" concrete (SLWC) made with an expanded slate lightweight coarse aggregate and normal weight sand; and an "all lightweight" concrete (ALWC) made with expanded slate lightweight aggregate for both coarse and fine aggregate fractions.

Table 2 Mixture proportions for three types of concrete tested at UNC Charlotte[1]

Mixture Constituent	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)
Cement (Type I) (lb/cy)	586	586	586
Fly Ash (lb/cy)	146	146	146
Sand (lb/cy)	1206	1224	---
Lightweight Fine Aggr. (lb/cy)	---	---	861
#67 stone (lb/cy)	1880	---	---
Lightweight Coarse Aggr. (½") (lb/cy)	---	960	960
Water (lb/cy)	300	300	300
Air entraining admixture (oz. per 100 lb of cementitious material)	---	0.70	0.70
Normal-range water reducing admixture (oz. per 100 lb of cementitious material)	5.0	5.0	5.0
High-range water reducing admixture (oz. per 100 lb of cementitious material)	2.3	2.5	2.5
Water-cementitious material ratio (w/cm)	0.41	0.41	0.41

Mixture proportions of the concrete are shown in Table 2. The cementitious material content and water/cementitious ratio was held constant for all mixtures. The normal weight coarse aggregate was a locally available granitic gneiss aggregate and the normal weight fine aggregate was a natural silica sand. Each mixture contained Class F fly ash and water-reducing admixtures to achieve the target slump of 6 inches. A nominal amount of air entraining admixture was used in the SLWC and ALWC mixtures. This will typically result in lower strengths being achieved for the mixes using lightweight aggregate, although in this particular case, the sand lightweight concrete mix had higher compressive and tensile strengths than the normal weight concrete. In practice, the cement content is usually increased for the lightweight concrete mixes to achieve the same design compressive strength at the specified age.

Concrete for the testing was obtained from a local ready mix concrete supplier. When the concrete arrived at the laboratory, tests were performed on the fresh concrete to determine the temperature, slump, air content, and unit weight. A summary of fresh concrete properties is provided in Table 3.

Table 3 Results of fresh concrete tests[1]

Quantity	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)
Concrete temperature (°F)	78.8	80.6	80.6
Slump (in)	7.3	9.5	9.8
Air content (%)	1.5	2.3	3.2
Unit weight (lb/ft^3)	144.2	124.3	109.2

TESTING PROGRAM AT AUBURN UNIVERSITY

Details of the testing program conducted by Byard and Schindler at Auburn University[2] are reported elsewhere. A brief summary of the program is given here.

For the Auburn University study, three different types of lightweight aggregate (shale, clay and slate) were used to make sand LWC and all LWC. Internally cured mixtures, for which a portion of the sand in a conventional mix was replaced with an equal volume of prewetted lightweight fines, were also tested, but these results are not presented in this paper. The normal weight concrete control mix used river gravel for the coarse aggregate. The slate lightweight aggregate used in this study came from the same source as the slate lightweight aggregate used in the UNC Charlotte study. As in the UNC Charlotte mixes, the cementitious material content and water/cementitious ratio were held constant for all mixtures. The proportions for the control concrete mix and the mixtures using the slate aggregate are shown in Table 4.

THERMAL PROPERTY TEST RESULTS

Test results for concrete thermal properties from the two studies mentioned above are reported and discussed in this section.

RESULTS OF TESTS AT UNC CHARLOTTE

Test results for concrete thermal properties from the UNC Charlotte study[1] are summarized in Table 5 and are discussed in the remainder of this section. Table 5 also includes test results for several mechanical properties that are used to determine the structural effect of temperature changes. Relative values of test results normalized to the normal weight concrete test results are presented in Table 5 and also in Figure 2.

Table 4 Mixture proportions for three types of concrete tested at Auburn University[2]

Quantity	**NWC**	**Slate SLWC**	**Slate ALWC**
Water Content (lb/yd^3)	260	276	276
Cement Content (lb/yd^3)	620	658	658
SSD Normalweight Coarse Aggregate (lb/yd^3)	1,761	0	0
SD Slate Lightweight Coarse Aggregate (lb/yd^3)	0	875	896
SSD Normalweight Fine Aggregate (lb/yd^3)	1,210	1,381	0
SD Slate Lightweight D Tank Fine Aggregate (lb/yd^3)	0	0	0
SD Slate Lightweight MS 16 Fine Aggregate (lb/yd^3)	0	0	945
Water-Reducing Admixture (oz/yd^3)	31.0	0.0	0.0
High-Range Water-Reducing Admixture (oz/yd^3)	0.0	39.5	8.2
Rheology-Controlling Admixture (oz/yd^3)	0.0	0.0	52.6
Air-Entraining Admixture (oz/yd^3)	0.8	6.6	7.4
Target Total Air Content (%)	5.5	5.5	5.5
Water-cement ratio (w/c)	0.42	0.42	0.42

Table 5 Mechanical and Thermal Test Results for Three Types of Concrete[1]

	Measured Values			Values Normalized to NWC		
	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)
Fresh unit weight (pcf)	144	124	109	1.000	0.862	0.757
Compressive strength, 28-day (psi)	8,040	9,480	6,605	1.000	1.179	0.822
Compressive strength, 56-day (psi)	8,660	10,005	8,095	1.000	1.155	0.935
Modulus of elasticity, 28-day (psi)	5,090,000	3,820,000	3,330,000	1.000	0.750	0.654
Modulus of elasticity, 56-day (psi)	5,390,000	4,480,000	3,240,000	1.000	0.831	0.601
Splitting tensile strength, 28-day (psi)	576	625	550	1.000	1.085	0.955
Modulus of rupture, 28-day (psi)	969	943	714	1.000	0.973	0.737
Coefficient of thermal expansion, 28-days (×10-6 in/in °F)	5.317	5.157	3.970	1.000	0.970	0.747
Heat capacity - weight basis, 120 days (BTU/lb·°F)	0.184	0.192	0.197	1.000	1.043	1.071
Heat capacity - volume basis, 120 days (BTU/ft3·°F)	28.55	23.77	21.00	1.000	0.833	0.736
Thermal conductivity, 120 days (BTU/(ft·hr·°F))	1.223	0.814	0.417	1.000	0.666	0.341
Thermal diffusivity (ft2/h) - COMPUTED *	0.0461	0.0341	0.0194	1.000	0.740	0.421

As shown in Table 5, the CTE values for the NWC mixture are on the order of 5.317×10^{-6} in/in·°F, which reasonably correlates with data for granites as shown in Table 3. The CTE values for the SLWC (5.157×10^{-6} in/in·°F) and ALWC mixtures (3.970×10^{-6} in/in·°F) show a significant reduction in CTE with increasing volume of lightweight aggregate.

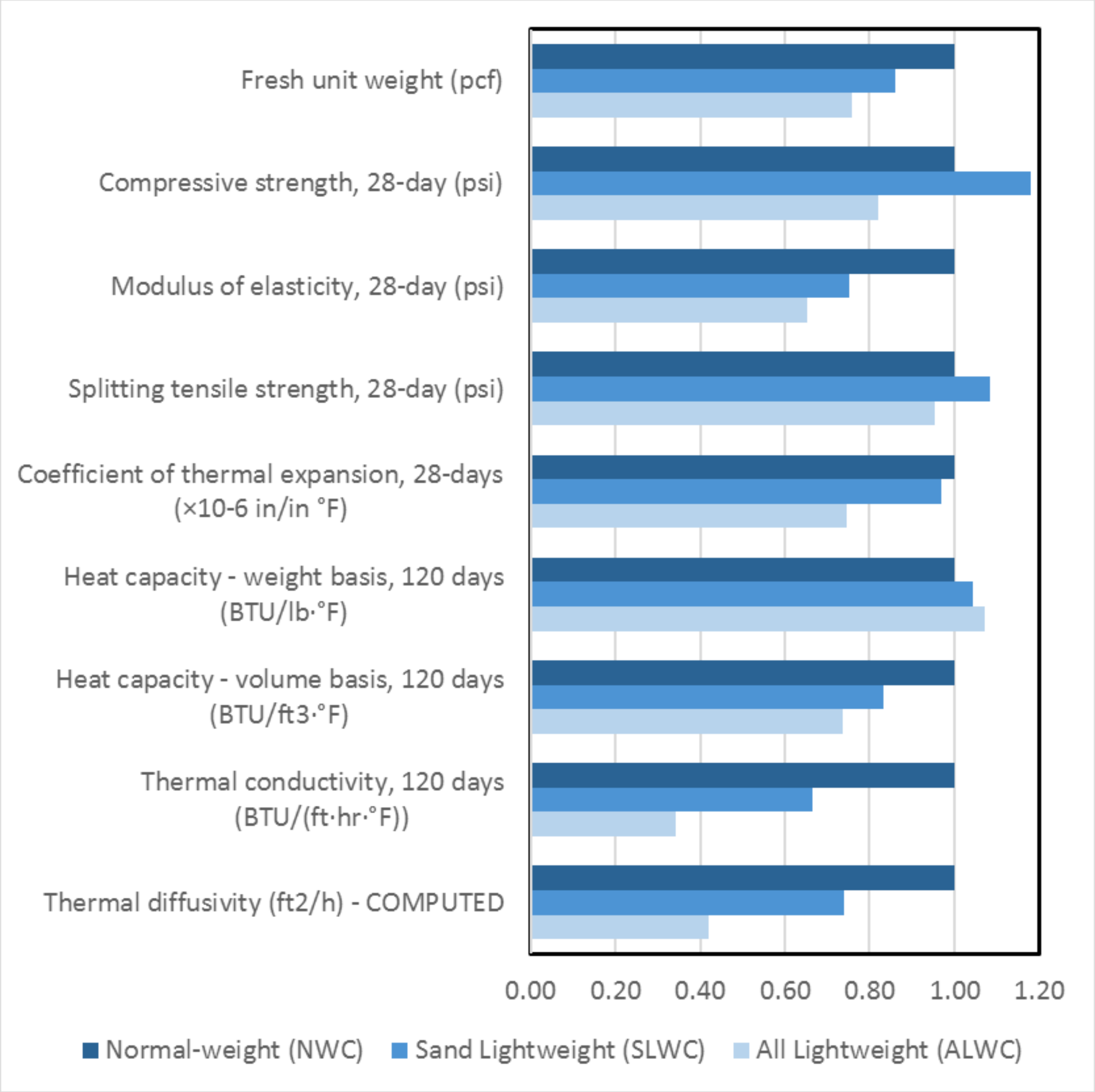

Figure 2 Relative Values of Mechanical and Thermal Test Results for Three Types of Concrete compared to NWC Results[1]

Test results for thermal conductivity and heat capacity are also shown in Table 5. As noted earlier in this report, these test specimens are bulk samples of concrete (not crushed powder), and therefore the void structure in the lightweight aggregates was preserved. Compared to the results for the NWC, a marked decrease in thermal conductivity is seen for both the SLWC and ALWC mixtures indicating the potential for enhanced insulation performance.

Heat capacity test results are given on a volumetric basis, and are shown in Table 5. Using unit weights of cylinder specimens conditioned to 50% relative humidity (same as test specimens), the heat capacity was computed on a weight basis and shown in Table 5. These results show reasonable consistency between test specimens. Since lightweight concrete has a lower unit weight, heat capacities based on volume are significantly lower for lightweight concrete than those for normal weight concrete. Heat capacities (by weight) for all mixtures are on the low end of the range of values provided for Pavement ME.

The thermal diffusivity was computed using Eq. (2) with the heat capacity expressed as a weight basis and the unit weight of cylinders described above was used for the density.

RESULTS OF TESTS AT AUBURN UNIVERSITY

Results for tests at Auburn University[2] are summarized in Table 6. These test results show very similar results for the three types of aggregate, with the greatest variation being in unit weight and modulus of elasticity. The thermal property test results were very consistent between the different types of lightweight aggregate. Relative values of test results normalized to the normal weight concrete results are also presented in Table 6.

Table 6 Measured and Relative Values of Mechanical and Thermal Test Results for Three Types of Concrete and Three Types of LWA compared to NWC Results[2]

	Measured Values			Values Normalized to NWC		
Type of Concrete / LWA	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)	Normal-weight (NWC)	Sand Lightweight (SLWC)	All Lightweight (ALWC)
Unit weight (lb/ft^3)*						
NWC	140.0			1.000		
Slate		113.6	95.5		0.811	0.682
Clay		111.2	91.3		0.794	0.652
Shale		110.6	87.1		0.790	0.622
Compressive strength (psi)						
NWC	5,505			1.000		
Slate		5,135	4,685		0.933	0.851
Clay		5,200	4,675		0.945	0.849
Shale		4,980	4,550		0.905	0.827
Modulus of Elasticity (ksi)						
NWC	4,650			1.000		
Slate		3,525	2,550		0.758	0.548
Clay		2,825	2,025		0.608	0.435
Shale		3,300	2,250		0.710	0.484
Splitting Tensile Strength (psi)						
NWC	438			1.000		
Slate		490	461		1.120	1.054
Clay		520	493		1.189	1.126
Shale		510	465		1.166	1.063
Coefficient of Thermal Expansion (με/°F)						
NWC	6.2			1.000		
Slate		5.1	4.3		0.823	0.694
Clay		5.1	4.0		0.823	0.645
Shale		5.2	4.0		0.839	0.645
Thermal Diffusivity (ft^2/hr)						
NWC	0.046			1.000		
Slate		0.033	0.029		0.717	0.630
Clay		0.035	0.03		0.761	0.652
Shale		0.035	0.029		0.761	0.630
Thermal conductivity (BTU·in./(ft^2·hr·°F)) - COMPUTED **						
NWC	14.7			1.000		
Slate		8.5	6.3		0.582	0.430
Clay		8.9	6.2		0.604	0.425
Shale		8.8	5.8		0.601	0.392

* - Unit weight shown is the calculated equilibrium density.

** - Computed using an assumed heat capacity of 0.19 ft^2/hr.

COMPARISON OF RESULTS

Results from testing at Auburn University are very similar to those from UNC Charlotte. Selected test results for the two testing programs are summarized in Table 7 for the slate lightweight aggregate that was used in both studies. Note that the type of aggregate used for the normal weight concrete in the two test programs was different.

Table 7 Selected test results for UNC Charlotte[1] and Auburn University[2] studies with slate lightweight aggregate

	UNC Charlotte			Auburn University		
	NWC	SLWC	ALWC	NWC	SLWC	ALWC
Fresh unit weight (lb/ft^3)	144	124	109	*142.7*	*119.5*	*104.2*
Equilibrium density * (lb/ft^3)	154.9	123.7	106.7	140.0	113.6	95.5
Compressive strength, 28-day (psi)	8,040	9,480	6,605	5,505	5,135	4,685
Modulus of elasticity (ksi)	5,090	3,820	3,330	4,650	3,525	2,550
Splitting tensile strength (psi)	576	625	550	438	490	461
Coeff. of thermal expansion ($\times 10^{-6}$ in./in. °F)	5.317	5.157	3.970	6.2	5.1	4.3
Thermal conductivity (BTU·in./(ft^2·hr·°F))	14.676	9.768	5.004	*14.7*	*8.5*	*6.3*
Thermal diffusivity (ft^2/hr)	*0.0461*	*0.0341*	*0.0194*	0.046	0.033	0.029

* - Measured densities after conditioning at 50% RH for UNC Charlotte; calculated densities for Auburn University

Note: Thermal conductivity and diffusivity values shown in italics did not appear in the respective study reports and have been computed from other values.

Comparisons between test results for the two studies:

The compressive strengths, modulus of elasticity and tensile strengths were higher for the UNC Charlotte study

In spite of the significant differences in mechanical properties, the thermal properties for the lightweight concrete mixes were very similar between the two studies

The coefficient of thermal expansion was higher for the Auburn University normal weight concrete mix, but the other thermal properties were very similar for the two normal weight concrete mixes

INFLUENCE OF THERMAL PROPERTIES ON BRIDGE DESIGN

The coefficient to thermal expansion of concrete is currently used for simple calculations in the design of bridges, such as joint and bearing movements and the thermal effects of superstructure movement on substructure elements. However, the other thermal properties are not typically used in any way. Furthermore, since the other thermal properties of concrete are not typically used, the potentially beneficial thermal properties of lightweight concrete have not been used. This section provides some considerations for further study regarding applications where the beneficial thermal properties of lightweight could be used to an advantage in bridge design. The analysis methods required to quantify the benefits of using the thermal properties of lightweight concrete are involved and are not readily accessible or understandable for most bridge engineers. Therefore, it would be useful to have experts in thermal analysis use the measured thermal properties to evaluate the differences in behavior and provide an idea of the magnitude of the possible effects on behavior.

The early age behavior of lightweight concrete is also discussed, because some have felt that using lightweight concrete may be problematic because of the higher initial concrete temperatures that may be experienced.

EARLY AGE BEHAVIOR

Because of the insulating properties of lightweight aggregate, initial temperatures of lightweight concrete are typically greater than for a normal weight concrete deck subjected to the same conditions and with similar mix proportions. This was demonstrated by Maggenti [20] for two 1 m (3.3 ft) cubes of concrete with high cementitious contents. Results from his tests appear in Figure 3, which depicts the early age temperature profiles of the two cubes. The same mix design was used for the two cubes with the only difference being that lightweight coarse aggregate was substituted for the normal weight coarse aggregate on an equal volume basis. All other constituents were identical.

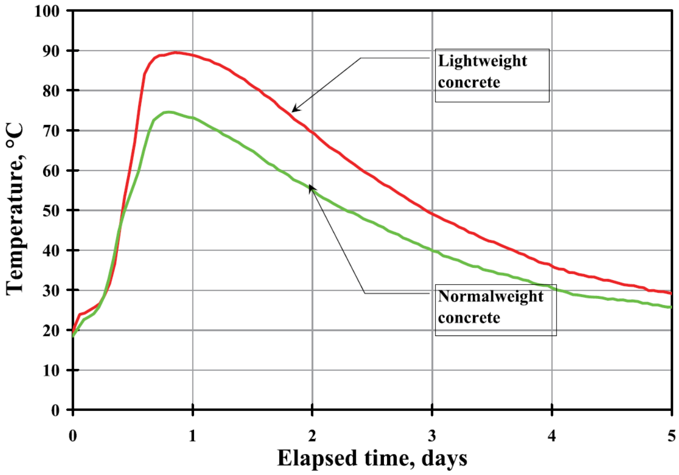

Figure 3 Comparison of core temperature readings for 1.0 m (3.3 ft) non-insulated cubes of normal weight and lightweight concrete. (°F = °C × 9/5 + 32)[20]

While increased temperatures in concrete elements, especially mass concrete elements, are generally a cause for concern, the effect of the greater initial temperature in lightweight concrete is less of a concern as long as the temperature remains below the level that may result in delayed ettringite formation. The lower coefficient of thermal expansion and modulus of elasticity of lightweight concrete (along with tensile strengths that are similar to normal weight concrete) allow it to tolerate larger differentials in temperature without cracking. The insulating properties of the lightweight concrete also tend to delay loss of heat to the environment, which may mitigate temperature differentials.

TEMPERATURE CHANGE IN DECK IN SERVICE

Assuming that the bridge deck will be the same thickness regardless of the type of concrete, a rough evaluation can be made regarding the change in temperature that would be experienced during a day as the deck is exposed to solar heating. To get a very rough idea of the potential difference in heating of a deck, a very simplified analysis is suggested. The approach assumes that, if the energy input is the same, then the change in temperature (neglecting gradient effects) would be related to the inverse of the heat capacity. Based on the reported heat capacity values, the change in temperature of a deck subjected to equal solar energy input would be equal to the relative ratios of the heat capacity on the volume basis (since the volume of the deck would be the same for the two designs). Therefore, the increase in temperature for a lightweight concrete deck could potentially be about 83% and 74% of that experienced for a normal weight concrete deck for a sand lightweight concrete and all lightweight concrete deck, respectively.

Since the temperature of the deck is expected to also be influenced by other factors, such as surface shortwave reflectivity, moisture gradients, thermal conductivity, and albedo, the determination of surface temperature of the deck is really a much more complex process. However, given the significantly reduced values of heat capacity and thermal conductivity for lightweight concrete, heat gain at the surface and subsequent transmission of heat through the deck could be anticipated to be significantly different than a conventional deck. Further study, including analytical modeling and field measurements, are needed to verify this possible difference in behavior and to better understand the effect of the different thermal properties on the heating of bridge decks.

While not directly related to this behavior, data on thermal lag and amplitude reduction that are presented in ACI 122[3] are instructive. Data for concrete is excerpted from Table 5.3.1 of the report in Table 8. While the approach for obtaining the data presented in the table is quite involved and beyond the scope of this current discussion, the data are instructive as discussed below.

The data in this table indicate that for a given daily temperature history input, the thermal lag in the structural [normal weight] concrete wall is less than for the structural lightweight concrete wall, indicating that the normal weight concrete heats up more readily than the lightweight concrete. The reduction in the amplitude change also shows that lightweight concrete would have a lower peak temperature than normal weight concrete. While these data represent complex processes that depend on a number of variables, they can be used as an indication that the use of lightweight concrete should result in reduced temperature changes in bridge elements subjected to daily solar heating.

Table 8 Thermal lag and amplitude reduction measurements from calibrated hot box tests (extracted from ACI 122-14 – Table 5.3.1)[3]

Quantity	Thermal lag (hr)	Amplitude change (%)
Structural concrete wall	4.0	-45
Structural lightweight concrete wall	5.5	-53
Low density concrete wall	8.5	-61

SUPERSTRUCTURE THERMAL MOVEMENTS

When bridge deck joints and expansion bearings are sized, a temperature change is assumed. However, the same temperature change is assumed for all types of concrete. The above analysis indicates that on a daily basis, the expected change in surface temperature for a lightweight concrete deck should be less, transmission of heat through the structure should be reduced, and the coefficient of thermal expansion would also be significantly less. Therefore, the maximum superstructure movements over a daily temperature cycle would be expected to be less for lightweight concrete decks compared to normal weight concrete decks. More complex modeling would be required to determine how much of a reduction in temperature change could be expected.

A simplified analysis with a sand lightweight concrete deck using UNC Charlotte data can be used as an example: the temperature change would likely be 83% of the normal weight concrete, and the CTE would be 97%, so the product of these two would be 81%, meaning that the superstructure movement could be anticipated to be about 80% of the movement expected for a normal weight concrete deck. If the Auburn University data for coefficient of thermal expansion is used for this example, the CTE would be about 82%, so the product of the two values would be 68%. It is recognized that this is a simplified evaluation, and the difference in temperature change between normal weight and lightweight concretes may be reduced because the change will be a gradient from the surface rather than a change through the full depth of the deck.

Any reduction in expected daily joint opening or bearing movement would improve the service life of these costly elements of a bridge. There are no known field study comparisons of joint openings or bearing movements for lightweight and normal weight concrete decks. Based on this simplified analysis using measured thermal properties, it appears that there may be a benefit from using lightweight concrete to reduce superstructure thermal movements. More study is needed to verify and quantify this effect.

It should also be noted that deck joint widths are generally sized considering seasonal variations in temperature rather than daily variations. In this case, the difference in superstructure movement would only depend on the coefficient of thermal expansion of the concrete and the seasonal variation in temperature. The use of lightweight concrete in the superstructure can still provide a significant benefit even for the seasonal variation in superstructure movements.

THERMAL MOMENTS IN SUBSTRUCTURE ELEMENTS

Where superstructure elements are connected integrally with the substructure, or where bearing movements are limited, the substructure must be designed to resist the movements of the superstructure that are caused by the seasonal variation in temperature. These issues are similar to the previously discussed item, but in this case, the effects depend on more factors, including the modulus of elasticity of the superstructure and columns. Further analysis is required to better quantify this effect.

RESTRAINT MOMENTS IN GIRDERS MADE CONTINUOUS FOR LIVE LOAD

The evaluation of moments induced in prestressed concrete girders made continuous for live load has been a topic of lively debate for many years. Thermal effects have been found to be a significant factor that may lead to positive moment cracking of continuity diaphragms. The cambering of the structure caused by heating of the deck from solar heating causes significant positive moments in the continuity diaphragms and girders. One author has experience where the effect of solar heating was observed to be several times more significant than the effect of loaded trucks crossing a span. Therefore, it would appear that these detrimental positive moments caused by thermal effects in continuous girder bridges should be reduced when lightweight concrete is used for the deck, due to the reduction in the increase in temperature of the deck from solar heating. This should be evaluated using analytical methods and field studies.

Differential shrinkage between the deck and girder is also a significant factor in generating restraint moments in continuous girders. Lightweight concrete may also have benefits in this regard since the shrinkage of lightweight concrete may be less than normal weight concrete, and the modulus of elasticity of lightweight concrete is reduced, which would reduce the force generated by deck shrinkage (and therefore the moment) that would be caused by differential shrinkage. Again, more study is needed to evaluate this effect.

MASS CONCRETE

Issues related to mass concrete placements are essentially the same as those discussed under the effects of early age behavior. Work is currently underway at Auburn University to study the possible beneficial use of lightweight concrete for mass concrete placements for its thermal properties rather than for its reduced density, although the reduced density can also be beneficial.

CONCLUSIONS

Laboratory testing of normal weight, sand lightweight, and all lightweight concrete mixtures has provided thermal property test results that can be used in a number of applications for design and analysis of structures and pavements. Of note, heat capacity and thermal conductivity tests were performed on bulk specimens (per ASTM C518) rather than crushing the concrete which destroys the pore structure of lightweight aggregates. Test results for coefficient of thermal expansion, heat capacity, and thermal conductivity for these mixtures compare reasonably to published data.

Review of the literature reveals no studies on the influence of thermal properties of lightweight concrete on the performance of bridge components. As indicated by test results from UNC Charlotte and Auburn University described in this paper, along with other data on thermal properties available in the literature, the thermal performance of lightweight concrete differs significantly from that of normal weight concrete. Based on the data presented, the following conclusions can be made.

The coefficient of thermal expansion and thermal conductivity of lightweight concrete decrease with increasing lightweight aggregate content and decreasing density.

The lower coefficient of thermal expansion for lightweight concrete will result in reduced volumetric change for a given increase or decrease in temperature, when compared to a normal weight concrete produced with many types of conventional coarse aggregate available in the US.

The lower coefficient of thermal expansion for lightweight concrete could provide advantages related to bridge joint performance, reducing the opening and closing movements which could potentially extend the life of joint seals and bearing systems.

Lightweight concrete has a lower thermal conductivity than normal weight concrete, likely resulting in differences in the thermal gradients that would be experienced by bridge components of similar construction and exposure.

The heat capacity of lightweight concrete as measured for this study was similar to conventional concrete on a mass basis, but significantly reduced on a volumetric basis due to the lower unit weight of lightweight concrete.

Based on the heat capacity and thermal conductivity values measured in the laboratory, the retention and movement of heat through structural components in a bridge will be different for lightweight concrete.

Theoretical consideration of the effects of the different thermal properties of lightweight concrete on several aspects of bridge behavior appear to be promising and worthy of further study.

In closing, the impact of heat capacity and thermal conductivity on the storage and transfer of thermal energy (heat) during a daily service cycle, as well on short-term and long-term performance of bridge components such as decks and superstructures is not well understood. Additional research in this area could include thermal modeling, as well as field studies using sensors and other measurement tools to gather data on real world performance. Thermal performance is also linked to the moisture state of concrete, and heat storage, transfer, and deformations are a complex phenomenon to understand and model. In recent years, the role of thermal and moisture gradients on curling and warping of pavements have been a focus of a significant research effort, resulting in a better understanding of pavement joint performance and the construction/materials/maintenance required to achieve suitable performance. A similar effort to study the effect of thermal and moisture gradients on bridge decks could yield similarly useful findings that could lead to materials selection and construction practices that extend the service life of joints, bridge decks, and consequently the entire bridge. Findings of modeling and field studies on a number of bridge components could be utilized to assist bridge designers in materials selection and concrete mixture design for new bridges, and could potentially offer insight in to the predicted service life of bridge components.

ACKNOWLEDGEMENTS

The support of STALITE, the manufacturer of the expanded slate lightweight aggregate used in the UNC Charlotte study, is appreciated. The support of the Materials Characterization Laboratory at UNC Charlotte is also appreciated.

REFERENCES

1. Cavalline, T.L. (2016). “Evaluation of Thermal Performance of Lightweight Concrete.” Final Report. STALITE, Salisbury, NC.

2. Byard, B.E. and Schindler, A.K. (2010). *Cracking Tendency of Lightweight Concrete.* Highway Research Center, Auburn, AL, 82 pp.

3. ACI Committee 122. (2014). *Guide to Thermal Properties of Concrete and Masonry Systems*. ACI 122R-14. Farmington Hills, MI: American Concrete Institute.

4. Valore, R. C., Jr. (1980). “Calculation of U-Values of Hollow Concrete Masonry,” *Concrete International*, 2(2), February, pp. 40-63.

5. Applied Research Associates. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report.* National Cooperative Highway Research Program (NCHRP). Project 1-37A. Available at: http://onlinepubs.trb.org/onlinepubs/archive/mepdg/guide.htm

6. AASHTO. (2015). *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice.* 2nd Edition. Washington, DC: American Association of State Highway Transportation Officials.

7. Federal Highway Administration (FHWA). (2010). *Local Calibration of the MEPDG Using Pavement Management Systems.* FHWA Report No. HIF-11-026. Available at: http://www.fhwa.dot.gov/pavement/management/pubs/hif11026/hif11026.pdf

8. Guclu, A., Ceylan, H., Gopalakrishnan, K., and Kim., S. (2009). "Sensitivity Analysis of Rigid Pavement Systems Using the Mechanistic-Empirical Design Guide Software." *ASCE Journal of Transportation Engineering*, 135(8), 555-562.

9. Lee, J.-H., Lee, J.-J., and Cho, B.-S. (2012). "Effective Prediction of Thermal Conductivity of Concrete Using Neural Network Method." *International Journal of Concrete Structures and Materials*. 6(3), 177-186.

10. Applied Research Associates. (2004). *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report. Part 2: Design Inputs.* National Cooperative Highway Research Program (NCHRP). Project 1-37A.

11. Tatro, S.B. (2006). "Chapter 22: Thermal Properties." *Significance of Tests and Properties of concrete and Concrete-Making Materials*. ASTM Special Technical Publication 169D, ASTM International, West Conshohocken, PA, pp. 226-237.

12. ASTM International. (2013). ASTM C177. *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus*. In Annual Book of ASTM Standards, Vol. 04.06: Thermal Insulation; Building and Environmental Acoustics. West Conshohocken, PA.

13. ASTM International. (2011). ASTM C1363. *Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus*. In Annual Book of ASTM Standards, Vol. 04.06: Thermal Insulation; Building and Environmental Acoustics. West Conshohocken, PA.

14. ASTM International. (2015). ASTM C518. *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*. In Annual Book of ASTM Standards, Vol. 04.06: Thermal Insulation; Building and Environmental Acoustics. West Conshohocken, PA.

15. Kibert, Charles J. (2012). *Sustainable Construction: Green Building Design and Delivery.* 3rd Edition, Wiley.

16. ACI. (2013). *ACI Concrete Terminology*. ACI CT-13. Farmington Hills, MI: American Concrete Institute.

17. AASHTO. (2014). *AASHTO LRFD Bridge Design Specifications, Customary U.S. Units.* 7th Edition, with 2015 Interim Revisions. Washington, DC. American Association of State Highway and Transportation Officials.

18. Mallela, J., Abbas, A., Harman, T., Rao, C., Liu, R., and Darter, M. (2005). "Measurement and significance of the coefficient of thermal expansion of concrete in rigid pavement design." Transportation Research Record: *Journal of the Transportation Research Board*, 1919, 38-46.

19. AASHTO. (2011). AASHTO T 336. *Standard Method of Test for Coefficient of Thermal Expansion of Hydraulic Cement Concrete.* Washington, DC. American Association of State Highway and Transportation Officials.

20. Maggenti, R. (2008). "From Passive to Active Thermal Control." *Concrete International*. 29(11), November, pp. 24-30.