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Characterization of Portland Cement Concrete Coefficient of Thermal Expansion in South Carolina

Report No: FHWA-SC-17-03

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Submitted to the South Carolina Department of Transportation

This research was sponsored by the South Carolina Department of Transportation. The opinions, findings and conclusions expressed in this report are those of the author(s) and not necessarily those of the SCDOT. This report does not comprise a standard, specification or regulation.

1. Report No. FHWA-SC-17-03	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Characterization of Portland Cement Concrete Coefficient of Thermal Expansion in South Carolina		5. Report Date October 31, 2016 6. Performing Organization Code
7. Author(s) Trent H. Dellinger Amir Poursee		8. Performing Organization Report No.
9. Performing Organization Name and Address Glenn Department of Civil Engineering Clemson University Clemson, SC, 29631-0911		10. Work Unit No. 11. Contract or Grant No. SPR 722
12. Sponsoring Agency Name and Address South Carolina Department of Transportation P.O. Box 191 Columbia, South Carolina 29202		13. Type of Report and Period Covered Draft of Final Report, 2015-2016 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The South Carolina Department of Transportation (SCDOT) sough to regionally calibrate specific input parameters used by the Mechanistic Empirical Pavement Design (MEPDG) software. These properties include the coefficient of thermal expansion (CTE), compressive strength, and unit weight of typical SC concrete mixtures. Additionally, splitting tensile strength was included in the experimental program. Laboratory produced mixtures were tested to identify the effective CTE value of the cement paste, sand, and coarse aggregate compotes typically used in SC concrete pavements. A 25 percent cement replacement of type F fly ash and a single source of natural sand was used in the mortar component of the concrete mixtures. A total three coarse aggregate sources were used in the form of no. 57 crushed stone product or a 75:25 blend of no. 57 and no. 789 crushed stone. The CTE values of the individual phases (i.e. cement paste, sand and coarse aggregates), and concrete mixtures were measured. The resulting CTE of paste and sand was 7.3 and 5.9×10^{-6} in./in./°F, respectively. The CTE of three coarse aggregates ranged from 2.96 to $3.83\times\text{to}^{-6}$ in./in./°F. The range of average CTE values of the concrete was 4.82 to 5.32×10^{-6} in./in./°F. The magnitude of the CTE values were shown not to be directly related to the compressive strength. Field cored specimens were also taken from a section of SC – 80 in Spartanburg county, SC, and analyzed. Three pavement slabs were arbitrarily selected along a 3.5-mi. pavement section. The targeted slabs were of the outside travel lane, with cores taken between the wheel paths at the leading end, middle, and trailing ends of each slab. There was not significant difference between the average CTE values of pavement slabs. The effective CTE of SC - 80 concrete pavement was determined to be 5.05×10^{-6} in./in./°F. The compressive strength and unit weight properties of the SC – 80 specimens suggested that the laboratory produced concrete mixtures from the first part of this study were representative of the concrete pavements in South Carolina.

17. Key Words Coefficient of Thermal Expansion, CTE, MEPDG	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

Form DOT F 1700.7 (8-69)

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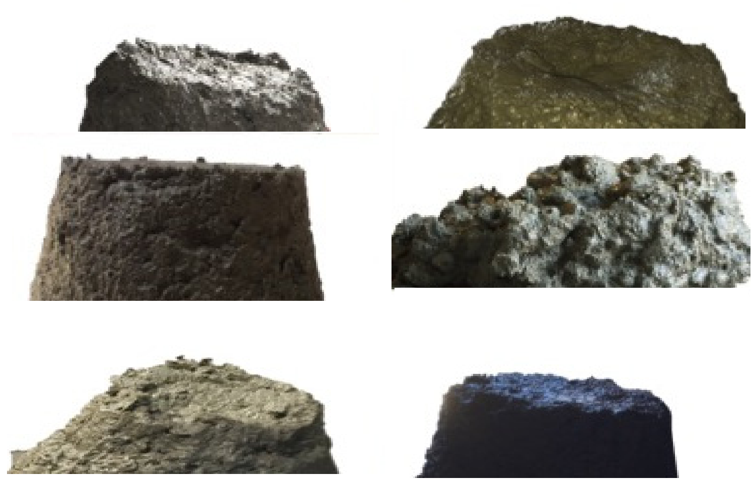
Acknowledgments

This project was funded by the South Carolina Department of Transportation and the Federal Highway Administration. Their support is greatly appreciated. The authors would like to acknowledge the assistance and feedback provided by personnel at the Office of Materials and Research of the South Carolina Department of Transportation.

Executive Summary

With FHWA support, AASHTO recently officially adopted a new "mechanistic-empirical" process for designing pavements in which nationally calibrated models are used to simulate and predict pavement behavior that are best-fit approximations based on observations from across the US and Canada. Unfortunately, the predicted pavement outcomes using national models may not be accurate for specific locations. For this reason, virtually all states that use AASHTO pavement design methods are most strongly encouraged to perform a calibration of the new pavement models to local conditions. Because the new process is a complete break from the old procedure, the design inputs are totally different and frequently based on properties that the Department has not previously measured. While some inputs can be reasonably estimated, it is important to actually measure key properties that have been found to have the greatest impact on design predictions to ensure accurate pavement designs.

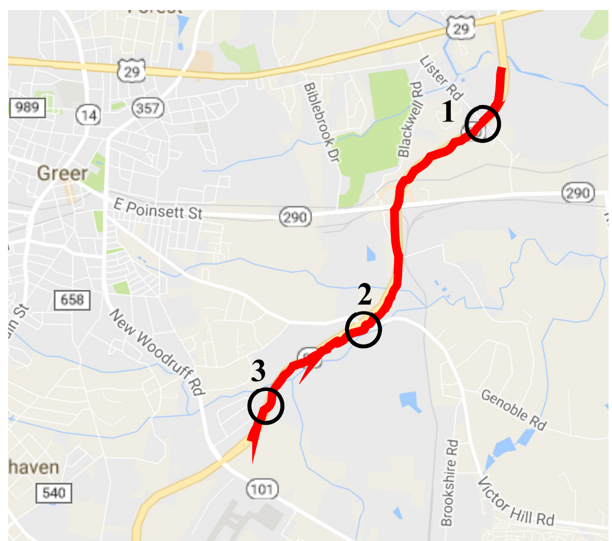
The South Carolina Department of Transportation (SCDOT) has desired to regionally calibrate specific input parameter used by the Mechanistic Empirical Pavement Design (MEPDG) software. These properties include the coefficient of thermal expansion (CTE), compressive strength, and unit weight of typical SC concrete mixtures. Additionally, splitting tensile strength was included in the experimental program.



Images of slump measurements of laboratory mixtures

This project determined the CTE of the most common pavement mixtures throughout the state of South Carolina using AASHTO T336-11 method. The data generated in this project provided a comprehensive overview of the CTE of concrete mixtures in South Carolina for direct implementation in designing PCC pavement and for the specification and testing of PCC materials. Laboratory produced mixtures were tested to identify the effective CTE value of the cement paste, sand, and coarse aggregate compotes typically used in SC concrete pavements. A 25 percent cement replacement of type F fly ash and a single source of natural sand was used in the mortar component of the concrete mixtures. A total three coarse aggregate sources were used in the form of no. 57 crushed stone product or a 75:25 blend of no. 57 and no. 789 crushed stone. The CTE values of the individual phases (i.e. cement paste, sand and coarse aggregates), and concrete mixtures were measured. The resulting CTE of paste and sand was 7.3 and 5.9×10^{-6} in./in./°F, respectively. The CTE of three coarse aggregates ranged from 2.96 to 3.83×10^{-6} in./in./°F. The range of average CTE values of the concrete was 4.82 to 5.32×10^{-6} in./in./°F. Results indicated that the CTE values were not directly related to the compressive strength on the concrete. The collected data were also used to calculate CTE values using the Tex-428-A method. Results from the Tex-428-A method in all but one data set, showed lower CTE values compared to the AASHTO T336-11 method. The maximum difference in CTE values between these test methods was 0.134×10^{-6} in./in./°F.

Field cored specimens were also taken from a section of SC – 80 in Spartanburg county, SC and analyzed. Three pavement slabs were arbitrary selected along a 3.5-mile pavement section. The targeted slabs were of the outside travel lane, with cores taken between the wheel paths at the leading end, middle, and trailing ends of each slab. Results showed no significant differences between the average CTE values of pavement slabs. The effective CTE of SC - 80 concrete pavement was determined to be 5.05×10^{-6} in./in./°F. The compressive strength and unit weight properties of the SC – 80 specimens suggested that the laboratory produced concrete mixtures from the first part of this study were representative of the concrete pavements in South Carolina.



Map of sampling locations along SC 80 and Example of sampling locations within a slab

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Chapter 1:
Introduction

The focus of this report was to determine the Coefficient of Thermal Expansion (CTE) of typical Portland Cement Concrete (PCC) mixtures with differing South Carolina (SC) aggregate sources. The design software, Mechanistic Empirical Pavement Design Guide (MEPDG), uses a default CTE value that is not specific to the state; thus, the South Carolina Department of Transportation (SCDOT) was interested in identifying the CTE of aggregate sources likely to be used in the production of concrete pavements in South Carolina.

1.1. Problem Statement

With Federal Highway Administration (FHWA) support, American Association of State Highway and Transportation Officials (AASHTO) officially adopted a new "mechanistic-empirical" process for designing pavements in which nationally calibrated models are used to simulate and predict pavement behavior that are best-fit approximations based on observations from across the United States and Canada. Unfortunately, the predicted pavement outcomes using national models may not be accurate for specific locations. For this reason, virtually all states that use AASHTO pavement design methods are strongly encouraged to perform a calibration of the new pavement models to local conditions. Due to the significant difference between the new process and the old procedure, the design inputs are totally different and frequently based on properties that the SCDOT has not previously measured. While some inputs can be reasonably estimated, it is important to actually measure key properties that have been found to have the greatest impact on design predictions to ensure accurate pavement designs. In 2010, the SCDOT research project, “Mechanistic/Empirical Design Guide Implementation,” found that the CTE of PCC is a key input in performance predictions for concrete pavement and is strongly influenced by the local materials used. It was not known, however, if the default CTE values used in the design procedure were representative of SC materials and conditions.

This project involved determining the CTE of concrete mixtures made with local sand and coarse aggregates used in the production of SC concrete pavements. With this data, an estimation of CTE of current and proposed pavement designs can be determined and used in MEPDG input parameters. The CTE of concrete pavements, in conjunction with pavement thickness, effects percent cracking projects generated by the MEPDG software. This study provides the regional calibration data for SC to be used alternatively to their respective default parameters in level 2 and 3 MEPDG inputs.

1.2. Project Objectives

Part 1: Evaluation of CTE of SC concrete aggregates

- A total of 6 sets of 18 cylindrical concrete specimens were produced for the primary objective of the study. Properties tested include determination of the CTE, unit weight, compressive strength, and splitting tensile strength at ages of 28-days and 90-days.
- A set of 3 cylindrical cement paste specimens and 3 cylindrical mortar specimens were produced; mixture proportions matched those found in the primary concrete mix design. The CTE values of these specimens were measured.
- The compressive strengths of the 28-day old specimens were determined. These results used to estimate level 2 MPEDG compressive strength inputs.
- Sets of 3 solid aggregate cores (dimensions consistent with specimens prepared for CTE testing) were produced from 2 of the 3 coarse aggregate sources used in this study. The CTE values of these specimens were measured. In addition, specimens were used in the verification of bulk specific gravity of the aggregate.
- The CTE of cement paste, fine aggregate (natural sand), and three SC coarse aggregates were determined.

Part 2: Evaluation of CTE of in-field PCC pavement, SC-80.

- A total of 3 sets of 3 cylindrical cored specimens were taken from a section concrete pavement along SC-80, between the intersections of SC-29 and SC-101. Each set of 3 cores represented the following locations across a single slab: leading end, middle, and trailing end along the centerline of the outside travel lane. The highway in the selected location had 4-lanes of travel (2 in each direction), grass median, and concrete shoulders.
- The following data were collected from each specimen: initial length, post-saw cut length, average diameter and unit weight.
- The CTE, density, and compressive strength of each specimen was evaluated.

Chapter 2:
Literature Review

Released in 2004 by the National Cooperative Highway Research Program (NCHRP), the Mechanistic Empirical Pavement Design Guide (MEPDG) is an advanced pavement design analysis to determine both the structural response and performance prediction within the design life of PCC pavements. Although widely considered a fundamental property of PCC pavement, the CTE has never been a critical factor in PCC pavement thickness design until recently when the MEPDG considered it a direct input parameter that was closely related to pavement performance [Applied Research Association, 2014]. Therefore, this new consideration makes it imperative to accurately measure the CTE for PCC pavements to predict critical pavement distresses that occur in PCC pavement lifecycles.

Several variables are now known to affect the CTE of concrete: the type and amount of aggregate, the type and amount of cement, and the concrete age, followed by a minimal CTE affect from cylinder size, water-cement ratio, sand-aggregate ratio and temperature.

Pearson proposed that differential CTE among constituents in concrete were to blame for the rapid failure of a specific concrete structure, which durability experiments could not reasonably place blame on freeze-thaw resistance or unsound aggregates. It was speculated by Meissner that a more homogeneous aggregate composition was more durable then concretes having a more heterogeneous aggregate composition (Pearson et al., 1942).

Parsons and Johnson emphasized the need to examine the CTE of aggregates typically used in concrete (Parsons and Johnson, 1944). They used the interferometer method to examine the CTE of numerous aggregate sources. In their study, they examined how the crystalline structure of aggregate effected its CTE and they also determined the CTE values of 26 aggregate sources. They observed that the measured CTE parallel and perpendicular of the crystalline axis can differ greatly. Within the temperature range of -4°F to +140°F (-20°C to +60°C), the CTE of quartz ranged from $4.1\parallel$ to $7.5\perp$ με/°F ($7.4\parallel$ to $13.5\perp$ με/°C) while the calcite ranged from $14.3\parallel$ to $-2.8\perp$

με/°F (25.7‖ to -5.04⊥ με/°C). Of the 26 aggregate sources, 19 samples were composed of the chert with more than 99% quartz of random crystalline orientation. Those samples exhibited relatively identical CTE of 6.3 με/°F (11.3 με/°C). Parsons and Johnson speculated that 6.3 με/°F (11.3 με/°C) was the average CTE of quartz among all crystalline directions. The average CTE of quartz as determined by matches well with recent tests of mortars produced with river sand (Siddiqui and Fowler, 2015).

Hockman and Kessler conducted a study of the granites using the same interferometer method described by Parsons and Johnson (Hockman and Kessler, 1950). They observed the CTE value of 3.7 με/°F (6.6 με/°C) and 3.3 με/°F (6.0 με/°C) during a heating cycle ranging from +32°F to +140°F (0°C to +60°C) for Rion and Newberry samples, respectively. While these values were 3.8 με/°F (6.9 με/°C) and 3.5 με/°F (6.3 με/°C) during a cooling cycle ranging from +140°F to +32°F (+60°C to 0°C). When averaging the CTE of the heating and cooling cycles, the CTE becomes 3.75 με/°F (6.75 με/°C) and 3.42 με/°F (6.15 με/°C) for Rion and Newberry samples, respectively. Hockman and Kessler also reported irregularities in the expansion rate of the aggregate when moisture was free to penetrate the aggregate surface. The effect of moisture on the CTE of concrete remains a topic of interest in recently published studies as well (Siddiqui et al., 2016; Siddiqui and Fowler, 2014).

Callan attempted to correlate the freeze-thaw durability factor of concrete with its corresponding difference in CTE between coarse aggregate and mortar (Callan, 1952). He suggested that the concrete durability factor reduced significantly when the difference in CTE of the coarse aggregate and the mortar was further apart, suggesting that coarse aggregate having an excessively small CTE would be more susceptible to freeze-thaw damage. Callan suggested that the difference of CTE between coarse aggregate and mortar should not exceed 3.0 με/°F (5.4 με/°C).

The extensive studies performed by Walker and his colleagues suggested that the CTE of concrete was related to the proportion of volume of the aggregates in the concrete (Walker et al., 1952). Much of their conclusions was also reported by the current prevailing characterization of CTE in concrete, such as more recent literature (Young et al., 2002).

Walker et al. works led Emanuel and Hulsey to present equations that predicted the CTE of a concrete when the weighted volumetric portion and CTE of each ingredient of concrete mixture was known (Emanuel and Hulsey, 1977). The Emanuel and Hulsey's prediction model equations are as following:

Equation 1: $\alpha_C = f_T (f_M f_A \beta_P \alpha_S + \beta_{FA}\alpha_{FA} + \beta_{CA}\alpha_{CA})$

Equation 2: $\beta_P + \beta_{FA} + \beta_{CA} = 1$

Where;

α_C = CTE of the concrete

α_S = CTE of saturated hardened cement paste

α_{FA} = CTE of the fine aggregate component

α_{CA} = CTE of the coarse aggregate component

β_P = Volumetric proportion of hardened cement paste

β_{FA} = Volumetric proportion of the fine aggregate component

β_{CA} = Volumetric proportion of the coarse aggregate component

β_T = Correction factor for temperature alteration (use 1.0 if controlled environment or 0.86 for outside exposure conditions)

f_m = Correction factor for moisture

f_A = Correction factor for age of concrete

Siddiqui and Fowler modified the prediction equations proposed by Emanuel and Hulsey to allow for the use of blended aggregates having varying CTE (Siddiqui and Fowler, 2015). In their investigation, they prepared different sets of samples with coarse aggregates with different CTE values. Then they used limestone, with the lowest CTE of all the aggregates, to replace volumetric portion of the aggregates used to make their specimens. Figure 1 shows the best-fit curves of the resulting CTE values. All values intercepted at the CTE value of concrete produced with 100% limestone. This method of using best-fit curves to predict the CTE of individual ingredients in the concrete was utilized in this project. Siddiqui and Fowler was also investigated the impact of paste volume on the CTE of concrete (Siddiqui and Fowler, 2015). They first proportioned the concrete for the cement content required to achieve theoretical paste volume. Theoretical paste volume was the paste volume that was equal to the void content of the dry rodded combined aggregates (coarse + fine aggregates). Then they deviated the paste volume (increased and decreased) from the theoretical paste volume to determine the effect of paste volume on the CTE of concrete. Their results showed that the CTE of concrete decreased as the cement paste volume decreased up to the theoretical paste volume. However, the CTE increased when the paste volume decreased below the theoretical paste volume. They hypothesized that the increase in CTE below the theoretical paste was due to the internal water pressure. When the paste content was below the theoretical paste volume, the concrete did not have enough paste to fill all the voids between aggregates, this additional voids increased the porosity of the concrete. Higher porosity in concrete led to higher amounts of liquid in the saturated concrete and since the liquid phase had a higher CTE than the solid phase higher CTE in saturated concrete with higher void content was observed. The measured CTE was observed to increase with the volume of cement paste increases or decreases from the volume of voids in unit volume of the rodded aggregate in concrete. Its suggested that more voids are present to allow for increased moisture in the concrete when the paste volume is too lean to fill voids not filled with aggregate; internal water pressure was believed to cause the increase in CTE. The increase in CTE when the cement paste volume is greater then the allowable void space can be contributed to the increased portion of a concrete component having a greater CTE then the aggregate.

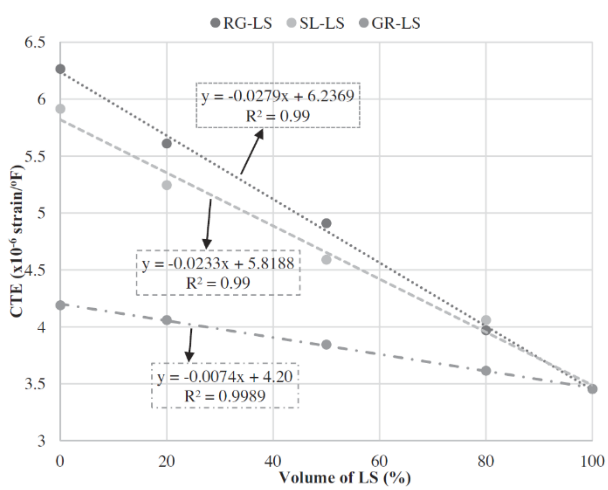

Figure 1: Benefit of blending low-CTE coarse aggregate with high-CTE coarse aggregate to reduce the CTE of concrete (Siddiqui and Fowler, 2015)

Emanuel and Hulsey also examined the results of concrete moisture saturation (Emanuel and Hulsey, 1977). Results from their study showed that that the CTE of concrete was greatest at a particular saturation level as shown in Figure 2

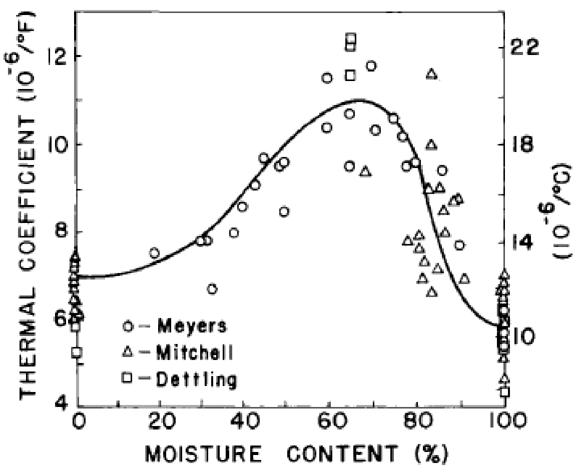

Figure 2: Variation of CTE of results from three studies complied to show correlation of CTE of concrete at different saturation levels (Emanuel and Hulsey, 1977).

In their use of CTE to reduce pavement stress in Jointed Plain Concrete Pavements (JPCP), Mallela and his colleagues found that an increase in CTE led to increased cracking, joint faulting, and International Roughness Index (IRI) in JPCP [Mallea et al., 2005]. In their examination of 673 cores from different pavement sections throughout the US, they also found a range of CTE values of PCC is between 5 and 7 με/°F (9 and 12.6 με/°C). The specific results of this Long Term Pavement Performance (LTPP) program also found that concrete made from igneous aggregates had CTE values around 5.2 με/°F (9.4 με/°C), and concrete from sedimentary rock had a typical value of 6 με/°F (10.8 με/°C). The mean CTE value of the entire data set was 5.7 με/°F (10.3 με/°C).

In another separate CTE analysis, Mindness et al. determined a range of 3.3 με/°F and 6.1 to 7.2 με/°F (6 με/°C and 11 to 13 με/°C), in limestone and quartzite samples respectively and that the CTE of cement pastes ranged between 10 and 11.1 με/°F (18 and 20 με/°C) [Mindess et al., 2003]. Consequently, the proportion of coarse aggregate in concrete mixtures should be considered when estimating the CTE.

For concrete with crushed limestone and siliceous sand, the CTE decreases significantly when the amount of crushed limestone increases. Although this increase is due to a smaller amount of CTE in the limestone than the cement paste [Mindess et al., 2003], with quartz gravel and siliceous sand, the concrete CTE increases slowly with the increase of the amount of quartz gravel. In their study of porous limestone, river gravel, and dense limestone, Alungbe et al. found that the CTEs of each of these aggregates differed significantly from one another. They also concluded that the water/cement ratio (0.53, 0.45, and 0.33) and cement content (508 lb/yd^3, 564 lb/yd^3, and 752 lb/yd^3) did not statistically show significant effects on the CTE [Alungbe et al., 1992].

Similarly, Won concluded that the aggregate geology, the volume of aggregate within the mixture, and the age of the specimen at the time of testing all affected the CTE of PCC. They also elucidated a near linear relationship between the percent volume of coarse aggregate in the concrete mixture and the resultant CTE, and found that the CTE values remained static for three weeks with the age of concrete [Won, 2005].

However, in their statistical investigation of the impact of sample age with an aggregate geology, Buck et al. concluded that the magnitude of CTE at 28 days was significantly lower than that of CTE at 90 and 180 days for most aggregate types. The difference of CTE between 28 days and 180 days varied from 0.08 to 0.52 με/°F (0.15 to 0.94 με/°C) [Buch et al., 2008]. They also found that the average 28-day CTE for concrete cylinders containing limestone, was 4.54 με /°F (8.18 με /°C), for concrete cylinders with dolomite coarse aggregate, ranged from 5.87 to 5.92 με /°F (10.57 to 10.65 με/ºC), for concrete cylinders with a gravel coarse aggregate, was 5.84 με /°F (10.52 με /°C) for concrete cylinders made with slag, was 5.71 με /°F (10.27 με /°C), and for concrete cylinders containing gabbro, which is an intrusive igneous rock for the coarse aggregate, was 5.41 με /°F (9.73 με/°C).

In their use of the MEPDG program to study the effects of CTE on pavement performance, Tanesi et al. found that an increase in the CTE value did indeed increase transverse cracking and faulting. Specifically, transverse cracking increased 15% between the CTE values of 5.5 με /°F (9.90 με /°C) and 6.5 με /°F (11.7 με /°C) and approximately 32% between the CTE values of 6.5

με /°F (11.7 με/°C) and 7.5 με /°F (13.5 με /°C). Specifically, transverse cracking was very prominent while faulting [Tanesi, 2007].

To explain the reasons for irregular longitudinal cracking, Chen and his colleagues performed field investigations on several PCC pavement segments. They compared a southbound segment of road with considerable cracking to a segment from northbound lane in the same location with no cracking. It was determined that the northbound lanes consisted of limestone aggregate and the southbound lanes consisted of siliceous river gravel aggregate. They concluded that the limestone, which has a relatively low CTE, expanded and contracted less than the siliceous river gravel, which has a relatively high CTE. Because of these conclusions, many Texas Department of Transportation (TxDOT) districts no longer allow the use of coarse aggregate that results in a CTE higher than 6 με /°F (10.8 με /°C) [Chen and Won, 2007].

Research conducted the last 10 years has been interested in using the CTE values of concrete in the MEPDG. This software provides default parameters based on nationally calibrated values, as summarized in Table 1 (Guclu et al., 2009). These values are subject to change when a state can provide regionally calibrated values to use as the alternative to the nationally calibrated defaults. The published studies (Crawford et al., 2010; Tanesi et al., 2010) suggest that each state should determine the CTE values of concrete using aggregate typically used for concrete pavements in that state.

Table 1: MEPDG default design inputs (Guclu et al., 2009)

Default Input Parameter	***Value***
Design life (years)	25
Initial IRI – m/km (in/ mi)	1 (63)
Terminal IRI – m/km (in / mi)	2.68 (170) (limit)
Transverse cracking (% slabs cracked)	15 (limit)
Mean joint faulting – cm (in)	0.4 (0.15) (limit)
Initial two-way AADTT	6,000
Number of lanes in design direction	2
Percent of trucks in design direction	50
Percent of trucks in design lane	90
Operational speed (mph)	60
Mean wheel location – cm (in)	46 (18)
Traffic wander standard deviation – cm (in)	25 (10)
Design lane width – m (ft)	3.65 (12)
Average axle spacing – m (ft)	3.65, 4.6, 5.5 (12, 15, 18)
Percent of trucks (%)	33, 33, 34
Permanent curl/warp effective temperature	-10
difference (°F)	4.6 (15)
Joint spacing – m (ft)	2.5 (1)
Dowel diameter – cm (in)	30.5 (12)
Dowel spacing – cm (in)	Granular
Base type	Erosion Resistant (3)
Erodibility index	0.85
Base/slab friction coefficient	Bonded
PCC-Base Interface	60
Loss of bond age (months)	0.85
Surface shortwave absorptivity	Minor (10%)
*Infiltration	3.65 (12)
*Drainage path length – m (ft)	2
*Pavement cross slope (%)	25 (10)
Layer thickness – cm (in)	24 (150)
Unit weight – kN/m3 (pcf)	0.2
Poisson's ratio	5.5
Coefficient of thermal expansion (per F° x 10- 6)	1.25
Thermal conductivity (BTU/hr-ft-F°)	0.28
Heat capacity (BTU/lb-F°)	0.42
Water/cement ratio	50
Reversible shrinkage (% of ultimate shrinkage)	35
Time to develop 50% of ultimate shrinkage (days)	Curing Compound
Curing method	4,750 (690)
28-day PCC modulus of rupture – kPa (psi)	

First published in 2000 and reconfirmed in 2006, the AASHTO-TP 60-00 method has been the primary tool for measuring the CTE of hydraulic cement concrete [AASHTO, 2000]. However, an error recently discovered in this standard regarding the calibration of the testing equipment resulted in the publication of a new supplement, AASHTO T 336-11[AASHTO, 2011]. This new standard, which is based on the TP 60-00, was introduced to rectify this calibration issue. The principle of both methods is very simple: they both measure the length change of a saturated concrete specimen placed vertically in a metal frame subjected to a specific temperature change controlled by a controlled temperature water bath [Tanesi, 2010]. The deformation of the frame is considered by measuring the length change of a specimen of known CTE, normally a 304 stainless steel specimen. While T60 considered a fixed value as the CTE of the metal frame, a new AASHTO T 336-11 does not assume any value for the calibration specimen. It instead requires that the CTE of the calibration specimen be determined by a certified independent laboratory.

Establishing Standard Test Method for CTE Testing

The CTE of concrete has been tested with various test apparatuses and methods, as seen in the literature prior to the introduction of AASHTO T336. In the AASHTO method, the calibration factor for the specimen holding frame was approximately 2.3 με/°C greater than when tested in accordance to ASTM E228[1]. The change to the calibration method is important because as the frame correction factor, C_f, increases, the effective CTE of the specimen being tested also increases; meaning that all test results prior to AASHTO T336-11 could be relatively greater than those were originally reported. As of 2010, many laboratories that have published CTE of PCC have used custom-built equipment (Crawford et al., 2010). Many of the results obtained from laboratories using custom-built equipment also used the assumed calibration factor of 17.3 με/°C to calculated the CTE of the specimen. It was recommended that each laboratory should calculate the correction factor with uniform calibration specimens regularly as the correction factor can change over time. Recommendations for improved testing were also provided in (Tanesi et al., 2010) which include recommendations for water level in the specimen water tank. When the water level differs from when the last calibration of the testing was performed, the expansion of the

[1] ASTM E228 Standard Test Method for Linear Thermal Expansion of Solid Materials with a Push-Rod Diloatometer.

frame would be different; meaning the calibration factor will not be valid to correct for the frame expansion. This effect should not be an issue with test equipment that uses fully submerged testing frames and LVDT's. Siddiqui and Fowler conducted experiments to evaluate the effects of internal water pressure on the CTE value. They concluded that the internal water pressure was associated with the higher CTE values reported by the TxDOT[2] method, Tex-428-A, versus the AASHTO T 336 method (Siddiqui and Fowler, 2014). Both test methods are based on the AASHTO TP 60 standard test. The results of this experiment showed the importance of maintaining internal relative humidity during conducting the CTE test. Thus, it would be reasonable suggesting that the research conducted on in-air specimens in the 1970's would not valid. Nevertheless, more research on the role of the moisture on CTE measurements is necessary to completely clarify this issue.

[2] Texas Department of Transportation, TxDOT.

Chapter 3:
Materials and Experimental Procedures

Materials

The following materials listed in Table 2 were used in the production of 6 sets of 18 concrete cylinders. 4 × 8 in. concrete cylinders were produced in a single batch. Images of the aggregates used in Part 1 are shown in Figure 3.

Table 2: Part 1 material information

Material	***Description***	***Production Location***	***Supplied by***
Type I/II Portland cement	1-ton pallet of 94 lbs. bags	Argos USA 463 Judge St Harleyville, SC 29448	Argos USA 463 Judge St Harleyville, SC 29448
Type F fly-ash	Sealed in 3 5-gallon plastic buckets	Santee Cooper Cross generation Station 553 Cross Station Road Pineville, SC 29468	Metrocon 2399 Norris Highway Central, SC 29630
Sand	1-ton bag		Glasscock Co. Inc. 5378 Broad St Sumter, SC 29154
Coarse aggregate No. 1	1-ton bag each of 57 and 789	Martin Marietta Aggregates 2125 State St Cayce, SC 29033	Martin Marietta Aggregates 2125 State St Cayce, SC 29033
Coarse aggregate No. 2	1-ton bag each of 57 and 789	Vulcan Materials 239 Mill Creek Rd Blacksburg, SC 29702	Vulcan Materials 239 Mill Creek Rd Blacksburg, SC 29702
Coarse aggregate No. 3	1-ton bag each of 57 and 789	Hanson Aggrgates 341 Becker Minerals Ln Jefferson, SC 29718	Hanson Aggrgates 341 Becker Minerals Ln Jefferson, SC 29718
Admixtures	½ gallon containers	Sika Corporation	Metrocon 2399 Norris Highway Central, SC 29630

(a) (b)

(c) (d)

(e) (f)

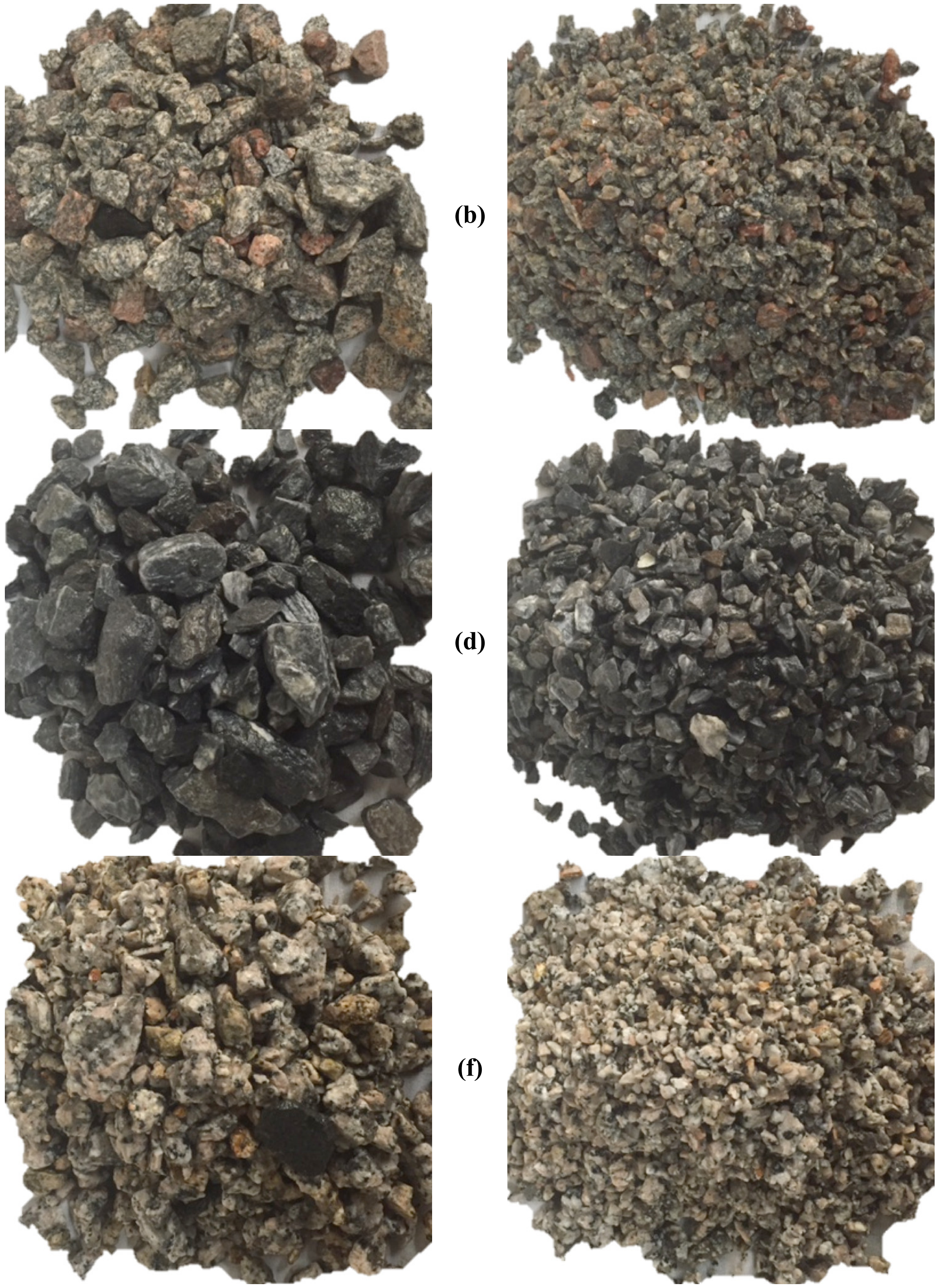

Figure 3: Images of aggregates; (a) Cayce 57, (b) Cayce 789, (c) Blacksburg 57, (d) Blacksburg 789, (e) Jefferson 57, and (f) Jefferson 789.

Laboratory Mixture Proportions (Part A)

Mixture proportions of the principle experimental mixtures of this study are shown in Table 3. The mixture proportions were based on a mix design provided by the SCDOT. Water/cementitious material ratio (w/cm) of ratio of 0.4 was used. This ratio yielded concrete with acceptable percent air and slump values. Table 3. shows the mixture propositions used in this investigation. The dosages of admixtures can be found in Table 4.

Table 3: Mix designs of laboratory test mixtures.

Material	*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*	*unit*
Cement:	414	414	414	414	414	414	lbs./yd^3
Fly-ash:	124	124	124	124	124	124	lbs./yd^3
Water:	215	215	215	215	269	215	lbs./yd^3
FA_{sand}:	1143	1143	1143	1143	1143	1143	lbs./yd^3
CA_{57}	1602	1732	1602	2002	2014	2002	lbs./yd^3
CA_{789+57}:	400	433	400	0	0	0	lbs./yd^3
AEA[1]:	1.5	1.5	1.5	1.5	1.5	1.5	oz./cwt
SE[2]:	2.0	2.0	2.0	2.0	2.0	2.0	oz./cwt
WR[3]:	11.0	11.0	11.0	11.0	5.5	11.0	oz./cwt

[1] Air-Entraining Admixture: AEA-14 by Sika®
[2] Set Extender: Plastiment® ES by Sika®
[3] Water-Reducer: SikaPlast®-300 GP by Sika®

Table 4: Admixtures dosages used in laboratory mixtures MX1 thru MX6 (Part A).

Admixture	*unit*	*MX1*	*MX2*	*MX3*	*MX4*	*MX5B*	*MX6*
Air Entraining Admixture (AEA):	fl.oz./cwt	1.5	1.5	1.5	1.5	1.5	1.5
	ml/cwt	98	96	98	98	98	98
Extended Set Admixture (ES):	fl.oz./cwt	2.0	2.0	2.0	2.0	2.0	2.0
	ml/cwt	131	131	131	131	130	131
Water-Reducing Admixture (WR):	fl.oz./cwt	11.0	11.0	11.0	11.0	5.5	11.0
	ml/cwt	718	718	118	718	359	718

Three different coarse aggregates from three different quarries in South Carolina were selected and used to prepare six different primary mixtures in this study. Mixtures MX1 and MX4 utilized Martin Marietta crushed stone from Cayce, SC; Mixtures MX2 and MX5B utilized Vulcan Materials Company crushed stone from Blacksburg, SC; and Mixtures MX3 and MX6 utilized Hanson Aggregates crushed stone from Jefferson, SC. The mixtures MXA and MXB represent cement paste (cement, fly-ash, water, and admixtures) and mortar (MXA with addition of sand) having identical ratios of constituents related to Mixtures MX1 thru MX6, except for MX5B. The mixture MX5B was produced with an increased water/cement ratio of 0.50; intending to reduce the compressive strength of the Blacksburg concrete to be more similar to that of the Cayce and Jefferson concrete mixtures. These additional mixtures, MXA and MXB were essential in determining the CTE value of the individual concrete components. In MX-1, MX-2, and MX-3 #57 coarse aggregates were used while MX-4, MX-5B, and MX-6 a combination of 80% of #57 and 20% of #789 coarse aggregates were utilized.

Each mixture was produced in a single batch. Concrete used to determine slump, air content, and unit-weight was discarded. A total of 18 concrete cylinders were produced per batch. Vibration and tamping-rod methods were employed to fill the concrete cylinders. Each specimen had nominal dimension of 4-in. in diameter and 8-in. in length. Each specimen was removed from their cylinder mold after 24-hr then introduced to the submersion water bath for curing, shown in Figure 4.

Figure 4: Temperature controlled and circulating submersion curing bath used to cure all laboratory mixtures.

Additional Aggregate Specimens

In addition to the laboratory specimens, large rocks from the Cayce and Blacksburg aggregate sources were cored to produce specimens, shown in Figure 5, for CTE testing in accordance to AASHTOO T336. A total of three specimens were produced from three different rocks from the two quarries. The results were compared with the calculated CTE values for their respective source.

Figure 5: Example of solid aggregate cores take from Cayce, SC (left) and Blacksburg, SC (right).

Field Cored Specimens (Part B)

With the assistant of SCDOT staff, concrete cores from pavement slabs were collected. The cores were collected from a section of SC 80 between the intersection of SC 101 and SC 29 in Spartanburg county. The locations of the three slabs are shown in Figure 6. Within each slab, a core was taken from the leading end, middle, and trailing end of the slab as shown in Figure 7.

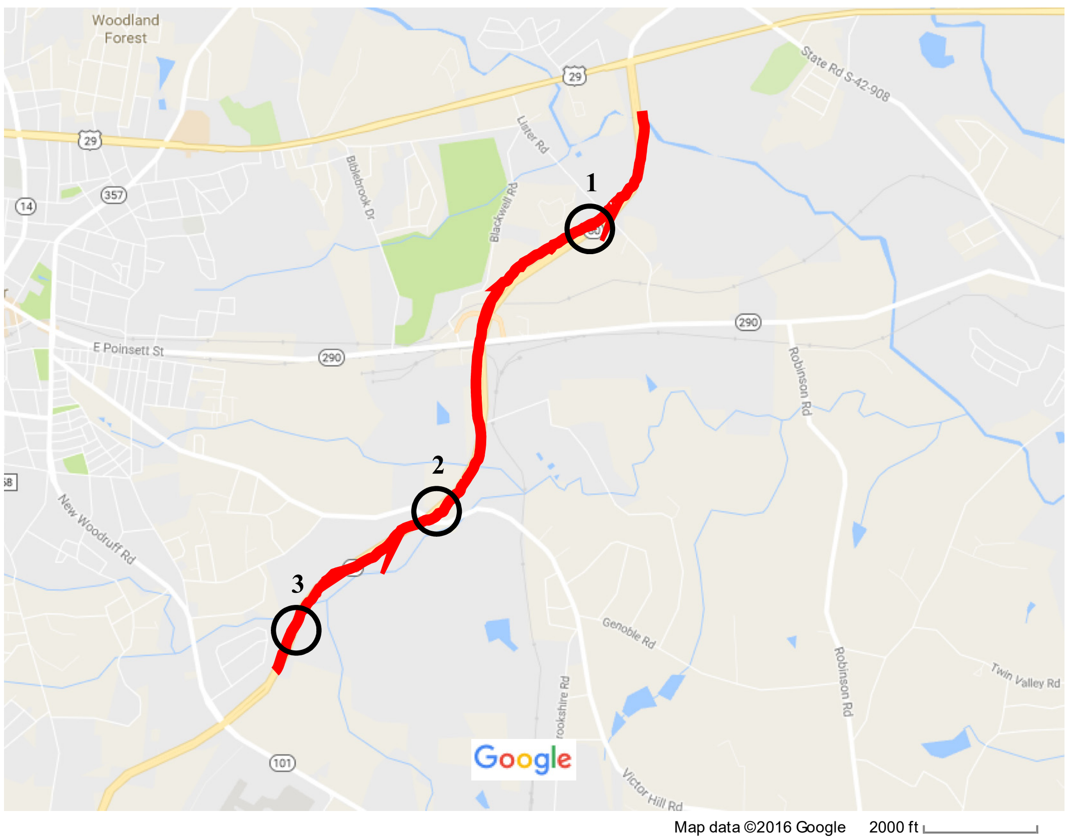

Figure 6: Map of sampling locations along SC 80.

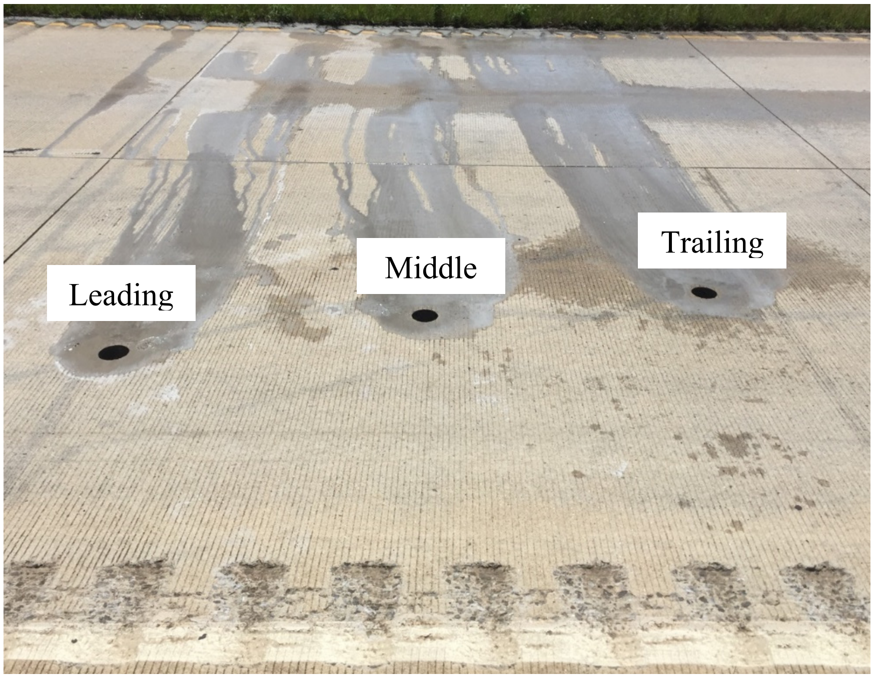

Figure 7: Example of sampling locations within a slab.

Relevant Testing Standards and Methods

Workability / Slump: ASTM C143 Standard test method for slump of hydraulic-cement concrete

A measurement of slump was taken immediately following mixing, prior to determination of percent air content.

Unit Weight (Fresh): ASTM C Standard test method for density (unit weight), yield, and air content (Gravimetric) of concrete

The fresh unit weight of the specimens was measured using this standard

Percent Air Content: ASTM C231 Standard test method for air content of freshly mixed concrete by the pressure method

The determination of air immediately followed the determination of slump and unit weight. Procedure for a type B meter was carried out for each batch of concrete. No correction was made for the aggregate.

Compressive Strength: ASTM C39 Standard test method for compressive strength of cylindrical concrete specimens

Concrete cylinders were submerged cured immediately following its removal from a mold. Specimens remained submerged until the time of testing. Saturated Surface Dry (SSD) weight of the specimens SSD weight was measured prior to testing for quality assurance. Reusable metal caps with rubber pads were used to cap the tops and bottoms of every specimen.

Splitting Tensile Strength: ASTM C496 Standard test method for splitting tensile strength of cylindrical Concrete Specimens

Similar to the cylinders used of compressive testing, concrete cylinders were submerged cured immediately following its removal from a mold. Specimens remained submerged until the time of testing. Specimen SSD weight was taken prior to testing for quality assurance.

Coefficient of Thermal Expansion: AASHTO T336 Standard method of test for coefficient of thermal expansion of hydraulic cement concrete

4×8 in. concrete cylinders were cast and submerged cured immediately following their removal from the molds. The top and bottom of each specimen were cut using wet saw-cut one week prior to testing to make the height of the cylinders equal to 7 in. Specimens immediately resumed submerged curing until the time of testing. Specimen SSD weight was taken prior to testing for quality assurance. Specimen submerged weights were also taken for unit weight determination (in accordance with ASTM C39). The CTE testing equipment manufactured by Pine Instrument, shown in Figure 8, was used in this study, which was capable of testing up to three specimens at once. Figure 9 shows one of the stainless steel CTE frame with titanium calibration standard.

Figure 8: Pine CTE test equipment.

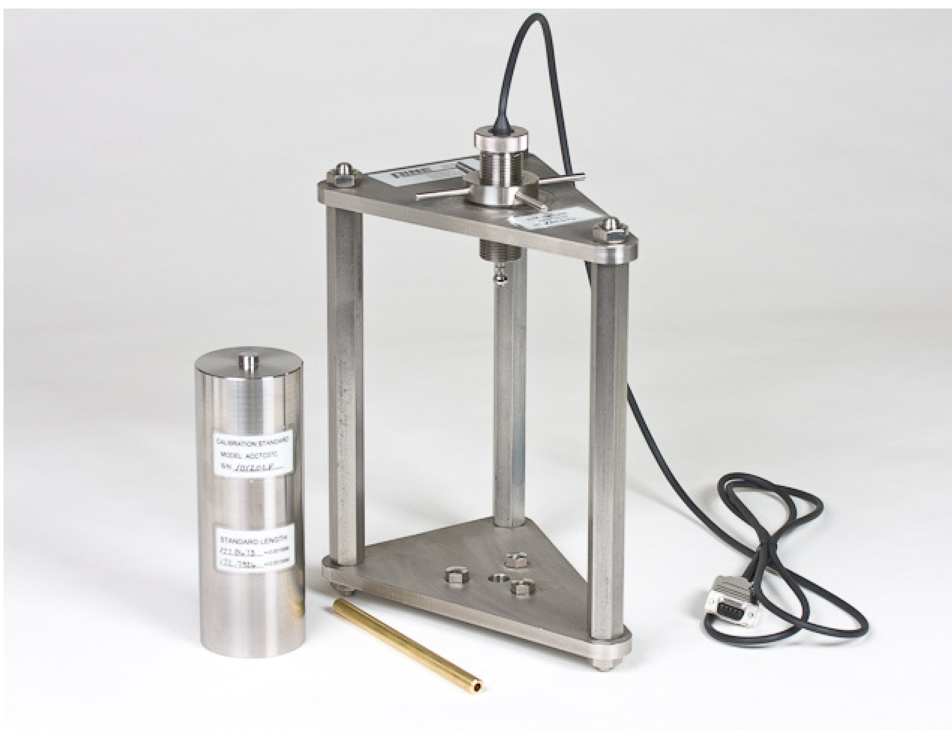

Figure 9: Stainless steel CTE frame with titanium calibration standard.

Coefficient of Thermal Expansion: Application of Tex-428-A method of calculating the coefficient of thermal expansion using linear regression equations

The test specimens were not retested in the Tex-428-A testing method; however, the method of calculating the CTE was applied to the data recorded using the AASHTO – T336 test program. A strain versus temperature curve was generated for each specimen. A linear regression line was generated from the strain data between the temperature range of 15°C and 45°C for each rising and falling temperature. The CTE value was calculated from the following equation:

$$CTE = \frac{m}{L_0} + C_f$$

Where;

m = the slope of the linear regression line

L_0 = the length of the specimen

C_f = the correction factor of the testing frame

The first rising segment of each data set was omitted from the average CTE because the segment did not satisfy the temperature range requirement. The CTE value for the two complete segments was averaged together to get the CTE value for the test specimen. The reported CTE values for a mixture the average CTE of the three specimen sets for each mixture. The 28-day and 90-day CTE values were calculated using the Tex-428-A method.

Statistical analysis of laboratory specimens

The average result of each specimen set was compared to all other data sets using two-tailed t-test with unequal variance to determine if any specimen sets was significantly different from each other. Data sets that rejected the null hypothesis represent significant difference in the two sets of data.

Chapter 4:
Results and Discussions

Properties of Laboratory Mixtures (Part A)

Mixture Proportions

The percentages of concrete constituents have been calculated to account for the specific gravity of the concrete constituents, shown in Table 5 and Table 6. The volumetric percentages of solids in the concrete, shown in Table 6, were used to calculate the CTE value of the individual components in the concrete. The CTE value of the cement paste, β_{paste}, the sand, β_{sand}, and each of the three coarse aggregates, β_{CA}, were calculated using the "Rule of Mixtures" equations. These values are calculated and shown later in this chapter.

Table 5: Percentages of solid concrete constituents in laboratory mixtures by weight (Part A)

Material	*Cement*	*Fly-ash*	*Water*	*Sand*	*CA 57*	*CA 789*
MX1 (Cayce)	10.6%	3.2%	5.5%	29.3%	41.0%	10.3%
MX2 (Blacksburg)	10.2%	3.0%	5.3%	28.1%	42.6%	10.6%
MX3 (Jefferson)	10.6%	3.2%	5.5%	29.3%	41.0%	10.3%
MX4 (Cayce)	10.6%	3.2%	5.5%	29.3%	51.3%	0.0%
MX5B (Blacksburg)	10.4%	3.1%	6.8%	28.8%	50.8%	0.0%
MX6 (Jefferson)	10.6%	3.2%	5.5%	29.3%	51.3%	0.0%
MXA (Paste)	54.6%	16.3%	28.4%	0.0%	0.0%	0.0%
MXB (Mortar)	21.8%	6.5%	11.3%	60.1%	0.0%	0.0%

Mixtures MX1, 2, 3, 4, 5B, and 6 contained < 0.014% of AEA, < 0.021% of ES, and < 0.107% of WR admixtures.
Mixture MXA contained 0.069% of AEA, 0.109% of ES, and 0.551% of WR admixtures.
Mixture MXB contained 0.028% of AEA, 0.220% of ES, and 0.220% of WR admixtures.

Table 6: Percentages of solid concrete constituents in laboratory mixtures by volume, excluding air content (Part A).

Material	*Cement*	*Fly-ash*	*Water*	*Sand*	*CA 57*	*CA 789*
MX1 (Cayce)	8.1%	3.3%	13.4%	27.0%	38.4%	9.6%
MX2 (Blacksburg)	8.1%	3.3%	13.4%	27.0%	38.4%	9.6%
MX3 (Jefferson)	8.1%	3.3%	13.4%	27.0%	38.4%	9.6%
MX4 (Cayce)	3.4%	1.3%	5.5%	11.1%	19.8%	0.0%
MX5B (Blacksburg)	8.2%	3.3%	16.7%	27.0%	44.7%	0.0%
MX6 (Jefferson)	8.1%	3.3%	13.4%	27.0%	47.9%	0.0%
MXA (Paste)	32.5%	13.0%	53.3%	0.0%	0.0%	0.0%
MXB (Mortar)	15.7%	6.3%	25.7%	51.8%	0.0%	0.0%

Mixtures MX1, 2, 3, 4, 5B, and 6 contained < 0.033% of AEA, < 0.044% of ES, and < 0.240% of WR admixtures.
Mixture MXA contained 0.128% of AEA, 0.174% of ES, and 0.956% of WR admixtures.
Mixture MXB contained 0.062% of AEA, 0.085% of ES, and 0.462% of WR admixtures.

Fresh Concrete Properties

Results of slump, air content and unit-weight of the fresh concrete mixtures are shown in Table 7.

Table 7: Properties of fresh concrete mixtures (Part A).

Mixture Identification:		*MX1*	*MX2*	*MX3*	*MX4*	*MX5B*	*MX6*
Slump[a]:	in.	2	1	5	3	9	3
Air Content[b]:	%	7.6	5.6	11.5	7.8	13.5	8.3
Unit Weight[c]:	lbs./ft^3	138	151	134	142	134	140
	kg/m^3	2,226	2,425	2,148	2,272	2,147	2,249

a. ASTIM C143 – 12
b. ASTM C231 – 10, Type B pressure meter.
c. ASTM C231 – 10, calculated from recorded mass of concrete used in Type B pressure meter bowl.

The slump recorded for mixtures MX1 and MX4 was similar at 2 to 3 in. with similar air content reading of 7.6-7.8 %. Mixtures MX3 and MX6 also showed similar slump of 3 to 5 in., with the air content of 8.3 to 11.5 %. The difference in slump can be attributed to the difference in air content. A reduced dosage of WR and the increase in w/cm of 0.40 to 0.50 was attributed to the difference of slump between mixtures MX2 and MX5B. Mixture MX5B also had a considerable increase in its air content. Figure 10 shows the slump measurements of each mixture.

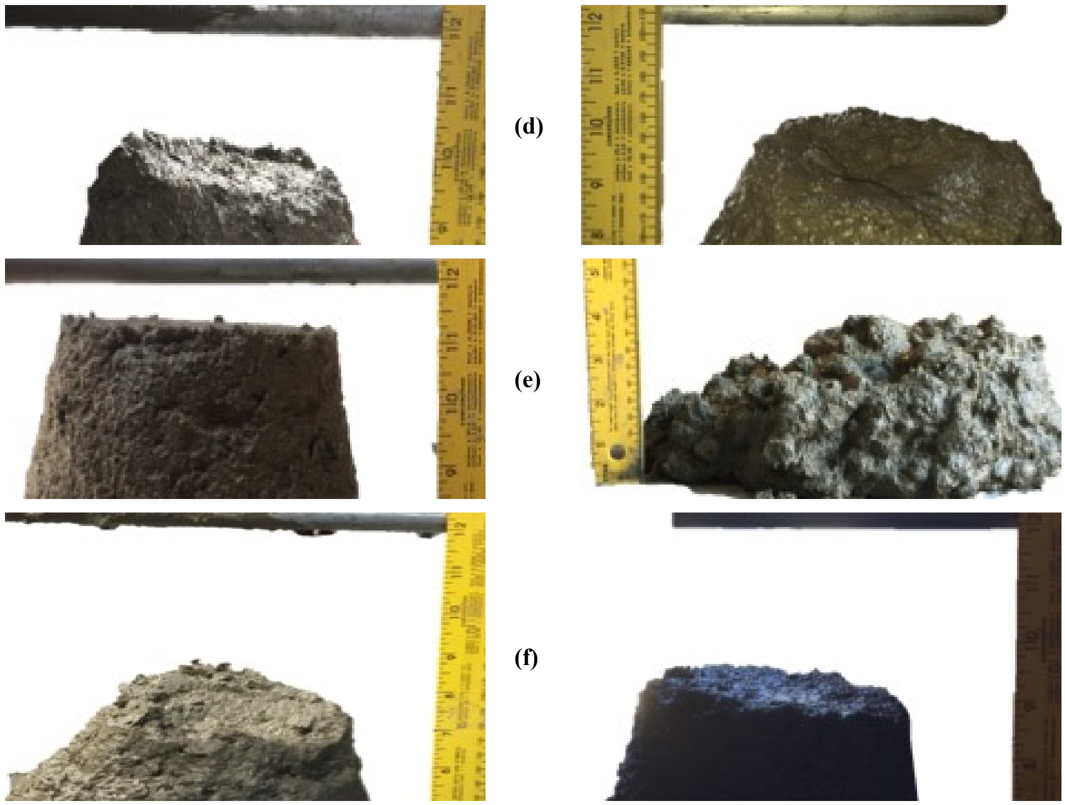

Figure 10: Images of slump measurements of laboratory mixtures; (a) MX1, (b) MX2, (c) MX3, (d) MX4, (e) MX5B, (f) MX6 (Part A).

The maximum theoretical density of the laboratory mixtures were also calculated which are shown in Table 8.

Table 8: Maximum theoretical density of laboratory mixtures (Part A).

Mixture Identification:		MX1	MX2	MX3	MX4	MX5B	MX6	MXA	MXB
Maximum Theoretical Density:	lbs./ft^3	151.1	157.4	151.1	151.1	153.7	151.1	117.0	141.4
	kg/m^3	2,420.7	2,521.4	2,420.7	2,420.7	2,462.8	2,420.7	1,874.3	2,265.6

Compressive strength results

Table 9 and Figure 11 show the results of the measurements of the compressive strengths of the concrete specimens. Variation within specimen sets were less than 10% (C.V. = < 10 %). The average percent increase in compressive strength from 28-days to 90-days was 24 % with a standard deviation of 3.6 %.

Table 9: Summary of 28-day and 90-day compressive strength results (Part A).

Age	*Mixture ID:*		*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*
28-days	Average	psi:	4,269	6,148	3,685	4,644	2,557	4,333
		MPa:	29.4	42.4	25.2	32.0	17.6	29.9
	Standard deviation	psi:	172	215	136	121	151	72
		MPa:	1.2	1.5	0.9	0.8	1.0	0.5
	Coefficient of Variation	%:	4.0	3.5	3.7	2.6	5.9	1.7
90-days	Average	psi:	5,495	7,498	4,394	5,923	3,177	5,230
		MPa:	37.9	51.7	30.3	40.8	21.9	36.1
	Standard deviation	psi:	349	90	209	111	97	35
		MPa:	2.4	0.6	1.4	0.8	0.7	0.2
	Coefficient of Variation	%:	6.4	1.2	4.8	1.9	3.1	0.7
Percent Increase from 28-day to 90-days		%:	28.7	21.9	20.1	27.5	24.2	20.7

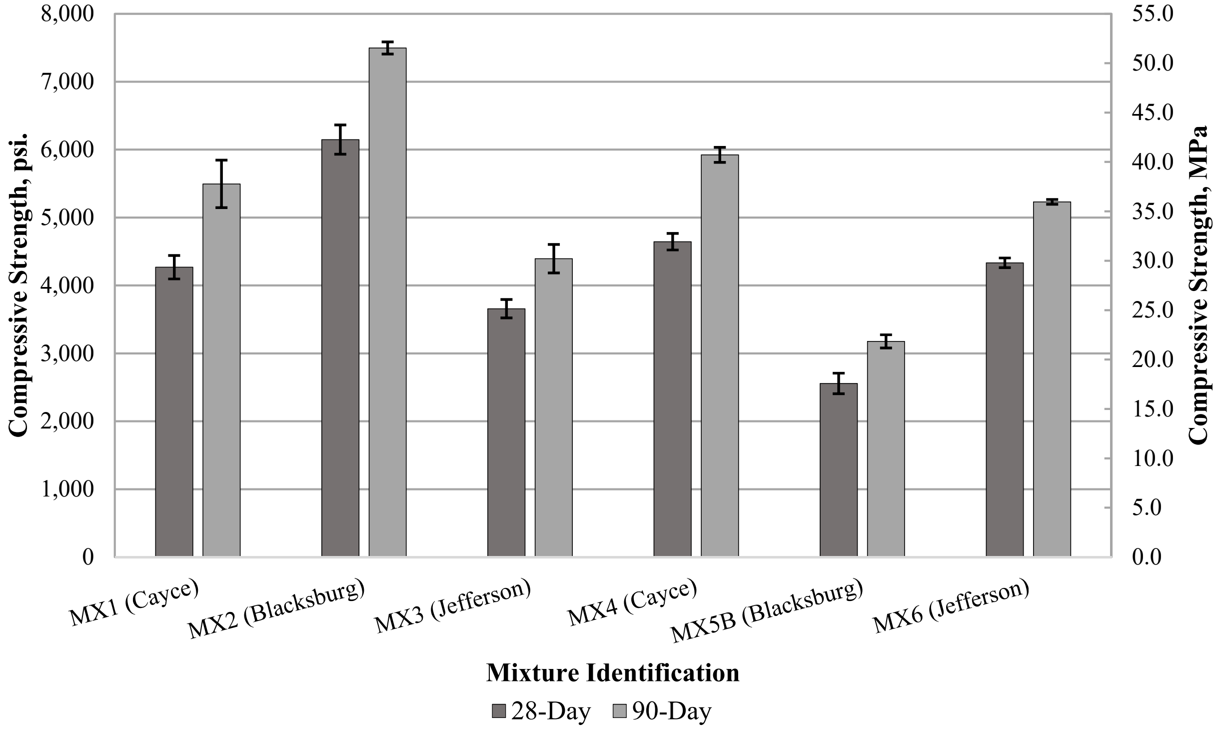

Figure 11: Compressive strength results of early-day (28-day) and later-age (90-day) of the laboratory specimen sets (Part A).

The MEPDG, requires the average 28-day compressive strength for Level 1 analysis; and the average 7, 14, 28, and 90-day compressive strength and a ratio of 20-yrs / 28-day compressive strength for Level 2 analysis. A level 2 analysis should be considered more accurate compared to Level 1 by accounting for the increase of compressive strength that concrete gains over time. In addition, the Level 2 input maybe more appropriate than Level 1, when replacing cement with pozzolans (that increase compressive strength at later ages) such as the Type F fly-ash used in this study, where strength gains will be more noticeable beyond 28-days.

The scope of this study did not include testing the compressive strength of the concrete mixtures at 7 and 14-days nor at 20-yrs. However, the compressive strength values of the specimens in various times beyond 90-days were measured and the results are showing in Table 10.

Table 10: Compressive strength results of the laboratory specimen sets tested at various later ages (Part A).

Mixture ID:		*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*
Age	days:	183	216	212	148	147	117
Average	psi:	5,979	7,939	4,740	6,328	3,375	6,019
	MPa:	41.2	54.7	32.7	43.6	23.3	41.5
Standard deviation	psi:	219	66	80	204	185	323
	MPa:	1.5	0.5	0.5	1.4	1.3	2.2
Coefficient of Variation	%:	3.7%	0.8%	1.7%	3.2%	5.5%	5.4%

A correction factor of 0.98 was applied to the compressive strength results as the ratio of length to diameter was 1.75. Specimens had a nominal height of 7-in. and diameter of 4-in.

Figure 12 shows the results of Table 9 and Table 10. Based on these results, the prediction estimations were determined for compressive strength. as shown in Table 11.

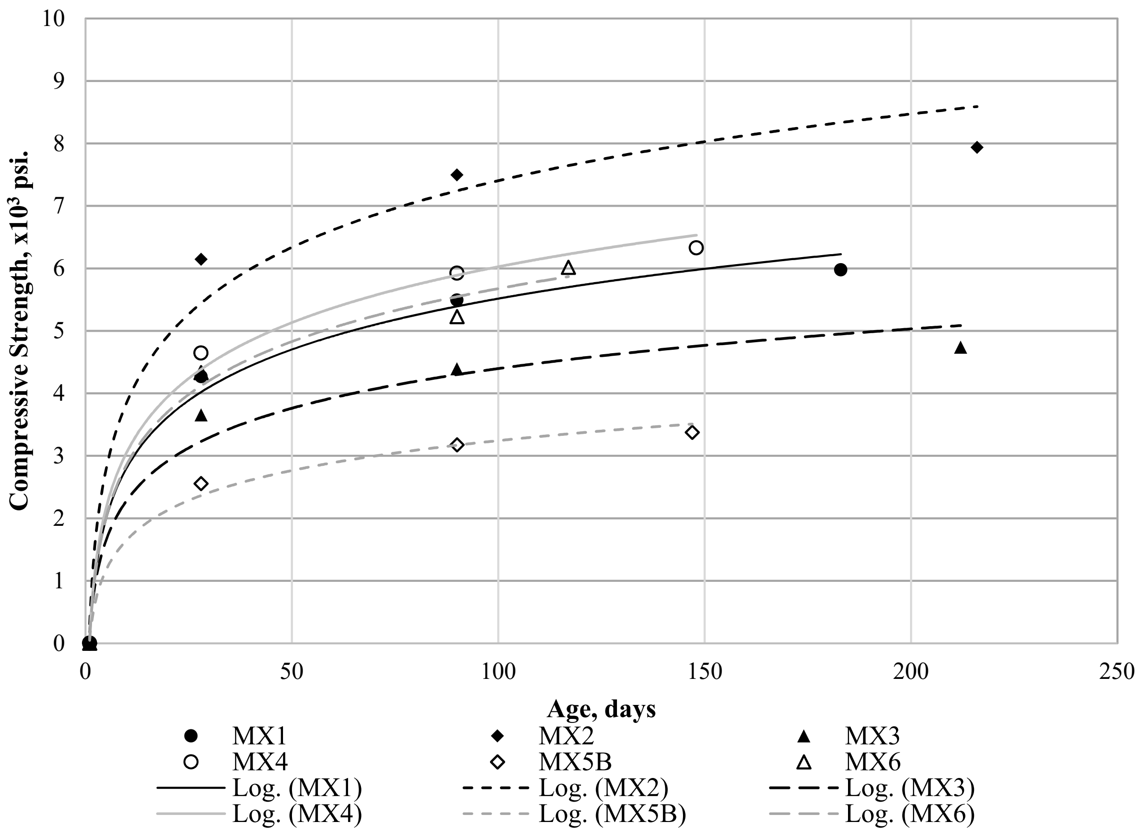

Figure 12: Projections of compressive strength for level-2 MEPDG inputs (Part A).

Table 11: Recommended level-2 MEPDG input values for compressive strength (Part A).

Set ID.	*Curve equation*	*7-day psi.*	*14-day psi.*	*28-day psi.*	*90-day psi.*	*20yr 28-day*
MX-1	$y = 1{,}175.1 \ln x + 104.48$ $R^2 = 0.99350$	2,391.1	3,205.6	4,020.2	5,392.2	2.63*
MX-2	$y = 1{,}540.2 \ln x + 310.52$ $R^2 = 0.97333$	3,307.6	4,375.2	5,442.8	7,241.1	2.57*
MX-3	$y = 916.1 \ln x + 177.56$ $R^2 = 0.97601$	1,960.2	2,595.2	3,230.2	4,299.8	2.58*
MX-4	$y = 1{,}288.8 \ln x + 90.559$ $R^2 = 0.99537$	2,598.4	3,491.8	4,385.1	5,889.9	2.64*
MX-5B	$y = 690.05 \ln x + 65.417$ $R^2 = 0.99189$	1,408.2	1,886.5	2,364.8	3,170.5	2.62*
MX-6	$y = 1{,}222.3 \ln x + 47.324$ $R^2 = 0.99211$	2,425.8	3,273.0	4,120.3	5,547.4	2.65*

* The value exceeds the maximum ratio allowable by the input field in MEPDG; Thus, the ratio of 2.0 should be used.

Splitting tensile strength results

The splitting tensile strength results are summarized in Table 12 and Figure 13. Results showed that there was no significant difference between the 28-day splitting tensile strength in mixtures MX1 or MX2. Mixture MX3 was significantly different than MX5B and MX6. Mixtures MX4 and MX6 were not significantly different, however, both mixtures were significantly different than MX5B. The results of the 90-day old specimens, showed that only mixture MX2 was significantly different than all other mixtures.

Table 12: Summary of 28-day and 90-day splitting tensile strength results (Part A).

Age	*Mixture ID:*		*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*
28-days	Average	psi:	494	495	406	508	377	488
		MPa:	3.4	3.4	2.8	3.5	2.6	3.4
	Standard deviation	psi:	56	48	4	49	7	68
		MPa:	0.39	0.33	0.02	0.34	0.05	0.14
	Coefficient of Variation	%:	11.4	9.8	0.9	9.7	2.0	4.1
90-days	Average	psi:	562	715	489	569	452	467
		MPa:	3.9	4.9	3.4	3.9	3.1	3.2
	Standard deviation	psi:	63	25	28	58	34	68
		MPa:	0.44	0.17	0.19	0.40	0.23	0.47
	Coefficient of Variation	%:	11.2	3.5	5.7	10.2	7.5	14.5
Percent Increase from 28-day to 90-days of age		%:	13.8	44.4	20.1	20.4	19.9	(-4.3)

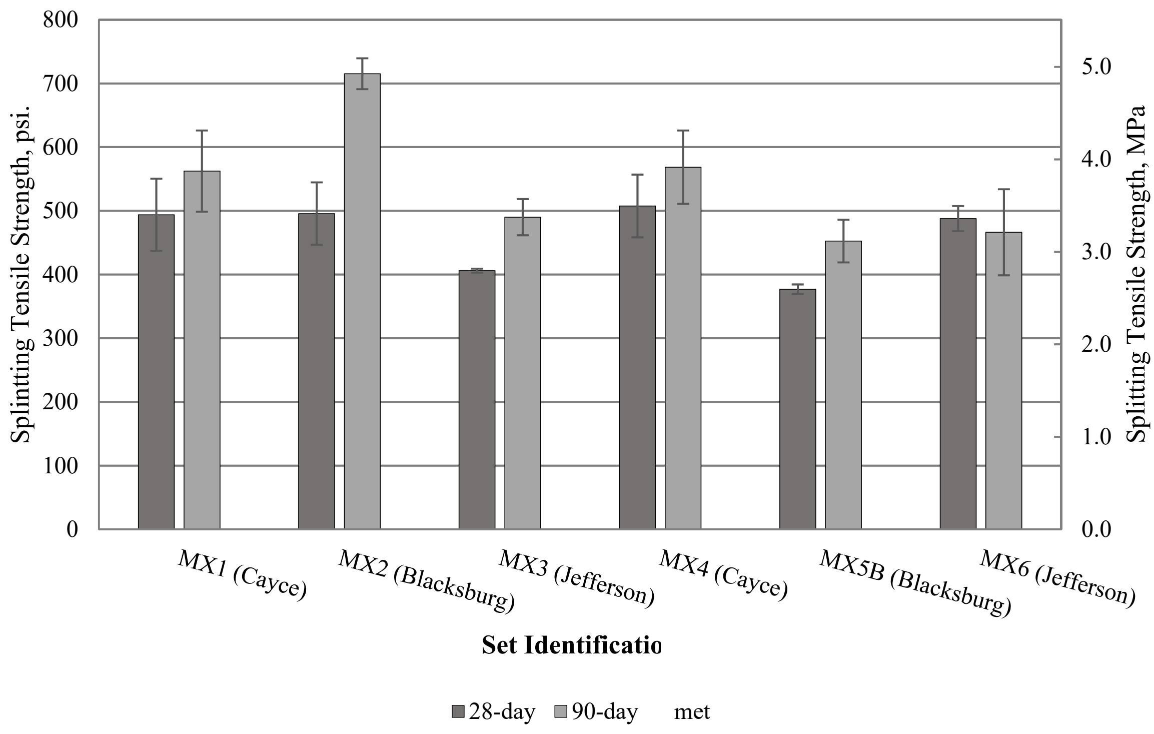

Figure 13: Splitting tensile strength results of early-age (28-day) and later-age (90-day) submerged-cured specimen sets (Part A).

Density and Air Content

The density and air content of the specimens at 28 and 90-days were calculated and the results are given in

Table 13 and Table 14 and Figure 14.

Table 13: Summary density results of 28-day and 90-day CTE specimen sets (Part A).

Age	***Mixture ID:***		***MX-1***	***MX-2***	***MX-3***	***MX-4***	***MX-5B***	***MX-6***	***MXA***	***MXB***
28-days	Average	lbs./ft³	140.3	151.8	136.3	142.3	138.0	140.5	118.0	130.2
		kg/m³	2,246.9	2,431.6	2,183.2	2,279.3	2,210.5	2,255.1	1,889.4	2,085.7
	Standard deviation	lbs./ft³	0.33	0.18	0.67	0.30	1.00	0.28	0.28	0.39
		kg/m³	5.29	2.83	10.8	4.85	16.09	4.41	4.44	6.20
	Coefficient of	%:	0.2	0.1	0.5	0.2	0.7	0.2	0.2	0.3
90-days	Average	lbs./ft³	140.4	151.9	137.6	141.8	138.6	140.5	..	..
		kg/m³	2,249.5	2,433.9	2,204.5	2,270.6	2,219.9	2,250.8	..	..
	Standard deviation	lbs./ft³	0.40	0.21	0.76	0.40	0.77	0.32	..	..
		kg/m³	6.40	3.34	12.2	6.40	12.35	5.18	..	..
	Coefficient of	%	0.3	0.1	0.6	0.3	0.6	0.2	..	..

Table 14: Average air content of hardened CTE specimens (Part A).

Mixture ID:			***MX-1***	***MX-2***	***MX-3***	***MX-4***	***MX-5B***	***MX-6***
28-day	Average	%:	7.2	3.6	9.8	5.8	10.2	7.0
90-day	Average	%:	7.1	3.5	8.9	6.2	9.9	7.0
Difference in Average Percent Air Content		%:	(-0.1)	(-0.1)	(-0.9)	0.4	(-0.4)	(-0.0)
Percent Increase of Average Percent Air Content		%:	(-1.5)	(-2.5)	(-9.0)	6.1	(-3.7)	(-0.4)

Air content determined using the maximum theoretical density and actual density of hardened concrete specimens.

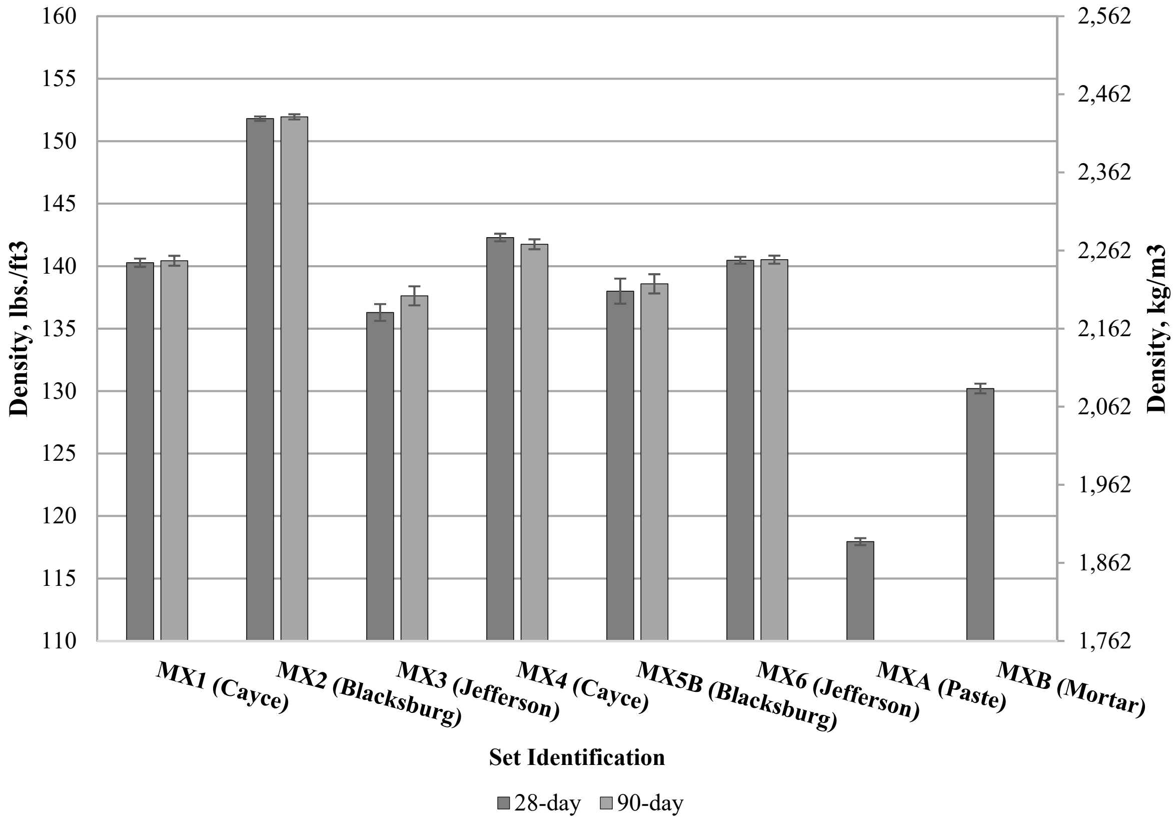

Figure 14: Comparison of early-age (28-day) and later-age (90-day) measured density values of laboratory produced specimen sets (Part A).

Coefficient of Thermal Expansion Results

The coefficient of thermal expansion results are summarized in Table 15 and Figure 15. All specimens were submerged until the time of the test. The average CTE results of 28-day and 90-day data sets are shown in Table 16. The mixtures containing Cayce and Blacksburg aggregates both showed a small percent increase in CTE between 28-days and 90-days of age. The mixtures containing Jefferson aggregate showed a small percent decrease in CTE between 28 and 90-days of age.

Table 15: Summary of average 28-day and 90-day CTE results (Part A).

Age	*Mixture ID:*		*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*	*MXA*	*MXB*
28-days	Average	με/°F:	4.823	5.252	5.055	4.845	5.269	5.322	7.303	6.574
		με/°C:	8.682	9.453	9.098	8.721	9.484	9.580	13.146	11.832
	Standard deviation	με/°F:	0.094	0.016	0.080	0.050	0.038	0.178	0.067	0.024
		με/°C:	0.168	0.030	0.144	0.091	0.069	0.320	0.121	0.044
	Coefficient of Variation	%:	1.9	0.3	1.6	1.0	0.7	3.3	0.9	0.4
90-days	Average	με/°F:	4.907	5.512	5.020	5.103	5.432	5.193	..	..
		με/°C:	8.832	9.921	9.036	9.185	9.778	9.347	..	..
	Standard deviation	με/°F:	0.011	0.037	0.082	0.025	0.090	0.104	..	..
		με/°C:	0.020	0.067	0.148	0.045	0.163	0.187	..	..
	Coefficient of Variation	%:	0.2	0.7	1.6	0.5	1.7	2.0	..	..
Percent Increase from 28-day strength		%:	1.73	4.95	-0.68	5.32	3.11	-2.44	..	..

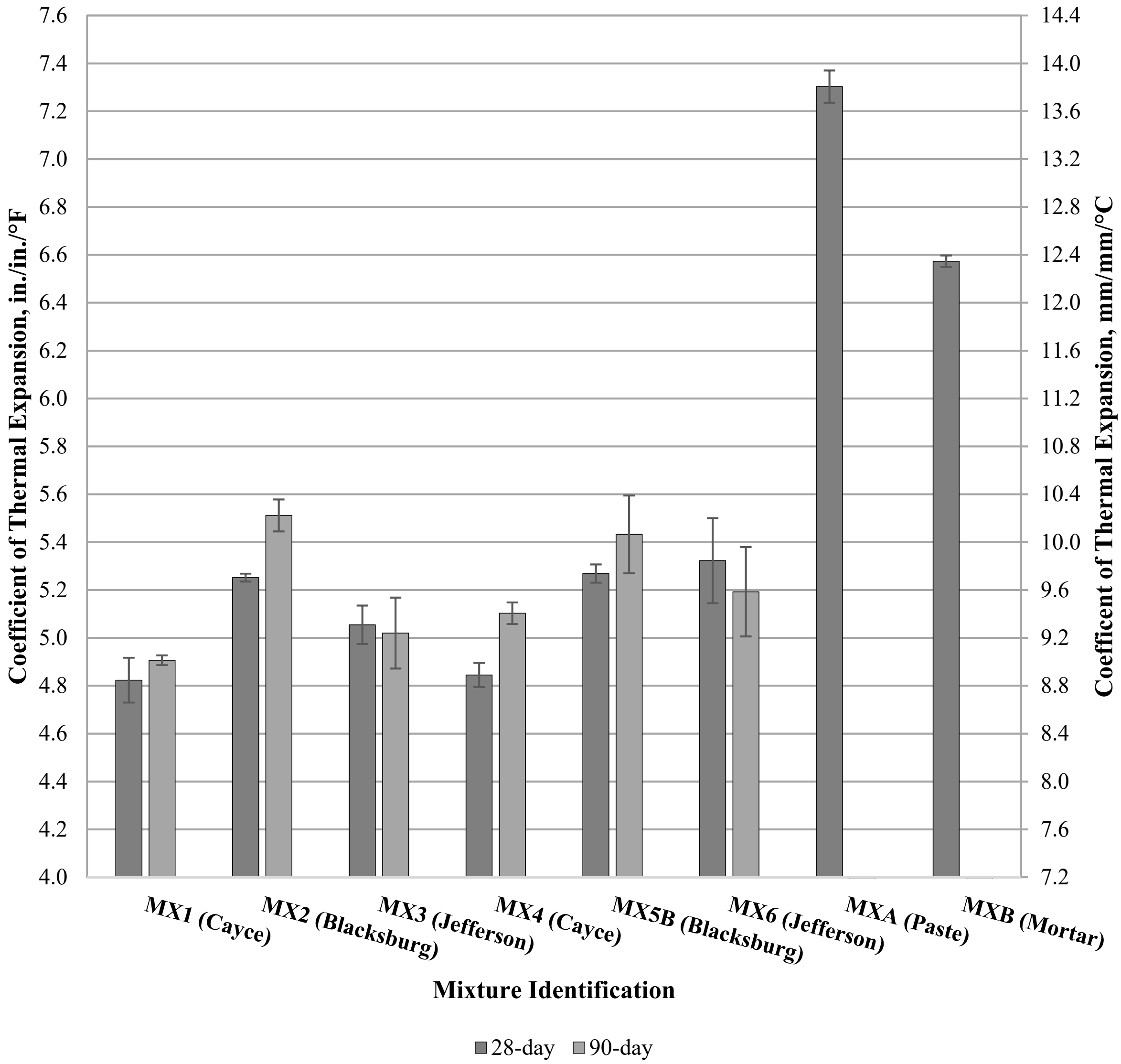

Figure 15: Comparison of early-age (28-day) and later-age (90-day) measured CTE values of laboratory produced specimen sets (Part A).

Table 16: Summary of average CTE results of combined 28 and 90-day results (Part A).

Mixture ID:		*MX-1*	*MX-2*	*MX-3*	*MX-4*	*MX-5B*	*MX-6*
Average	με/°F:	4.865	5.382	5.037	4.974	5.350	5.258
	με/°C:	8.757	9.687	9.067	8.953	9.631	9.464
Standard deviation	με/°F:	0.075	0.145	0.075	0.146	0.109	0.148
	με/°C:	0.135	0.260	0.135	0.262	0.196	0.267
Coefficient of Variation	%:	1.5	2.7	1.5	2.9	2.0	2.8

The "Rule-of-Mixtures" was used to determine the CTE value of the cement paste, sand, and coarse aggregates used in this study as following:

$$\propto_p = \beta_p \propto_s$$

$$\propto_{p(MX-A)} = 1\times 7.303\times10^{-6} = 7.303\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{mortar} = \beta_p \propto_s + \beta_{FA} \propto_{FA}$$

$$\propto_{FA(MX-B)} = \frac{\propto_{mortar(MX-B)} - \beta_p \propto_s}{\beta_{FA}} = \frac{6.574\times10^{-6} - (0.4787\times7.303\times10^{-6})}{0.5213}$$

$$= 5.903\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{concrete} = \beta_p \propto_s + \beta_{FA} \propto_{FA} + \beta_{CA} \propto_{CA}$$

$$\propto_{CA(MX-1)} = \frac{\propto_{concrete(MX-1)} - \beta_p \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{4.823\times10^{-6} - (0.2486\times7.303\times10^{-6}) - (0.2704\times5.903\times10^{-6})}{0.4810}$$

$$= 2.934\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{CA(MX-2)} = \frac{\propto_{concrete(MX-2)} - \beta_p \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{5.252\times10^{-6} - (0.2393\times7.303\times10^{-6}) - (0.2602\times5.903\times10^{-6})}{0.5005}$$

$$= 3.932\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{CA(MX-3)} = \frac{\propto_{concrete(MX-3)} - \beta_{\mathrm{p}} \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{5.055\times10^{-6} - (0.2486\times7.303\times10^{-6}) - (0.2704\times5.903\times10^{-6})}{0.4810}$$

$$= 3.415\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{CA(MX-4)} = \frac{\propto_{concrete(MX-4)} - \beta_p \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{4.845\times10^{-6} - (0.2486\times7.303\times10^{-6}) - (0.2704\times5.903\times10^{-6})}{0.4810}$$

$$= 2.980\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{CA(MX-5B)} = \frac{\propto_{concrete(MX-5B)} - \beta_p \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{5.269\times10^{-6} - (0.2723\times7.303\times10^{-6}) - (0.2609\times5.903\times10^{-6})}{0.4668}$$

$$= 3.728\times10^{-6}\ in/in/°\mathrm{F}$$

$$\propto_{CA(MX-6)} = \frac{\propto_{concrete(MX-6)} - \beta_p \propto_s - \beta_{FA} \propto_{FA}}{\beta_{CA}}$$

$$= \frac{5.322\times10^{-6} - (0.2486\times7.303\times10^{-6}) - (0.2704\times5.903\times10^{-6})}{0.4810}$$

$$= 3.972\times10^{-6}\ in/in/°\mathrm{F}$$

The results of the "Rule-of-Mixtures" calculations are summarized in Table 17. The CTE value of the cement paste is considerably greater than that of the aggregate, with a value of 7.303 με/°F. The CTE value of the fine aggregate, natural sand from Sumter, SC, was greater than any crushed stone aggregate, with a value of 5.903 με/°F. The CTE value of the crushed stone coarse aggregates, in order of increasing magnitude was Cayce, Jefferson, and Blacksburg with average CTE values of 2.957, 3.694, and 3.830 με/°F, respectively.

Table 17: Summary of CTE values of concrete components using the "Rule-of-Mixtures" (Part A).

Material Description	*CTE Value, $\mu\varepsilon$/°F*
Cement Paste (with fly-ash, w/c=0.4, and admixtures)	7.303
Natural Sand (Sumter, SC)	5.903
Blended (75:25) No. 57 &789 (Cayce, SC)	2.934
Blended (75:25) No. 57 &789 (Blacksburg, SC)	3.932
Blended (75:25) No. 57 &789 (Jefferson, SC)	3.415
No. 57 Coarse Aggregate (Cayce, SC)	2.980
No. 57 Coarse Aggregate (Blacksburg, SC)	3.728
No. 57 Coarse Aggregate (Jefferson, SC)	3.972
Average Cayce crushed stone	2.957
Average Blacksburg crushed stone	3.830
Average Jefferson crushed stone	3.694

The 28-day CTE results, showed that concrete containing Cayce crushed stone was significantly different then concrete containing either Blacksburg or Jefferson crushed stone. As was expected, concrete containing the same aggregate with approximately identical volumetric proportions would not be significantly different, even if aggregate gradation differs between concrete mixtures. It was observed that mixtures MX1 and MX4, MX2 and MX5B, and MX3 and MX6 were not significantly different, respectively. Additionally, mixtures MX2, MX3, MX5B, and MX6 were considerably different. It can be concluded that the Blacksburg and Jefferson aggregates did not produce concrete with significantly different CTE values. The 90-day CTE results were not completely similar to the 28-day CTE analysis. The mixtures containing Blacksburg and Jefferson aggregates were not significantly different, as was observed when analyzing the 28-day CTE data. However, mixtures containing Cayce were significantly different. At 90-days, concrete containing Cayce and Jefferson aggregates were not significantly different, provided their gradation was similar.

Comparing calculated CTE with tested CTE of solid aggregate cores

The CTE values the cored aggregate specimens are shown in Table 18The average was taken from sets of three specimens from both Cayce and Blacksburg aggregate quarries.

Table 18: Summary of CTE results of Cayce and Blacksburg solid aggregate cored specimens with average calculated CTE of aggregate in concrete specimens.

Mixture ID:		***Cayce***	***Blacksburg***
Average	με/°F:	3.586	3.896
	με/°C:	6.455	7.013
Standard deviation	με/°F:	0.351	1.088
	με/°C:	0.632	1.958
Coefficient of Variation	%:	9.8	27.9
Average Calculated CTE from Concrete Specimens	με/°F:	2.957	3.830
	με/°C:	5.323	6.894

While the Cayce specimens were more consistent, the CTE of the aggregates from Blacksburg were more closely matched the calculated CTE of the aggregates. The variation in the Blacksburg data was attributed to the uniformity of the aggregates. The Cayce specimens appeared to be more homogenous than the Blacksburg cores, as seen in Figure 16. The grain direction was noticeable within the Blacksburg cores; safe to assume that Blacksburg did not expand and contract uniformly in every direction. In both instances, the calculated CTE values were lower than the measured CTE of the aggregate.

(a)

(b)

Figure 16: Examination of grain direction uniformity within solid aggregate cores, (a) Cayce cores and (b) Blacksburg cores shown in bottom row.

Properties of Field Cored Concrete (Part B)

The CTE, density, and compressive strength of the cored concrete specimens taken from SC – 80 are summarized in Table 19 and also shown in Figure 17, Figure 18 and Figure 19. The magnitude of compressive strength did not correlate with the magnitude of CTE of a particular concrete. The average CTE values per slab are shown in Figure 20. The comparison between the results showed no significant difference in average CTE between each slab.

Table 19: Summary of results of field cored specimens taken from SC-80 (Part B).

Slab ID.:	*Core Location*	*Coefficient of Thermal Expansion*		*Density (Unit Weight)*		*Compressive Strength*	
		in./in./°F	*mm/mm/°C*	*lbs./ft^3*	*kg/m^3*	*psi.*	*MPa*
Slab 1	Leading	4.699×10^{-6}	8.458×10^{-6}	151.77	2,431	4,689	32.3
	Middle	4.930×10^{-6}	8.874×10^{-6}	150.56	2,412	6,351	43.8
	Trailing	4.985×10^{-6}	8.973×10^{-6}	153.95	2,466	7,268	50.1
	Average	4.871×10^{-6}	8.768×10^{-6}	152.10	2,436	6,103	42.1
	Std. Dev.	0.152×10^{-6}	0.273×10^{-6}	1.72	27	1,307	9.0
	C.V.	3.1 %		1.1 %		21.4 %	
Slab 2	Leading	5.191×10^{-6}	9.345×10^{-6}	148.12	2,373	6,883	47.5
	Middle	5.176×10^{-6}	9.317×10^{-6}	148.29	2,375	4,976	34.3
	Trailing	5.211×10^{-6}	9.381×10^{-6}	149.54	2,395	5,213	35.9
	Average	5.193×10^{-6}	9.347×10^{-6}	148.65	2,381	5,691	39.2
	Std. Dev.	0.018×10^{-6}	0.032×10^{-6}	0.77	12	1,039	7.2
	C.V.	0.3 %		0.5 %		18.3 %	
Slab 3	Leading	5.062×10^{-6}	9.112×10^{-6}	147.91	2,369	5,334	36.8
	Middle	5.045×10^{-6}	9.081×10^{-6}	148.68	2,382	5,177	35.7
	Trailing	5.144×10^{-6}	9.259×10^{-6}	149.34	2,392	5,428	37.4
	Average	5.084×10^{-6}	9.151×10^{-6}	148.64	2,381	5,313	36.6
	Std. Dev.	$0.0.053 \times 10^{-6}$	0.095×10^{-6}	0.71	11	126	0.9
	C.V.	1.0 %		0.5 %		2.4 %	

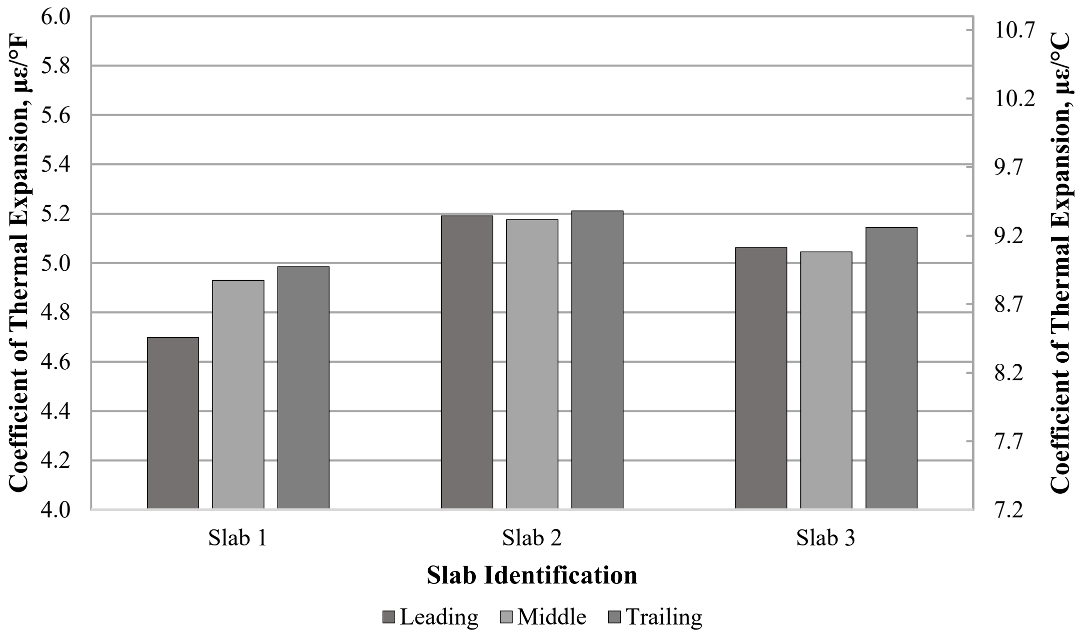

Figure 17: CTE results of each cored specimen taken along SC-80 (Part B).

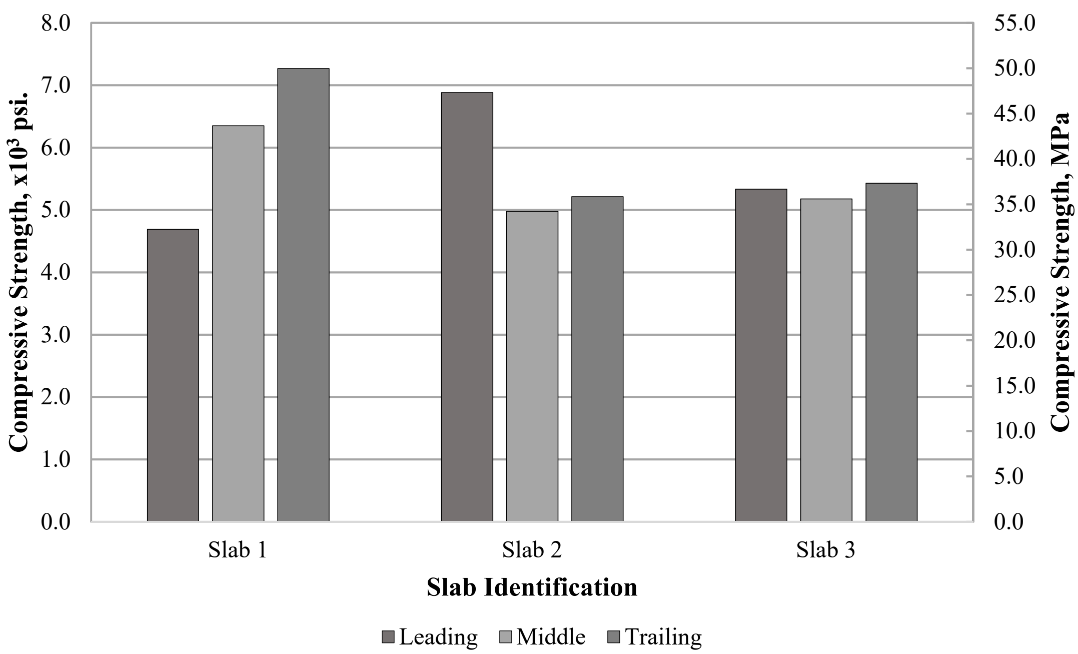

Figure 18: Compressive strength results of cored specimens taken along SC-80 (Part B).

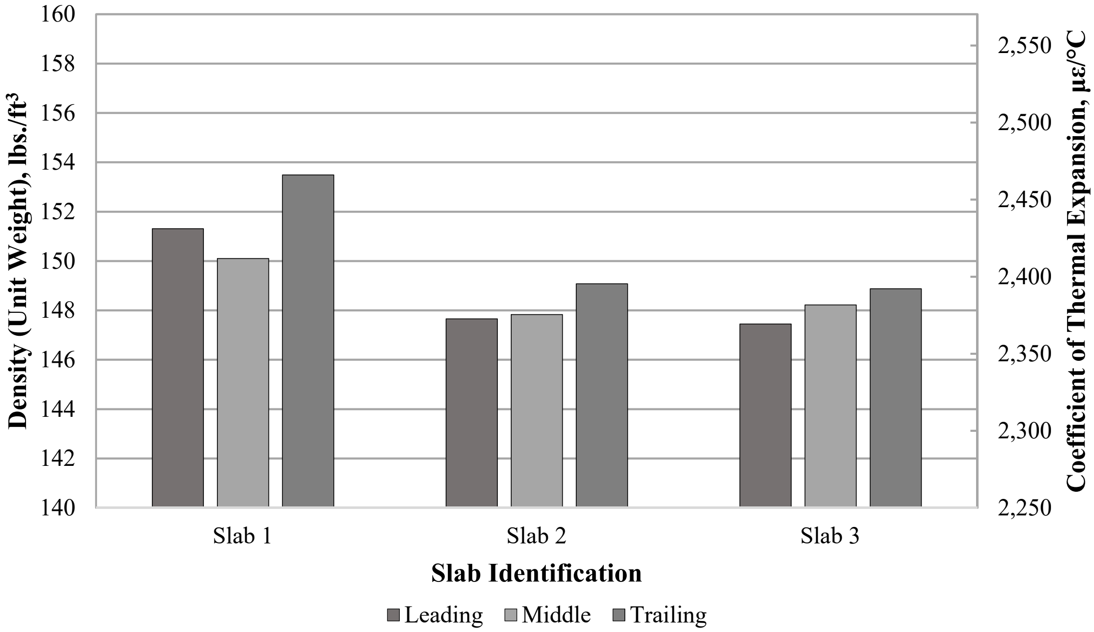

Figure 19: Density (unit weight) results of cored specimens taken along SC-80 (Part B).

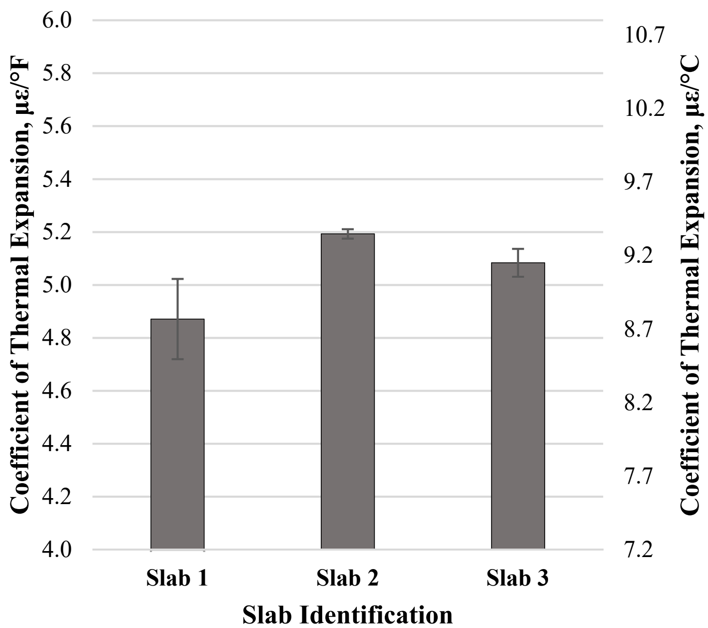

Figure 20: Average CTE results of each slab taken along SC-80 (Part B).

Results of MEPDG analysis

The results of Part A of this report was used in the MEPDG software to generate distress predictions. The initial distress predictions were conducted to establish a baseline in which to compare parameters unique to South Carolina against the default parameters in the MEPDG software. The baseline pavement was 11 inches thick with a joint spacing of 15 feet and dowel bars with a diameter of 1.5 inches. The baseline input variables for CTE, unit weight, and compressive strength were adjusted until the output predictions were below a threshold for faulting and cracking, selected by the SCDOT design engineer. The results of Part A of this study were used as level 1 input parameters. All other parameters remained identical to the base line inputs. It was observed that increasing the CTE value would cause the percent cracking to increase; however, when compressive strength increased, percent cracking was less affected by the increase of CTE. It should be noted that these MEPDG results utilized a 20-yr/28-day ratio of 1.29.

Coefficient of Thermal Expansion Results Using Tex-428-A Method

The results shown in Table 20 were calculated using the Tex-428-A methods on the results obtained during the AASHTO-T336 testing of laboratory specimens. The Tex-428-A method produced results that were less than those calculated by the AASHTO-T336 method.

Table 20: Summary of average 28-day and 90-day CTE results per Tex-428-A method (Part A).

Age	***Mixture ID:***		***MX-1***	***MX-2***	***MX-3***	***MX-4***	***MX-5B***	***MX-6***	***MXA***	***MXB***
28-days	Average	με/°F:	4.796	5.220	4.917	4.802	5.177	5.403	6.501	6.444
		με/°C:	8.633	9.396	8.850	8.644	9.319	9.726	11.701	11.599
	Standard deviation	με/°F:	0.055	0.037	0.038	0.085	0.049	0.318	0.039	0.123
		με/°C:	0.100	0.066	0.068	0.153	0.088	0.573	0.069	0.221
	Coefficient of Variation	%:	1.2	0.7	0.8	1.8	0.9	5.9	0.6	1.9
90-days	Average	με/°F:	4.843	5.480	4.901	5.206	5.508	5.339	..	..
		με/°C:	8.718	9.863	8.822	9.371	9.915	9.611	..	..
	Standard deviation	με/°F:	0.070	0.057	0.048	0.123	0.139	0.055	..	..
		με/°C:	0.127	0.103	0.086	0.221	0.250	0.099	..	..
	Coefficient of Variation	%:	1.5	1.0	1.0	2.4	2.5	1.0	..	..
Percent Increase from 28-day strength		%:	0.98	4.97	-0.32	8.42	6.40	-1.18	..	..

Statistical Analysis of Results (Part A)

Statistical analysis of compression strength results was conducted and shown in Table 21 and Table 22. The analysis could identify the mixtures that were distinctly different from each other with respect to their compressive strength. Only MX-1 and MX-6 appeared not to be significantly different at 28-days. By 90-days, MX-1 was not significantly different from mixtures 4 and 6.

Table 21: Statistical analysis of 28-day compressive strength results (Part A).

Set ID.	MX-1	MX-2	MX-3	MX-4	MX-5B	MX-6
MX-1	1.0000	0.0003 Reject	0.0085 Reject	0.0368 Reject	0.0002 Reject	0.5934
MX-2		1.0000	0.0004 Reject	0.0018 Reject	<0.0000 Reject	0.0052 Reject
MX-3			1.0000	0.0007 Reject	0.0007 Reject	0.0047 Reject
MX-4				1.0000	0.0001 Reject	0.0315 Reject
MX-5B					1.0000	0.0003 Reject
MX-6						1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Table 22: Statistical analysis of 90-day compressive strength results (Part A).

Set ID.	MX-1	MX-2	MX-3	MX-4	MX-5B	MX-6
MX-1	1.0000	0.0106 Reject	0.0184 Reject	0.1806	0.0081 Reject	0.3213
MX-2		1.0000	0.0002 Reject	<0.0000 Reject	<0.0000 Reject	<0.0000 Reject
MX-3			1.0000	0.0015 Reject	0.0028 Reject	0.0208 Reject
MX-4				1.0000	<0.0000 Reject	0.0093 Reject
MX-5B					1.0000	0.0001 Reject
MX-6						1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Statistical Analysis of Splitting Tensile Strength (Part A)

Statistical analysis of splitting tensile strength results was conducted and shown in Table 23 and Table 24. The analysis showed the mixtures that were distinctly different from each other with respect to their splitting tensile strength. Mixtures with blended coarse aggregate were not significantly different at 28-days; however, by 90-days only mixture MX-2 was significantly different from all other mixtures.

Table 23: Statistical analysis of 28-day splitting tensile strength results (Part A).

Set ID.	**MX-1**	**MX-2**	**MX-3**	**MX-4**	**MX-5B**	**MX-6**
MX-1	1.0000	0.9689	0.1160	0.7658	0.0715	0.8785
MX-2		1.0000	0.0875	0.7793	0.0537	0.8148
MX-3			1.0000	0.0706	0.0086 Reject	0.0194 Reject
MX-4				1.0000	0.0452 Reject	0.5637
MX-5B					1.0000	0.0028 Reject
MX-6						1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Table 24: Statistical analysis of 90-day splitting tensile strength results (Part A).

Set ID.	MX-1	MX-2	MX-3	MX-4	MX-5B	MX-6
MX-1	1.0000	0.0302 Reject	0.1700	0.9082	0.0775	0.1475
MX-2		1.0000	0.0005 Reject	0.0268 Reject	0.0004 Reject	0.0092 Reject
MX-3			1.0000	0.1246	0.2145	0.6147
MX-4				1.0000	0.0572	0.1170
MX-5B					1.0000	0.7730
MX-6						1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Statistical Analysis of Coefficient of Thermal Expansion (Part A)

Statistical analysis of compression strength results was conducted and shown in Table 25 through Table 27. The mixtures 1, 2,3, 4, 5B and 6 were not significantly different. This suggested that blended coarse aggregate had no significant impact on the CTE of the concrete at 28-days and 90-days. Mixtures 1, 3, 5B, and 6 did not show a significant difference of CTE from 28-days to 90-days. It was also concluded that the compressive strength did not affect the CTE value because there was no significant difference in the CTE between mixtures 2 and 5B even though the compressive strength was drastically different between these two mixtures containing Blacksburg aggregate.

Table 25: Statistical analysis of 28-day CTE results using AASHTO – T336 test method (Part A).

Set ID.	MX1	MX2	MX3	MX4	MX5B	MX6	MXA	MXB
MX1	1.0000	0.0160 Reject	0.0313 Reject	0.7451	0.0047 Reject	0.0231 Reject	<0.000 Reject	0.0010 Reject
MX2		1.0000	0.0531	0.0056 Reject	0.5268	0.5627	0.0004 Reject	<0.0000 Reject
MX3			1.0000	0.0313 Reject	0.0250 Reject	0.0977	<0.0000 Reject	0.0010 Reject
MX4				1.0000	0.0003 Reject	0.0465 Reject	<0.0000 Reject	<0.0000 Reject
MX5B					1.0000	0.6595	<0.0000 Reject	<0.0000 Reject
MX6						1.0000	0.0004 Reject	0.0068 Reject
MXA							1.0000	0.0004 Reject
MXB								1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Table 26: Statistical analysis of 90-day CTE results using AASHTO – T336 test method (Part A).

Set ID.	MX1	MX2	MX3	MX4	MX5B	MX6
MX1	1.0000	0.0014 Reject	0.1418	0.0011 Reject	0.0098 Reject	0.0416 Reject
MX2		1.0000	0.0025 Reject	<0.0001 Reject	0.2546	0.0153 Reject
MX3			1.0000	0.2362	0.0043 Reject	0.0866
MX4				1.0000	0.0259 Reject	0.2824
MX5B					1.0000	0.0393 Reject
MX6						1.0000

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria besτed on 95% confidence interval.

Table 27: Statistical analysis of 28-day versus 90-day CTE results (Part A).

Set ID.		28-day of Age					
		MX1	MX2	MX3	MX4	MX5B	MX6
90-days of age	MX1	0.2649	0.0013 Reject	0.0521	0.0376 Reject	0.0013 Reject	0.0102 Reject
	MX2		0.0016 Reject	0.0410 Reject	0.0033 Reject	0.0763	0.4343
	MX3			0.6295	0.4232	0.0056 Reject	0.1420
	MX4				0.0041 Reject	0.0022 Reject	0.0136 Reject
	MX5B					0.0630	0.3195
	MX6						0.3548

The reported p-values are derived from a two-tailed t-test having unequal variance. Rejection criteria bested on 95% confidence interval.

Chapter 5:
Conclusions

Conclusions of Part A

- Concrete made from Blacksburg aggregate showed significantly higher compressive strengths and splitting tensile strengths compared to the concrete made with Cayce and Jefferson coarse aggregates.
- Cayce aggregates produced significantly stronger concrete versus Jefferson aggregates.
- CTE properties did not appear to be effected by the initial w/cm ratio.
- The average CTE value of Blacksburg solid aggregate cores was close to the values extrapolated from the laboratory concrete specimens, while the CTE of Cayce cores was higher than that extrapolated from the laboratory concrete specimens. This observation was attributed to the more homogenous structure of the Blacksburg cores compared to the Cayce cores.
- The Tex-428-A method for calculating the CTE of concrete resulted a lower CTE value than the AASHTO – T336.

  Statistical analysis showed that the compressive strength of concrete and the fineness of the coarse aggregate did not affect the CTE of concrete.

Conclusions of Part B

- There was no significant difference in CTE values of cored sample from the concrete pavement slabs.
- No relationship was observed between the compressive strength and CTE values of the cored samples.

References

AASHTO, T 336: Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete. 2011: Washington, D.C.

AASHTO, TP60-00: Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete, TP60-00, 2000. 2000.

Alungbe G. D., Tia M., and Bloomquist D. G., Effects of aggregate, water/cement ratio, and curing on the coefficient of linear thermal expansion of concrete. Transportation Research Record (TRR), 1992. 1335: p. 44-51.

Applied Research Association Inc. - ERES Consultants Division, Guide for mechanistic-empirical design of new and rehabilitated pavement structures. 2004, National Cooperative Highway Research Program (NCHRP) Champaign, Il.

Buch N., Jahangirnejad S., and Kravchenko S. Laboratory investigation of effects of aggregate geology and sample age on coefficient of thermal expansion of portland cement concrete. in Transportation Research Board 87th Annual Meeting 2008. Washington DC.

Callan, E.J., 1952. Thermal Expansion of Aggregates and Concrete Durability, in: Journal Proceedings. pp. 485–504.

Chen D. and Won M., Field investigations of cracking on concrete pavements. ASCE Journal of Performance of Constructed Facilities, 2007. 21(6): p. 450-458.

Crawford, G., Gudimettla, J., Tanesi, J., 2010. Interlaboratory study on measuring coefficient of thermal expansion of concrete. Transp. Res. Rec. J. Transp. Res. Board 58–65.

Emanuel, J.H., Hulsey, J.L., 1977. Prediction of the thermal coefficient of expansion of concrete, in: Journal Proceedings. pp. 149–155.

Guclu, A., Ceylan, H., Gopalakrishnan, K., Kim, S., 2009. Sensitivity analysis of rigid pavement systems using the mechanistic-empirical design guide software. J. Transp. Eng. 135, 555–562.

Hein, D.K., Sullivan, S., 2012. Concrete coefficient of thermal expansion (CTE) and its significance in mechanistic-empirical pavement design, in: Annual Conference of the Transportation Association of Canada: Advances in Pavement Evaluation and Instrumentation. Available: Http://Conf. Tac-Atc. Ca/English/Annualconference/tac2012/Docs/session9/Sullivan. Pdf.

Hockman, A., Kessler, D.W., 1950. Thermal and moisture expansion studies of some domestic granites. US Bur Stand J Res 44, 395–410.

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

Mindess S., Young J. F., and Darwin D., Concrete. 2 ed. 2003, Englewood Cliffs, New Jersey: Prentice-Hall Inc.

Parsons, W.H., Johnson, W.H., 1944. Factors Affecting the Thermal Expansion of Concrete EXPANSION OF CONCRETE AGGREGATE MATERIALS........, in: Journal Proceedings. pp. 457–468.

Pearson, J.C., 1941. A Concrete Failure at Attributed to Aggregate of Low Thermal Coefficient, in: Journal Proceedings. pp. 29–36.

Pearson, J.C., Hornibrook, F.B., Meissner, H.S., Young, R.B., Kellam, B., Davis, R.E., Withey, M., Swayze, M.A., Walker, C.G., Reagel, F.V., Willis, T.F., 1942. Discussion of a paper by J. C.

Pearson: A Concrete Failure at Attributed to Aggregate of Low Thermal Coefficient, in: Journal Proceedings. pp. 29–36.
Siddiqui, M.S., Fowler, D.W., 2014. Effect of internal water pressure on the measured coefficient of thermal expansion of concrete. J. Mater. Civ. Eng. 27, 4014151.

Siddiqui, M.S., Fowler, D.W., 2015. A systematic optimization technique for the coefficient of thermal expansion of Portland cement concrete. Constr. Build. Mater. 88, 204–211. doi:10.1016/j.conbuildmat.2015.04.008

Siddiqui, M.S., Grasley, Z., Fowler, D.W., 2016. Internal water pressure development in saturated concrete cylinder subjected to coefficient of thermal expansion tests: Poroelastic model. Constr. Build. Mater. 112, 996–1004. doi:10.1016/j.conbuildmat.2016.02.081

Tanesi J., Kutay M. E., Abbas A., and Meininger R., Effect of coefficient of thermal expansion test variability on concrete pavement performance as predicted by mechanistic-empirical pavement design guide. Transportation Research Record (TRR), 2007. 2020: p. 40-44.

Tanesi, J., Crawford, G., Nicolaescu, M., Meininger, R., Gudimettla, J., 2010. New AASHTO T336-09 Coefficient of Thermal Expansion Test Method: How Will It Affect You? Transp. Res. Rec. J. Transp. Res. Board 52–57.

Walker, S., Bloem, D.L., Mullen, W.G., 1952. Effects of temperature changes on concrete as influenced by aggregates, in: Journal Proceedings. pp. 661–679.

Won M., Improvements of testing procedures for concrete coefficient of thermal expansion. Transportation Research Record (TRR), 2005. 1919: p. 23-25.

Young, J. F., Mindess, S., Darwin, D., 2002. Concrete. Prentice Hall.

Appendix

Table A - 1: Properties of compressive strength of mixtures MX-1-28 and MX-1-90

Compressive Strength Set MX1-28 tested at 28-days of age				
Specimen ID	unit	MX1-28-1	MX1-28-2	MX1-28-3
Weight, W_{SSD}	lbs.	8.107	8.147	8.225
	g	3,677.1	3,695.5	3,730.9
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	51,220	54,300	55,400
	kN	227.84	241.54	246.43
Compressive Strength,	psi.	4,076	4,321	4,409
	MPa	28.1	29.8	30.4
Compressive Strength Set MX1-90 tested at 90-days of age				
Specimen ID	unit	MX1-90-1	MX1-90-2	MX1-90-3
Weight, W_{SSD}	lbs.	8.171	8.194	8.256
	g	3,706.5	3,716.6	3,744.7
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	68,700	64,850	73,610
	kN	305.59	288.47	327.43
Compressive Strength,	psi.	5,467	5,161	5,858
	MPa	37.7	35.6	40.4

Table A - 2: Properties of compressive strength of mixtures MX-2-28 and MX-2-90.

Compressive Strength Set MX2-28 tested at 28-days of age				
Specimen ID	unit	MX2-28-1	MX2-28-2	MX2-28-3
Weight, W_{SSD}	lbs.	8.781	8.877	8.929
	g	3,982.9	4,026.6	4,050.3
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	74,160	78,430	79,170
	kN	329.88	348.87	352.17
Compressive Strength,	psi.	5,901	6,241	6,300
	MPa	40.7	43.0	43.4
Compressive Strength Set MX2-90 tested at 90-days of age				
Specimen ID	unit	MX2-90-1	MX2-90-2	MX2-90-3
Weight, W_{SSD}	lbs.	8.801	8.834	8.783
	g	3,992	4,007	3,984
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	92,910	94,860	94,860
	kN	413.28	421.96	421.96
Compressive Strength,	psi.	7,394	7,549	7,549
	MPa	51.0	52.1	52.1

Table A - 3: Properties of compressive strength of mixtures MX-3-28 and MX-3-90.

Compressive Strength Set MX3-28 tested at 28-days of age				
Specimen ID	unit	MX3-28-1	MX3-28-2	MX3-28-3
Weight, W_{SSD}	lbs.	7.993	8.002	8.031
	g	3,626	3,630	3,643
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	44,030	46,590	47,270
	kN	195.86	207.27	210.27
Compressive Strength,	psi.	3,504	3,708	3,762
	MPa	24.2	25.6	25.9
Compressive Strength Set MX3-90 tested at 90-days of age				
Specimen ID	unit	MX3-90-1	MX3-90-2	MX3-90-3
Weight, W_{SSD}	lbs.	8.055	7.947	7.964
	g	3,654	3,605	3,613
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	58,010	54,840	52,790
	kN	258.04	243.94	234.82
Compressive Strength,	psi.	4,616	4,364	4,201
	MPa	31.8	30.1	29.0

Table A - 4: Properties of compressive strength of mixtures MX-4-28 and MX-4-90.

Compressive Strength Set MX4-28 tested at 28-days of age				
Specimen ID	unit	MX4-28-1	MX4-28-2	MX4-28-3
Weight, W_{SSD}	lbs.	8.221	8.262	8.300
	g	3,729	3,748	3,765
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	60,090	57,760	57,220
	kN	267.29	256.93	254.53
Compressive Strength,	psi.	4,782	4,596	4,553
	MPa	33.0	31.7	31.4
Compressive Strength Set MX4-90 tested at 90-days of age				
Specimen ID	unit	MX4-90-1	MX4-90-2	MX4-90-3
Weight, W_{SSD}	lbs.	8.309	8.307	8.245
	g	3,769	3,768	3,740
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	74,570	72,970	75,750
	kN	331.70	324.59	336.95
Compressive Strength,	psi.	5,934	5,807	6,028
	MPa	40.9	40.0	41.6

Table A - 5: Properties of compressive strength of mixtures MX-5B-28 and MX-5B-90.

Compressive Strength Set MX5B-28 tested at 28-days of age				
Specimen ID	unit	MX5B-28-1	MX5B-28-2	MX5B-28-3
Weight, W_{SSD}	lbs.	7.984	7.998	8.016
	g	3,622	3,628	3,636
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	31,510	34,260	30,620
	kN	140.16	152.40	136.20
Compressive Strength,	psi.	2,507	2,726	2,437
	MPa	17.3	18.8	16.8
Compressive Strength Set MX5B-90 tested at 90-days of age				
Specimen ID	unit	MX5B-90-1	MX5B-90-2	MX5B-90-3
Weight, W_{SSD}	lbs.	8.051	8.036	8.040
	g	3,652	3,645	3,647
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	38,580	40,220	40,960
	kN	171.61	178.91	182.20
Compressive Strength,	psi.	3,070	3,201	3,259
	MPa	21.2	22.1	22.5

Table A - 6: Properties of compressive strength of mixtures MX-6-28 and MX-6-90.

Compressive Strength Set MX6-28 tested at 28-days of age				
Specimen ID	unit	MX6-28-1	MX6-28-2	MX6-28-3
Weight, W_{SSD}	lbs.	8.226	8.182	8.193
	g	3,731	3,712	3,716
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	53,540	54,460	55,340
	kN	238.16	242.25	246.16
Compressive Strength,	psi.	4,261	4,334	4,404
	MPa	29.4	29.9	30.4
Compressive Strength Set MX6-90 tested at 90-days of age				
Specimen ID	unit	MX6-90-1	MX6-90-2	MX6-90-3
Weight, W_{SSD}	lbs.	8.232	8.232	8.262
	g	3,734	3,734	3,747
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	8”	8”	8”
	mm	203.2	203.2	203.2
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	65,500	66,230	65,440
	kN	291.36	294.61	291.09
Compressive Strength,	psi.	5,212	5,270	5,208
	MPa	35.9	36.3	35.9

Table A - 7: Properties of compressive strength of CTE specimens of MX-1-28.

Compressive Strength of CTE Set MX1-28 tested at 183-days of age				
Specimen ID	unit	MX1-28-1	MX1-28-2	MX1-28-3
Production Date	-	12/09/15	12/09/15	12/09/15
Tested Date	-	06/09/16	06/09/16	06/09/16
Age	days	183	183	183
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	7.023”	7.064”	7.051”
	mm	178.378	179.423	179.090
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	74,840	75,260	79,890
	kN	332.90	334.77	355.37
Compressive Strength	psi.	5,956	5,989	6,357
	MPa	41.1	41.3	43.8
L/D	-	1.76	1.77	1.76
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	5,836	5,869	6,230
	Mpa	40.2	40.5	43.0

Table A - 8: Properties of compressive strength of CTE specimens of MX-2-28.

Compressive Strength of CTE Set MX2-28 tested at 216-days of age				
Specimen ID	unit	MX2-28-1	MX2-28-2	MX2-28-3
Production Date	-	12/10/15	12/10/15	12/10/15
Tested Date	-	07/13/16	07/13/16	07/13/16
Age	days	216	216	216
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	7.058”	7.063”	7.065”
	mm	179.273	179.398	179.458
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	102,780	101,330	101,280
	kN	457.19	450.74	450.52
Compressive Strength	psi.	8,179	8,064	8,060
	MPa	56.4	55.6	55.6
L/D	-	1.76	1.77	1.77
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	8,015	7,902	7,898
	Mpa	55.3	54.5	54.5

Table A - 9: Properties of compressive strength of CTE specimens of MX-3-28.

Compressive Strength of CTE Set MX3-28 tested at 212-days of age				
Specimen ID	unit	MX3-28-1	MX3-28-2	MX3-28-3
Production Date	-	12/14/15	12/14/15	12/14/15
Tested Date	-	07/13/16	07/13/16	07/13/16
Age	days	212	212	212
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	7.068”	7.064”	7.071”
	mm	179.515	179.420	179.608
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	59,720	60,860	61,760
	kN	265.65	270.72	274.72
Compressive Strength	psi.	4,752	4,843	4,915
	MPa	32.8	33.4	33.9
L/D	-	1.77	1.77	1.77
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	4,657	4,746	4,816
	Mpa	32.1	32.7	33.2

Table A - 10: Properties of compressive strength of CTE specimens of MX-4-28.

Compressive Strength of CTE Set MX4-28 tested at 148-days of age				
Specimen ID	unit	MX4-28-1	MX4-28-2	MX4-28-3
Production Date	-	02/16/16	02/16/16	02/16/16
Tested Date	-	07/13/16	07/13/16	07/13/16
Age	days	148	148	148
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	6.974”	6.963”	6.978”
	mm	177.143	176.848	177.233
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	78,140	82,380	82,920
	kN	347.58	366.44	368.85
Compressive Strength	psi.	6,218	6,556	6,599
	MPa	42.9	45.2	45.5
L/D	-	1.74	1.74	1.74
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	6,094	6,424	6,467
	Mpa	42.0	44.3	44.6

Table A - 11: Properties of compressive strength of CTE specimens of MX-5B-28.

Compressive Strength of CTE Set MX5B-28 tested at 147-days of age				
Specimen ID	unit	MX5B-28-1	MX5B-28-2	MX5B-28-3
Production Date	-	02/17/16	02/17/16	02/17/16
Tested Date	-	07/13/16	07/13/16	07/13/16
Age	days	147	147	147
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	6.991”	6.981”	6.989”
	mm	177.575	177.330	177.528
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107x10^{-3}$	$8.107x10^{-3}$	$8.107x10^{-3}$
Ultimate Load, *P*	lbs.	42,140	46,010	41,690
	kN	187.45	204.66	185.45
Compressive Strength	psi.	3,353	3,661	3,318
	MPa	23.1	25.2	22.9
L/D	-	1.75	1.75	1.75
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	3,286	3,588	3,251
	Mpa	22.7	24.7	22.4

Table A - 12: Properties of compressive strength of CTE specimens of MX-6-28.

Compressive Strength of CTE Set MX6-28 tested at 117-days of age				
Specimen ID	unit	MX6-28-1	MX6-28-2	MX6-28-3
Production Date	-	03/18/16	03/18/16	03/18/16
Tested Date	-	07/13/16	07/13/16	07/13/16
Age	days	117	117	117
Avg. Dia., ∅	in.	4”	4”	4”
	mm	101.6	101.6	101.6
Avg. Length, *L*	in.	6.977”	6.956”	6.939”
	mm	177.225	176.673	176.263
Avg. Cross-Sectional Area, *A*	in^2	12.566”	12.566”	12.566”
	m^2	$8.107 x 10^{-3}$	$8.107 x 10^{-3}$	$8.107 x 10^{-3}$
Ultimate Load, *P*	lbs.	74,660	74,920	81,970
	kN	332.10	333.26	364.62
Compressive Strength	psi.	5,941	5,962	6,523
	MPa	41.0	41.1	45.0
L/D	-	1.74	1.74	1.73
Correction Factor	-	0.98	0.98	0.98
Corrected Strength	psi.	5,822	5,843	6,393
	Mpa	40.1	40.3	44.1

Table A - 13: Properties of splitting tensile strength specimen sets MX-1-28 and MX-1-90.

Splitting Tensile Strength Set MX1-28 tested at 28-days of age				
Specimen ID	unit	MX1-28-1	MX1-28-2	MX1-28-3
Weight, W_{SSD}	lbs.	8.223	8.236	8.277
	g	3,729.7	3,735.9	3,754.4
Avg. Dia., *d*	in.	3.997	4.001	3.998
	mm	101.52	101.63	101.54
Avg. Length, *l*	in.	8.007	8.018	8.028
	mm	203.37	203.66	203.91
Ultimate Load, *P*	lbs.	28100	22970	23520
	kN	124.995	102.176	104.622
Splitting Tensile Strength	psi.	559	456	467
	MPa	3.85	3.14	3.22
Splitting Tensile Strength Set MX1-90 tested at 90-days of age				
Specimen ID	unit	MX1-90-1	MX1-90-2	MX1-90-3
Weight, W_{SSD}	lbs.	8.185	8.235	8.256
	g	3,712.7	3,735.3	3,744.9
Avg. Dia., *d*	in.	4.000	4.008	4.015
	mm	101.59	101.80	101.98
Avg. Length, *l*	in.	7.991	8.024	8.033
	mm	202.98	203.81	204.05
Ultimate Load, *P*	lbs.	31550	28160	25400
	kN	140.341	125.262	112.985
Splitting Tensile Strength	psi.	628	557	501
	MPa	4.33	3.84	3.46

Table A - 14: Properties of splitting tensile strength specimen sets MX-2-28 and MX-2-90.

Splitting Tensile Strength Set MX2-28 tested at 28-days of age				
Specimen ID	unit	MX2-28-1	MX2-28-2	MX2-28-3
Weight, W_{SSD}	lbs.	8.943	8.948	8.966
	g	4,056.7	4,058.6	4,066.7
Avg. Dia., *d*	in.	4.001	4.005	3.997
	mm	101.64	101.73	101.52
Avg. Length, *l*	in.	8.035	8.069	8.090
	mm	204.08	204.96	205.49
Ultimate Load, *P*	lbs.	22170	26470	26730
	kN	98.617	117.744	118.901
Splitting Tensile Strength	psi.	439	521	526
	MPa	3.03	3.60	3.63
Splitting Tensile Strength Set MX2-90 tested at 90-days of age				
Specimen ID	unit	MX2-90-1	MX2-90-2	MX2-90-3
Weight, W_{SSD}	lbs.	8.905	8.963	8.925
	g	4,039.4	4,065.7	4,048.3
Avg. Dia., *d*	in.	4.005	4.008	4.005
	mm	101.73	101.80	101.72
Avg. Length, *l*	in.	8.016	8.029	8.046
	mm	203.60	203.94	204.38
Ultimate Load, *P*	lbs.	37400	35910	35120
	kN	166.363	159.736	156.222
Splitting Tensile Strength	psi.	742	710	694
	MPa	5.11	4.90	4.78

Table A - 15: Properties of splitting tensile strength specimen sets MX-3-28 and MX-3-90.

Splitting Tensile Strength Set MX3-28 tested at 28-days of age				
Specimen ID	unit	MX3-28-1	MX3-28-2	MX3-28-3
Weight, W_{SSD}	lbs.	7.924	7.934	7.963
	g	3,594.4	3,598.6	3,612.1
Avg. Dia., *d*	in.	4.002	4.007	4.001
	mm	101.66	101.79	101.64
Avg. Length, *l*	in.	7.995	7.974	7.999
	mm	203.08	202.54	203.18
Ultimate Load, *P*	lbs.	20390	20550	20270
	kN	90.699	91.411	90.165
Splitting Tensile Strength	psi.	406	409	403
	MPa	2.80	2.82	2.78
Splitting Tensile Strength Set MX3-90 tested at 90-days of age				
Specimen ID	unit	MX3-90-1	MX3-90-2	MX3-90-3
Weight, W_{SSD}	lbs.	8.033	8.017	8.006
	g	3,643.6	3,636.3	3,631.6
Avg. Dia., *d*	in.	4.006	3.996	4.020
	mm	101.75	101.51	102.11
Avg. Length, *l*	in.	7.998	7.991	7.989
	mm	203.15	202.96	202.93
Ultimate Load, *P*	lbs.	26160	24430	23370
	kN	116.365	108.670	103.955
Splitting Tensile Strength	psi.	520	487	463
	MPa	3.58	3.36	3.19

Table A - 16: Properties of splitting tensile strength specimen sets MX-4-28 and MX-4-90.

Splitting Tensile Strength Set MX4-28 tested at 28-days of age				
Specimen ID	unit	MX4-28-1	MX4-28-2	MX4-28-3
Weight, W_{SSD}	lbs.	8.231	8.275	8.304
	g	3,733.7	3,753.5	3,766.5
Avg. Dia., *d*	in.	3.986	4.008	4.009
	mm	101.24	101.82	101.84
Avg. Length, *l*	in.	7.987	7.991	7.998
	mm	202.86	202.96	203.15
Ultimate Load, *P*	lbs.	23860	28400	24240
	kN	106.135	126.329	107.825
Splitting Tensile Strength	psi.	477	564	481
	MPa	3.29	3.89	3.32
Splitting Tensile Strength Set MX4-90 tested at 90-days of age				
Specimen ID	unit	MX4-90-1	MX4-90-2	MX4-90-3
Weight, W_{SSD}	lbs.	8.218	8.313	8.235
	g	3,727.5	3,770.9	3,735.4
Avg. Dia., *d*	in.	4.006	4.019	4.010
	mm	101.76	102.10	101.86
Avg. Length, *l*	in.	7.972	8.014	7.981
	mm	202.48	203.56	202.72
Ultimate Load, *P*	lbs.	31750	27860	26240
	kN	141.231	123.927	116.721
Splitting Tensile Strength	psi.	633	551	522
	MPa	4.36	3.80	3.60

Table A - 17: Properties of splitting tensile strength specimen sets MX-5B-28 and MX-5B-90.

Splitting Tensile Strength Set MX5B-28 tested at 28-days of age				
Specimen ID	unit	MX5B-28-1	MX5B-28-2	MX5B-28-3
Weight, W_{SSD}	lbs.	7.985	7.999	8.035
	g	3,622.1	3,628.5	3,644.4
Avg. Dia., *d*	in.	4.007	4.017	4.009
	mm	101.79	102.04	101.82
Avg. Length, *l*	in.	8.001	7.993	7.994
	mm	203.23	203.03	203.05
Ultimate Load, *P*	lbs.	19380	18650	18940
	kN	86.207	82.959	84.249
Splitting Tensile Strength	psi.	385	370	376
	MPa	2.65	2.55	2.59
Splitting Tensile Strength Set MX5B-90 tested at 90-days of age				
Specimen ID	unit	MX5B-90-1	MX5B-90-2	MX5B-90-3
Weight, W_{SSD}	lbs.	7.995	8.036	8.011
	g	3,626.5	3,645.2	3,633.8
Avg. Dia., *d*	in.	4.011	3.993	4.011
	mm	101.88	101.43	101.87
Avg. Length, *l*	in.	8.036	8.007	7.998
	mm	204.11	203.38	203.15
Ultimate Load, *P*	lbs.	22330	24630	21480
	kN	99.329	109.560	95.548
Splitting Tensile Strength	psi.	441	490	426
	MPa	3.04	3.38	2.94

Table A - 18: Properties of splitting tensile strength specimen sets MX-6-28 and MX-6-90.

Splitting Tensile Strength Set MX6-28 tested at 28-days of age				
Specimen ID	unit	MX6-28-1	MX6-28-2	MX6-28-3
Weight, W_{SSD}	lbs.	8.186	8.196	8.210
	g	3,713.1	3,717.7	3,724.2
Avg. Dia., *d*	in.	4.016	4.001	4.009
	mm	102.01	101.64	101.84
Avg. Length, *l*	in.	8.022	8.025	8.000
	mm	203.77	203.84	203.21
Ultimate Load, *P*	lbs.	25800	23790	24280
	kN	114.764	105.823	108.003
Splitting Tensile Strength	psi.	510	472	482
	MPa	3.52	3.25	3.32
Splitting Tensile Strength Set MX6-90 tested at 90-days of age				
Specimen ID	unit	MX6-90-1	MX6-90-2	MX6-90-3
Weight, W_{SSD}	lbs.	8.209	8.212	8.222
	g	3,723.6	3,724.8	3,729.4
Avg. Dia., *d*	in.	4.010	4.022	4.020
	mm	101.87	102.15	102.12
Avg. Length, *l*	in.	8.033	8.008	8.008
	mm	204.05	203.41	203.42
Ultimate Load, *P*	lbs.	27230	23120	20430
	kN	121.125	102.843	90.877
Splitting Tensile Strength	psi.	538	457	404
	MPa	3.71	3.15	2.79

Table A - 19: Properties of CTE specimen set MX-1-28.

CTE Set MX1-28 tested at 28-days of age				
Specimen ID	unit	MX1-28-1	MX1-28-2	MX1-28-3
Unit Weight	lbs/ft^3	140.65	140.09	140.07
	g/cc	2.253	2.244	2.244
W_{SSD}	g	3254.3	3265.9	3257.2
W_{SUB}	g	1813.5	1814.2	1809.1
Volume, V	cc	1444.41	1455.34	1451.73
Length, 1	mm	178.05	179.15	179.49
2	mm	178.07	179.16	178.83
3	mm	178.87	179.30	178.64
4	mm	178.52	180.08	179.40
Average Length , $L_{\varnothing}$	mm	178.378	179.423	179.090
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	22.40	22.40	22.40
T_1	°C	50.12	50.12	50.12
T_2	°C	10.27	10.27	10.27
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.73	27.73	27.73
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.87	39.87	39.87
Length measured, L_0	mm	0.1020	0.1517	0.0983
L_1	mm	0.0592	0.1181	0.0442
L_2	mm	0.1125	0.1647	0.1140
L_3	mm	0.0590	0.1178	0.0439
$\Delta Lm_0=L_1-L_0$	mm	-0.0428	-0.0336	-0.0542
$\Delta Lm_1=L_2-L_1$	mm	0.0534	0.0465	0.0699
$\Delta Lm_2=L_3-L_2$	mm	-0.0536	-0.0468	-0.0701
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0797	0.0751	0.0928
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1145	-0.1080	-0.1333
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1146	0.1080	0.1334
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0368	0.0416	0.0386
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0612	-0.0615	-0.0635
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0610	0.0612	0.0632
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$7.45x10^{-6}$	$8.35x10^{-6}$	$7.77x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$8.60x10^{-6}$	$8.59x10^{-6}$	$8.89x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$8.58x10^{-6}$	$8.56x10^{-6}$	$8.86x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$8.59x10^{-6}$	$8.58x10^{-6}$	$8.87x10^{-6}$
CTE_{avg}	in/in/°F	$4.77x10^{-6}$	$4.76x10^{-6}$	$4.93x10^{-6}$

Table A - 20: Properties of CTE specimen set MX-1-90.

CTE Set MX1-90 tested at 90-days of age				
Specimen ID	unit	MX1-90-1	MX1-90-2	MX1-90-3
Unit Weight	lbs/ft^3	139.97	140.68	140.64
	g/cc	2.242	2.253	2.253
W_{SSD}	g	3219.6	3237.5	3217.9
W_{SUB}	g	1787.2	1804.4	1793.1
Volume, V	cc	1435.99	1436.69	1428.37
Length, 1	mm	177.41	177.25	176.15
2	mm	176.94	176.76	175.85
3	mm	176.83	176.81	176.20
4	mm	177.40	177.17	176.26
Average Length , $L_{\emptyset}$	mm	177.145	176.998	176.115
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	22.26	22.26	22.26
T_1	°C	50.15	50.15	50.15
T_2	°C	10.29	10.29	10.29
T_3	°C	50.16	50.16	50.16
$\Delta T_0=T_1-T_0$	°C	27.89	27.89	27.89
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.87	39.87	39.87
Length measured, L_0	mm	0.1080	0.1529	0.1031
L_1	mm	0.0724	0.1226	0.0562
L_2	mm	0.1237	0.1670	0.1256
L_3	mm	0.0720	0.1225	0.0559
$\Delta Lm_0=L_1-L_0$	mm	-0.0356	-0.0304	-0.0469
$\Delta Lm_1=L_2-L_1$	mm	0.0512	0.0444	0.0694
$\Delta Lm_2=L_3-L_2$	mm	-0.0517	-0.0445	-0.0697
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0796	0.0746	0.0918
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1138	-0.1066	-0.1311
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1138	0.1066	0.1312
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0440	0.0442	0.0449
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0625	-0.0621	-0.0617
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0621	0.0621	0.0615
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$8.91x10^{-6}$	$8.95x10^{-6}$	$9.14x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$8.86x10^{-6}$	$8.80x10^{-6}$	$8.79x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$8.79x10^{-6}$	$8.79x10^{-6}$	$8.75x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$8.82x10^{-6}$	$8.80x10^{-6}$	$8.77x10^{-6}$
CTE_{avg}	in/in/°F	$4.90x10^{-6}$	$4.89x10^{-6}$	$4.87x10^{-6}$

Table A - 21: Properties of CTE specimen set MX-2-28.

CTE Set MX2-28 tested at 28-days of age				
Specimen ID	unit	MX2-28-1	MX2-28-2	MX2-28-3
Unit Weight	lbs/ft^3	151.97	151.62	151.82
	g/cc	2.434	2.429	2.432
W_{SSD}	g	3534.9	3529.4	3536.4
W_{SUB}	g	2086.4	2079.8	2085.9
Volume, V	cc	1452.13	1453.23	1454.14
Length, 1	mm	179.08	179.72	179.47
2	mm	179.51	179.07	179.23
3	mm	179.67	179.14	179.29
4	mm	178.83	179.66	179.84
Average Length , $L_{\varnothing}$	mm	179.273	179.398	179.458
Frame Correction, C_f	mm/mm/°C	16.109×10^{-6}	15.102×10^{-6}	18.680×10^{-6}
Temperature, T_0	°C	23.53	23.53	23.53
T_1	°C	50.15	50.15	50.15
T_2	°C	10.27	10.27	10.27
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	26.61	26.61	26.61
$\Delta T_1=T_2-T_1$	°C	-39.88	-39.88	-39.88
$\Delta T_2=T_3-T_2$	°C	39.88	39.88	39.88
Length measured, L_0	mm	0.1054	0.1504	0.1015
L_1	mm	0.0755	0.1305	0.0620
L_2	mm	0.1231	0.1711	0.1285
L_3	mm	0.0758	0.1311	0.0624
$\Delta Lm_0=L_1-L_0$	mm	-0.0299	-0.0200	-0.0395
$\Delta Lm_1=L_2-L_1$	mm	0.0476	0.0406	0.0664
$\Delta Lm_2=L_3-L_2$	mm	-0.0473	-0.0400	-0.0661
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0769	0.0721	0.0892
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1152	-0.1080	-0.1337
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1152	0.1080	0.1337
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0469	0.0521	0.0497
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0675	-0.0674	-0.0672
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0679	0.0680	0.0676
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	9.84×10^{-6}	10.92×10^{-6}	10.41×10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.45×10^{-6}	9.42×10^{-6}	9.40×10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.50×10^{-6}	9.51×10^{-6}	9.44×10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.47×10^{-6}	9.47×10^{-6}	9.42×10^{-6}
CTE_{avg}	in/in/°F	5.26×10^{-6}	5.26×10^{-6}	5.23×10^{-6}

Table A - 22: Properties of CTE specimen set MX-2-90.

CTE Set MX2-90 tested at 90-days of age				
Specimen ID	unit	MX2-90-1	MX2-90-2	MX2-90-3
Unit Weight	lbs/ft^3	151.70	152.04	152.09
	g/cc	2.430	2.435	2.436
W_{SSD}	g	3493.7	3503.6	3499.1
W_{SUB}	g	2059.6	2068.6	2066.4
Volume, V	cc	1437.69	1438.60	1436.29
Length, 1	mm	177.24	177.31	176.91
2	mm	177.07	176.99	176.74
3	mm	176.73	177.24	176.88
4	mm	176.71	177.68	176.94
Average Length , $L_{\varnothing}$	mm	176.938	177.305	176.868
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	22.38	22.38	22.38
T_1	°C	50.15	50.15	50.15
T_2	°C	10.30	10.30	10.30
T_3	°C	50.17	50.17	50.17
$\Delta T_0=T_1-T_0$	°C	27.77	27.77	27.77
$\Delta T_1=T_2-T_1$	°C	-39.85	-39.85	-39.85
$\Delta T_2=T_3-T_2$	°C	39.87	39.87	39.87
Length measured, L_0	mm	0.1050	0.1491	0.1053
L_1	mm	0.0755	0.1248	0.0634
L_2	mm	0.1187	0.1614	0.1257
L_3	mm	0.0754	0.1250	0.0635
$\Delta Lm_0=L_1-L_0$	mm	-0.0295	-0.0243	-0.0419
$\Delta Lm_1=L_2-L_1$	mm	0.0432	0.0366	0.0623
$\Delta Lm_2=L_3-L_2$	mm	-0.0433	-0.0364	-0.0622
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0791	0.0744	0.0917
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1136	-0.1067	-0.1317
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1136	0.1068	0.1317
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0496	0.0500	0.0498
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0703	-0.0701	-0.0693
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0703	0.0704	0.0695
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$10.10x10^{-6}$	$10.16x10^{-6}$	$10.14x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$9.98x10^{-6}$	$9.92x10^{-6}$	$9.84x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$9.97x10^{-6}$	$9.96x10^{-6}$	$9.85x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$9.97x10^{-6}$	$9.94x10^{-6}$	$9.85x10^{-6}$
CTE_{avg}	in/in/°F	$5.54x10^{-6}$	$5.52x10^{-6}$	$5.47x10^{-6}$

Table A - 23: Properties of CTE specimen set MX-3-28.

CTE Set MX3-28 tested at 28-days of age				
Specimen ID	unit	MX3-28-1	MX3-28-2	MX3-28-3
Unit Weight	lbs/ft^3	135.61	136.96	136.30
	g/cc	2.172	2.194	2.183
W_{SSD}	g	3139.7	3171.3	3159.7
W_{SUB}	g	1698	1729.4	1716.1
Volume, V	cc	1445.31	1445.51	1447.22
Length, 1	mm	177.24	177.31	176.91
2	mm	177.07	176.99	176.74
3	mm	176.73	177.24	176.88
4	mm	176.71	177.68	176.94
Average Length , $L_{\emptyset}$	mm	176.938	177.305	176.868
Frame Correction, C_f	mm/mm/°C	16.109×10^{-6}	15.102×10^{-6}	18.680×10^{-6}
Temperature, T_0	°C	22.27	22.27	22.27
T_1	°C	50.13	50.13	50.13
T_2	°C	10.27	10.27	10.27
T_3	°C	50.16	50.16	50.16
$\Delta T_0=T_1-T_0$	°C	27.86	27.86	27.86
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.88	39.88	39.88
Length measured, L_0	mm	0.1147	0.1506	0.1051
L_1	mm	0.0908	0.1310	0.0697
L_2	mm	0.1409	0.1747	0.1371
L_3	mm	0.0903	0.1307	0.0694
$\Delta Lm_0=L_1-L_0$	mm	-0.0240	-0.0196	-0.0354
$\Delta Lm_1=L_2-L_1$	mm	0.0502	0.0437	0.0674
$\Delta Lm_2=L_3-L_2$	mm	-0.0506	-0.0440	-0.0676
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0806	0.0755	0.0935
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1153	-0.1080	-0.1337
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1153	0.1081	0.1338
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0566	0.0558	0.0580
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0651	-0.0643	-0.0664
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0647	0.0641	0.0662
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	11.32×10^{-6}	11.17×10^{-6}	11.60×10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.09×10^{-6}	8.99×10^{-6}	9.27×10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.04×10^{-6}	8.95×10^{-6}	9.24×10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.07×10^{-6}	8.97×10^{-6}	9.26×10^{-6}
CTE_{avg}	in/in/°F	5.04×10^{-6}	4.98×10^{-6}	5.14×10^{-6}

Table A - 24: Properties of CTE specimen set MX-3-90.

CTE Set MX3-90 tested at 90-days of age				
Specimen ID	unit	MX3-90-1	MX3-90-2	MX3-90-3
Unit Weight	lbs/ft^3	138.37	137.66	136.84
	g/cc	2.216	2.205	2.192
W_{SSD}	g	3174.3	3153.7	3147.7
W_{SUB}	g	1745.7	1727.1	1715.3
Volume, V	cc	1432.18	1430.18	1435.99
Length, 1	mm	177.13	176.81	177.09
2	mm	176.79	177.11	177.35
3	mm	176.45	176.44	177.40
4	mm	176.34	176.37	177.06
Average Length , $L_\varnothing$	mm	176.678	176.683	177.225
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	22.69	22.69	22.69
T_1	°C	50.15	50.15	50.15
T_2	°C	10.29	10.29	10.29
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.46	27.46	27.46
$\Delta T_1=T_2-T_1$	°C	-39.85	-39.85	-39.85
$\Delta T_2=T_3-T_2$	°C	39.85	39.85	39.85
Length measured, L_0	mm	0.1032	0.1032	0.1447
L_1	mm	0.0691	0.1135	0.0582
L_2	mm	0.1194	0.1567	0.1249
L_3	mm	0.0689	0.1132	0.0579
$\Delta Lm_0=L_1-L_0$	mm	-0.0341	0.0104	-0.0865
$\Delta Lm_1=L_2-L_1$	mm	0.0503	0.0431	0.0667
$\Delta Lm_2=L_3-L_2$	mm	-0.0506	-0.0435	-0.0671
$\Delta Lf_0=C_f*L_\varnothing*\Delta T_0$	mm	0.0781	0.0733	0.0909
$\Delta Lf_1=C_f*L_\varnothing*\Delta T_1$	mm	-0.1134	-0.1063	-0.1319
$\Delta Lf_2=C_f*L_\varnothing*\Delta T_2$	mm	0.1134	0.1063	0.1319
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0441	0.0836	0.0044
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0631	-0.0632	-0.0652
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0629	0.0629	0.0648
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$9.09 x10^{-6}$	$17.24 x10^{-6}$	$0.90 x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$8.97 x10^{-6}$	$8.98 x10^{-6}$	$9.23 x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$8.93 x10^{-6}$	$8.93 x10^{-6}$	$9.18 x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$8.95 x10^{-6}$	$8.95 x10^{-6}$	$9.21 x10^{-6}$
CTE_{avg}	in/in/°F	$4.97 x10^{-6}$	$4.97 x10^{-6}$	$5.11 x10^{-6}$

Table A - 25: Properties of CTE specimen set MX-4-28.

CTE Set MX4-28 tested at 28-days of age				
Specimen ID	unit	MX4-28-1	MX4-28-2	MX4-28-3
Unit Weight	lbs/ft^3	142.10	142.13	142.64
	g/cc	2.276	2.277	2.285
W_{SSD}	g	3273	3262.7	3276.7
W_{SUB}	g	1838.7	1833.2	1846.2
Volume, V	cc	1437.89	1433.08	1434.09
Length, 1	mm	177.10	177.27	177.47
2	mm	177.33	176.90	176.99
3	mm	177.48	176.33	177.03
4	mm	176.66	176.89	177.44
Average Length , $L_{\emptyset}$	mm	177.143	176.848	177.233
Frame Correction, C_f	mm/mm/°C	$16.109 x 10^{-6}$	$15.102 x 10^{-6}$	$18.680 x 10^{-6}$
Temperature, T_0	°C	22.42	22.42	22.42
T_1	°C	50.15	50.15	50.15
T_2	°C	10.30	10.30	10.30
T_3	°C	50.15	50.15	50.15
$\Delta T_0=T_1-T_0$	°C	27.73	27.73	27.73
$\Delta T_1=T_2-T_1$	°C	-39.84	-39.84	-39.84
$\Delta T_2=T_3-T_2$	°C	39.84	39.84	39.84
Length measured, L_0	mm	0.1092	0.1486	0.1046
L_1	mm	0.0734	0.1196	0.0574
L_2	mm	0.1259	0.1643	0.1270
L_3	mm	0.0728	0.1193	0.0572
$\Delta Lm_0=L_1-L_0$	mm	-0.0358	-0.0290	-0.0471
$\Delta Lm_1=L_2-L_1$	mm	0.0525	0.0447	0.0696
$\Delta Lm_2=L_3-L_2$	mm	-0.0531	-0.0451	-0.0699
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0791	0.0741	0.0918
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1137	-0.1064	-0.1319
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1137	0.1064	0.1319
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0433	0.0450	0.0447
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0612	-0.0617	-0.0623
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0606	0.0614	0.0620
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$8.82 x 10^{-6}$	$9.18 x 10^{-6}$	$9.09 x 10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$8.67 x 10^{-6}$	$8.76 x 10^{-6}$	$8.83 x 10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$8.58 x 10^{-6}$	$8.71 x 10^{-6}$	$8.79 x 10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$8.63 x 10^{-6}$	$8.73 x 10^{-6}$	$8.81 x 10^{-6}$
CTE_{avg}	in/in/°F	$4.79 x 10^{-6}$	$4.85 x 10^{-6}$	$4.89 x 10^{-6}$

Table A - 26: Properties of CTE specimen set MX-4-90.

CTE Set MX4-90 tested at 90-days of age				
Specimen ID	unit	MX4-90-1	MX4-90-2	MX4-90-3
Unit Weight	lbs/ft^3	142.10	141.83	141.31
	g/cc	2.276	2.272	2.264
W_{SSD}	g	3272.5	3248.6	3253.5
W_{SUB}	g	1838.4	1822.3	1819.8
Volume, V	cc	1437.69	1429.87	1437.29
Length, 1	mm	177.38	176.27	177.24
2	mm	177.73	177.14	177.12
3	mm	177.65	176.73	177.47
4	mm	177.54	176.23	177.26
Average Length , $L_{\varnothing}$	mm	177.575	176.593	177.273
Frame Correction, C_f	mm/mm/°C	17.417×10^{-6}	16.256×10^{-6}	18.709×10^{-6}
Temperature, T_0	°C	20.96	20.96	20.96
T_1	°C	50.15	50.15	50.15
T_2	°C	10.28	10.28	10.28
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	29.19	29.19	29.19
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.86	39.86	39.86
Length measured, L_0	mm	0.1039	0.1435	0.1005
L_1	mm	0.0602	0.1077	0.0542
L_2	mm	0.1183	0.1569	0.1211
L_3	mm	0.0593	0.1071	0.0535
$\Delta Lm_0=L_1-L_0$	mm	-0.0437	-0.0358	-0.0462
$\Delta Lm_1=L_2-L_1$	mm	0.0581	0.0492	0.0669
$\Delta Lm_2=L_3-L_2$	mm	-0.0591	-0.0498	-0.0676
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0903	0.0838	0.0968
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1233	-0.1144	-0.1322
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1233	0.1144	0.1322
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0466	0.0480	0.0506
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0652	-0.0653	-0.0653
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0642	0.0646	0.0646
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	8.99×10^{-6}	9.32×10^{-6}	9.77×10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.21×10^{-6}	9.27×10^{-6}	9.24×10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.07×10^{-6}	9.18×10^{-6}	9.14×10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.14×10^{-6}	9.23×10^{-6}	9.19×10^{-6}
CTE_{avg}	in/in/°F	5.08×10^{-6}	5.13×10^{-6}	5.11×10^{-6}

Table A - 27: Properties of CTE specimen set MX-5B-28.

CTE Set MX5B-28 tested at 28-days of age				
Specimen ID	unit	MX5B-28-1	MX5B-28-2	MX5B-28-3
Unit Weight	lbs/ft^3	137.28	137.57	139.14
	g/cc	2.199	2.204	2.229
W_{SSD}	g	3164.5	3166.7	3205.8
W_{SUB}	g	1729	1733.3	1771.1
Volume, V	cc	1439.10	1436.99	1438.30
Length, 1	mm	177.71	176.84	177.31
2	mm	177.55	177.29	177.27
3	mm	177.16	177.59	177.80
4	mm	177.88	177.60	177.73
Average Length , $L_{\emptyset}$	mm	177.575	177.330	177.528
Frame Correction, C_f	mm/mm/°C	$16.109 x 10^{-6}$	$15.102 x 10^{-6}$	$18.680 x 10^{-6}$
Temperature, T_0	°C	22.31	22.31	22.31
T_1	°C	50.15	50.15	50.15
T_2	°C	10.30	10.30	10.30
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.84	27.84	27.84
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.85	39.85	39.85
Length measured, L_0	mm	0.1096	0.1522	0.0962
L_1	mm	0.0780	0.1284	0.0539
L_2	mm	0.1258	0.1682	0.1191
L_3	mm	0.0788	0.1294	0.0546
$\Delta Lm_0=L_1-L_0$	mm	-0.0316	-0.0238	-0.0423
$\Delta Lm_1=L_2-L_1$	mm	0.0478	0.0398	0.0652
$\Delta Lm_2=L_3-L_2$	mm	-0.0470	-0.0388	-0.0645
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0797	0.0746	0.0923
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1140	-0.1067	-0.1322
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1140	0.1067	0.1321
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0481	0.0508	0.0501
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0662	-0.0669	-0.0669
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0669	0.0679	0.0676
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$9.73 x 10^{-6}$	$10.28 x 10^{-6}$	$10.13 x 10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$9.35 x 10^{-6}$	$9.47 x 10^{-6}$	$9.46 x 10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$9.46 x 10^{-6}$	$9.61 x 10^{-6}$	$9.56 x 10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$9.41 x 10^{-6}$	$9.54 x 10^{-6}$	$9.51 x 10^{-6}$
CTE_{avg}	in/in/°F	$5.23 x 10^{-6}$	$5.30 x 10^{-6}$	$5.28 x 10^{-6}$

Table A - 28: Properties of CTE specimen set MX-5B-90.

CTE Set MX5B-90 tested at 90-days of age				
Specimen ID	unit	MX5B-90-1	MX5B-90-2	MX5B-90-3
Unit Weight	lbs/ft^3	138.80	139.22	137.73
	g/cc	2.223	2.230	2.206
W_{SSD}	g	3190.9	3195.1	3145.5
W_{SUB}	g	1759.3	1766	1723.3
Volume, V	cc	1435.19	1432.68	1425.76
Length, 1	mm	177.63	177.41	175.65
2	mm	176.94	176.93	176.09
3	mm	177.04	175.97	177.05
4	mm	177.33	176.93	175.93
Average Length , $L_{\varnothing}$	mm	177.235	176.810	176.180
Frame Correction, C_f	mm/mm/°C	17.417 $x10^{-6}$	16.256$x10^{-6}$	18.709$x10^{-6}$
Temperature, T_0	°C	23.01	23.01	23.01
T_1	°C	50.15	50.15	50.15
T_2	°C	10.29	10.29	10.29
T_3	°C	50.15	50.15	50.15
$\Delta T_0=T_1-T_0$	°C	27.14	27.14	27.14
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.86	39.86	39.86
Length measured, L_0	mm	0.1020	0.1425	0.1047
L_1	mm	0.0703	0.1162	0.0690
L_2	mm	0.1241	0.1611	0.1333
L_3	mm	0.0707	0.1165	0.0695
$\Delta Lm_0=L_1-L_0$	mm	-0.0317	-0.0263	-0.0357
$\Delta Lm_1=L_2-L_1$	mm	0.0538	0.0449	0.0643
$\Delta Lm_2=L_3-L_2$	mm	-0.0534	-0.0446	-0.0637
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0838	0.0780	0.0895
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1231	-0.1146	-0.1314
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1231	0.1146	0.1314
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0521	0.0517	0.0538
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0693	-0.0697	-0.0671
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0697	0.0700	0.0677
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	10.84 $x10^{-6}$	10.77 $x10^{-6}$	11.25 $x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.80 $x10^{-6}$	9.88 $x10^{-6}$	9.56$x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.86 $x10^{-6}$	9.93 $x10^{-6}$	9.63 $x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	9.83 $x10^{-6}$	9.91 $x10^{-6}$	9.60 $x10^{-6}$
CTE_{avg}	in/in/°F	5.46 $x10^{-6}$	5.50 $x10^{-6}$	5.33 $x10^{-6}$

Table A - 29: Properties of CTE specimen set MX-6-28.

CTE Set MX6-28 tested at 28-days of age				
Specimen ID	unit	MX6-28-1	MX6-28-2	MX6-28-3
Unit Weight	lbs/ft^3	140.26	140.36	140.78
	g/cc	2.247	2.248	2.255
W_{SSD}	g	3229	3221.9	3226.5
W_{SUB}	g	1795.4	1792.5	1799.3
Volume, V	cc	1437.19	1432.98	1430.78
Length, 1	mm	176.96	176.34	176.10
2	mm	177.12	177.25	176.45
3	mm	177.44	177.05	176.19
4	mm	177.38	176.05	176.31
Average Length , $L_{\varnothing}$	mm	177.225	176.673	176.263
Frame Correction, C_f	mm/mm/°C	17.417 x10^{-6}	16.256x10^{-6}	18.709x10^{-6}
Temperature, T_0	°C	21.74	21.74	21.74
T_1	°C	50.15	50.15	50.15
T_2	°C	10.27	10.27	10.27
T_3	°C	50.15	50.15	50.15
$\Delta T_0=T_1-T_0$	°C	28.41	28.41	28.41
$\Delta T_1=T_2-T_1$	°C	-39.88	-39.88	-39.88
$\Delta T_2=T_3-T_2$	°C	39.88	39.88	39.88
Length measured, L_0	mm	0.0985	0.1419	0.0999
L_1	mm	0.0579	0.1091	0.0549
L_2	mm	0.1113	0.1546	0.1214
L_3	mm	0.0567	0.1083	0.0544
$\Delta Lm_0=L_1-L_0$	mm	-0.0406	-0.0328	-0.0450
$\Delta Lm_1=L_2-L_1$	mm	0.0533	0.0455	0.0665
$\Delta Lm_2=L_3-L_2$	mm	-0.0546	-0.0462	-0.0670
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0877	0.0816	0.0937
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1231	-0.1145	-0.1315
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1231	0.1145	0.1315
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0471	0.0488	0.0487
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0698	-0.0691	-0.0650
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0685	0.0683	0.0645
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	9.35 x10^{-6}	9.72 x10^{-6}	9.72 x10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.87 x10^{-6}	9.80 x10^{-6}	9.25 x10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.96 x10^{-6}	9.69 x10^{-6}	9.18 x10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.73 x10^{-6}	9.75 x10^{-6}	9.21 x10^{-6}
CTE_{avg}	in/in/°F	5.44 x10^{-6}	5.42 x10^{-6}	5.12 x10^{-6}

Table A - 30: Properties of CTE specimen set MX-6-90.

CTE Set MX6-90 tested at 90-days of age				
Specimen ID	unit	MX6-90-1	MX6-90-2	MX6-90-3
Unit Weight	lbs/ft^3	140.44	140.87	140.24
	g/cc	2.250	2.257	2.246
W_{SSD}	g	3255.2	3265.2	3242.2
W_{SUB}	g	1811.8	1821.8	1802.5
Volume, V	cc	1447.02	1447.02	1443.31
Length, 1	mm	178.74	178.42	177.52
2	mm	178.64	177.91	178.33
3	mm	178.56	178.26	178.24
4	mm	179.06	178.78	177.87
Average Length , $L_{\emptyset}$	mm	178.750	178.343	177.990
Frame Correction, C_f	mm/mm/°C	17.417 x10^{-6}	16.256x10^{-6}	18.709x10^{-6}
Temperature, T_0	°C	22.13	22.13	22.13
T_1	°C	50.14	50.14	50.14
T_2	°C	10.31	10.31	10.31
T_3	°C	50.15	50.15	50.15
$\Delta T_0=T_1-T_0$	°C	28.02	28.02	28.02
$\Delta T_1=T_2-T_1$	°C	-39.83	-39.83	-39.83
$\Delta T_2=T_3-T_2$	°C	39.84	39.84	39.84
Length measured, L_0	mm	0.1031	0.1409	0.0968
L_1	mm	0.0587	0.1027	0.0534
L_2	mm	0.1171	0.1521	0.1182
L_3	mm	0.0584	0.1026	0.0532
$\Delta Lm_0=L_1-L_0$	mm	-0.0444	-0.0382	-0.0435
$\Delta Lm_1=L_2-L_1$	mm	0.0584	0.0494	0.0648
$\Delta Lm_2=L_3-L_2$	mm	-0.0587	-0.0495	-0.0650
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0872	0.0812	0.0933
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1240	-0.1155	-0.1326
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1240	0.1155	0.1327
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0429	0.0430	0.0498
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0656	-0.0661	-0.0678
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0653	0.0660	0.0677
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	8.56 x10^{-6}	8.61 x10^{-6}	9.99 x10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.21 x10^{-6}	9.30 x10^{-6}	9.56 x10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.17 x10^{-6}	9.29 x10^{-6}	9.55 x10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.19x10^{-6}	9.29 x10^{-6}	9.55 x10^{-6}
CTE_{avg}	in/in/°F	5.11 x10^{-6}	5.16 x10^{-6}	5.31 x10^{-6}

Table A - 31: Properties of CTE specimen set MX-A.

CTE Set MXA tested at 28-days of age				
Specimen ID	unit	MXA-1	MXA-2	MXA-3
Unit Weight	lbs/ft^3	117.93	117.69	118.24
	g/cc	1.889	1.885	1.894
W_{SSD}	g	2712	2695.2	2714.7
W_{SUB}	g	1279.9	1269.1	1285
Volume, V	cc	1435.69	1429.67	1433.28
Length, 1	mm	176.84	176.15	176.42
2	mm	176.72	176.44	176.21
3	mm	176.61	176.00	176.82
4	mm	177.04	176.26	176.35
Average Length , $L_{\varnothing}$	mm	176.803	176.213	176.450
Frame Correction, C_f	mm/mm/°C	17.417 $x10^{-6}$	16.256$x10^{-6}$	18.709$x10^{-6}$
Temperature, T_0	°C	23.11	23.11	23.11
T_1	°C	50.15	50.15	50.15
T_2	°C	10.28	10.28	10.28
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.03	27.03	27.03
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.86	39.86	39.86
Length measured, L_0	mm	0.1050	0.1455	0.1006
L_1	mm	0.0816	0.1280	0.0739
L_2	mm	0.1118	0.1506	0.1118
L_3	mm	0.0817	0.1278	0.0733
$\Delta Lm_0=L_1-L_0$	mm	-0.0235	-0.0175	-0.0267
$\Delta Lm_1=L_2-L_1$	mm	0.0302	0.0226	0.0379
$\Delta Lm_2=L_3-L_2$	mm	-0.0301	-0.0227	-0.0386
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0832	0.0774	0.0892
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1228	-0.1142	-0.1316
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1227	0.1142	0.1316
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0598	0.0599	0.0625
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0925	-0.0916	-0.0936
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0927	0.0914	0.0930
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	12.51 $x10^{-6}$	12.58 $x10^{-6}$	13.11 $x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	13.13 $x10^{-6}$	13.04 $x10^{-6}$	13.31 $x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	13.15 $x10^{-6}$	13.02 $x10^{-6}$	13.23 $x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	13.14 $x10^{-6}$	13.03 $x10^{-6}$	13.27 $x10^{-6}$
CTE_{avg}	in/in/°F	7.30 $x10^{-6}$	7.24 $x10^{-6}$	7.37 $x10^{-6}$

Table A - 32: Properties of CTE specimen set MX-B.

CTE Set MXB tested at 28-days of age				
Specimen ID	unit	MXB-1	MXB-2	MXB-3
Unit Weight	lbs/ft^3	130.58	129.81	130.23
	g/cc	2.092	2.079	2.086
W_{SSD}	g	2988	2970.1	2986.8
W_{SUB}	g	1563.1	1545.3	1558.6
Volume, V	cc	1428.47	1428.37	1431.78
Length, 1	mm	176.06	176.10	176.26
2	mm	176.00	176.37	176.16
3	mm	176.42	175.87	177.09
4	mm	175.98	175.95	176.53
Average Length , $L_\varnothing$	mm	176.115	176.073	176.510
Frame Correction, C_f	mm/mm/°C	17.417 $x10^{-6}$	16.256$x10^{-6}$	18.709$x10^{-6}$
Temperature, T_0	°C	20.96	20.96	20.96
T_1	°C	50.15	50.15	50.15
T_2	°C	10.28	10.28	10.28
T_3	°C	50.15	50.15	50.15
$\Delta T_0=T_1-T_0$	°C	29.19	29.19	29.19
$\Delta T_1=T_2-T_1$	°C	-39.87	-39.87	-39.87
$\Delta T_2=T_3-T_2$	°C	39.87	39.87	39.87
Length measured, L_0	mm	0.1043	0.1436	0.1025
L_1	mm	0.0740	0.1193	0.0681
L_2	mm	0.1134	0.1500	0.1166
L_3	mm	0.0739	0.1194	0.0680
$\Delta Lm_0=L_1-L_0$	mm	-0.0303	-0.0243	-0.0344
$\Delta Lm_1=L_2-L_1$	mm	0.0394	0.0307	0.0485
$\Delta Lm_2=L_3-L_2$	mm	-0.0394	-0.0307	-0.0486
$\Delta Lf_0=C_f*L_\varnothing*\Delta T_0$	mm	0.0895	0.0835	0.0964
$\Delta Lf_1=C_f*L_\varnothing*\Delta T_1$	mm	-0.1223	-0.1141	-0.1317
$\Delta Lf_2=C_f*L_\varnothing*\Delta T_2$	mm	0.1223	0.1141	0.1317
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0592	0.0592	0.0620
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0829	-0.0834	-0.0832
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0829	0.0835	0.0830
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	11.52 $x10^{-6}$	11.53 $x10^{-6}$	12.04 $x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	11.81 $x10^{-6}$	11.88 $x10^{-6}$	11.82 $x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	11.80 $x10^{-6}$	11.89 $x10^{-6}$	11.80 $x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	11.81 $x10^{-6}$	11.88 $x10^{-6}$	11.81 $x10^{-6}$
CTE_{avg}	in/in/°F	6.56 $x10^{-6}$	6.60 $x10^{-6}$	6.56 $x10^{-6}$

Table A - 33: Properties of CTE specimen set KC100.

Specimen ID	unit	KC100-1	KC100-2	KC100-3
Unit Weight	lbs/ft^3	164.86	164.32	163.66
	g/cc	2.641	2.632	2.622
W_{SSD}	g	3696.9	3711.9	3678.2
W_{SUB}	g	2300.5	2305.2	2278.7
Volume, V	cc	1399.90	1410.23	1403.01
Length, 1	mm	178.58	176.73	175.25
2	mm	176.58	176.94	176.43
3	mm	176.01	176.92	175.69
4	mm	177.12	177.66	175.21
Average Length , $L_{\varnothing}$	mm	177.073	177.063	175.645
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	23.15	23.15	23.15
T_1	°C	50.15	50.15	50.15
T_2	°C	10.29	10.29	10.29
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.00	27.00	27.00
$\Delta T_1=T_2-T_1$	°C	-39.86	-39.86	-39.86
$\Delta T_2=T_3-T_2$	°C	39.85	39.85	39.85
Length measured, L_0	mm	0.0977	0.1436	0.0965
L_1	mm	0.0450	0.1030	0.0394
L_2	mm	0.1176	0.1598	0.1243
L_3	mm	0.0446	0.1028	0.0391
$\Delta Lm_0=L_1-L_0$	mm	-0.0527	-0.0406	-0.0571
$\Delta Lm_1=L_2-L_1$	mm	0.0726	0.0568	0.0849
$\Delta Lm_2=L_3-L_2$	mm	-0.0731	-0.0569	-0.0851
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0770	0.0722	0.0886
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1137	-0.1066	-0.1308
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1137	0.1066	0.1307
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0243	0.0316	0.0315
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0411	-0.0498	-0.0459
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0406	0.0496	0.0456
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$5.09 x10^{-6}$	$6.62 x10^{-6}$	$6.64 x10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$5.82 x10^{-6}$	$7.06 x10^{-6}$	$6.55 x10^{-6}$
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$5.75 x10^{-6}$	$7.03 x10^{-6}$	$6.52 x10^{-6}$
$CTE_{avg1,2}$	mm/mm/°C	$5.79 x10^{-6}$	$7.04 x10^{-6}$	$6.53 x10^{-6}$
CTE_{avg}	in/in/°F	$3.22 x10^{-6}$	$3.91 x10^{-6}$	$3.63 x10^{-6}$

Table A - 34: Properties of CTE specimen set BB100.

Specimen ID	unit	BB100-1	BB100-2	BB100-3
Unit Weight	lbs/ft^3	170.08	169.70	178.64
	g/cc	2.724	2.718	2.862
W_{SSD}	g	3894.8	3890.7	4100.3
W_{SUB}	g	2468.8	2463	2671
Volume, V	cc	1429.57	1431.28	1432.88
Length, 1	mm	176.41	176.57	177.68
2	mm	176.21	175.72	176.82
3	mm	176.93	176.32	176.32
4	mm	176.70	177.79	176.45
Average Length , $L_{\varnothing}$	mm	176.563	176.600	176.818
Frame Correction, C_f	mm/mm/°C	$16.109x10^{-6}$	$15.102x10^{-6}$	$18.680x10^{-6}$
Temperature, T_0	°C	23.44	23.44	23.44
T_1	°C	50.16	50.16	50.16
T_2	°C	10.32	10.32	10.32
T_3	°C	50.15	50.15	50.15
T_4	°C	10.31	10.31	10.31
T_5	°C	50.16	50.16	50.16
T_6	°C	10.30	10.30	10.30
T_7	°C	50.16	50.16	50.16
T_8	°C	10.36	10.36	10.36
T_9	°C	50.15	50.15	50.15
T_{10}	°C	10.35	10.35	10.35
$\Delta T_0=T_1-T_0$	°C	26.72	26.72	26.72
$\Delta T_1=T_2-T_1$	°C	-39.84	-39.84	-39.84
$\Delta T_2=T_3-T_2$	°C	39.83	39.83	39.83
$\Delta T_3=T_4-T_3$	°C	-39.84	-39.84	-39.84
$\Delta T_4=T_5-T_4$	°C	39.85	39.85	39.85
$\Delta T_5=T_6-T_5$	°C	-39.86	-39.86	-39.86
$\Delta T_6=T_7-T_6$	°C	39.85	39.85	39.85
$\Delta T_7=T_8-T_7$	°C	-39.80	-39.80	-39.80
$\Delta T_8=T_9-T_8$	°C	39.80	39.80	39.80
$\Delta T_9=T_{10}-T_9$	°C	-39.80	-39.80	-39.80
Length measured, L_0	mm	0.0997	0.1430	0.0956
L_1	mm	0.0421	0.1116	0.0652
L_2	mm	0.1289	0.1823	0.1393
L_3	mm	0.0425	0.1230	0.0753
L_4	mm	0.1291	0.1903	0.1460

Table A - 34 continued...				
L_5	mm	0.0423	0.1282	0.0796
L_6	mm	0.1290	0.1945	0.1496
L_7	mm	0.0419	0.1314	0.0823
L_8	mm	0.1286	0.1974	0.1519
L_9	mm	0.0416	0.1337	0.0843
L_{10}	mm	0.1285	0.1995	0.1539
$\Delta Lm_0=L_1-L_0$	mm	-0.0576	-0.0314	-0.0304
$\Delta Lm_1=L_2-L_1$	mm	0.0868	0.0707	0.0741
$\Delta Lm_2=L_3-L_2$	mm	-0.0864	-0.0593	-0.0640
$\Delta Lm_3=L_4-L_3$	mm	0.0866	0.0673	0.0707
$\Delta Lm_4=L_5-L_4$	mm	-0.0868	-0.0621	-0.0664
$\Delta Lm_5=L_6-L_5$	mm	0.0867	0.0663	0.0699
$\Delta Lm_6=L_7-L_6$	mm	-0.0871	-0.0632	-0.0673
$\Delta Lm_7=L_8-L_7$	mm	0.0867	0.0661	0.0697
$\Delta Lm_8=L_9-L_8$	mm	-0.0870	-0.0638	-0.0677
$\Delta Lm_9=L_{10}-L_9$	mm	0.0869	0.0659	0.0696
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0822	0.0767	0.0884
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1225	-0.1144	-0.1318
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1225	0.1144	0.1318
$\Delta Lf_3=C_f*L_{\emptyset}*\Delta T_3$	mm	-0.1225	-0.1144	-0.1318
$\Delta Lf_4=C_f*L_{\emptyset}*\Delta T_4$	mm	0.1225	0.1144	0.1318
$\Delta Lf_5=C_f*L_{\emptyset}*\Delta T_5$	mm	-0.1226	-0.1144	-0.1319
$\Delta Lf_6=C_f*L_{\emptyset}*\Delta T_6$	mm	0.1226	0.1144	0.1318
$\Delta Lf_7=C_f*L_{\emptyset}*\Delta T_7$	mm	-0.1224	-0.1143	-0.1317
$\Delta Lf_8=C_f*L_{\emptyset}*\Delta T_8$	mm	0.1224	0.1142	0.1317
$\Delta Lf_9=C_f*L_{\emptyset}*\Delta T_9$	mm	-0.1224	-0.1143	-0.1317
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0246	0.0453	0.0580
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0357	-0.0436	-0.0577
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0361	0.0550	0.0678
$\Delta La_3=\Delta Lm_3+\Delta Lf_3$	mm	-0.0359	-0.0470	-0.0611
$\Delta La_4=\Delta Lm_4+\Delta Lf_4$	mm	0.0357	0.0523	0.0654
$\Delta La_5=\Delta Lm_5+\Delta Lf_5$	mm	-0.0359	-0.0481	-0.0619
$\Delta La_6=\Delta Lm_6+\Delta Lf_6$	mm	0.0354	0.0513	0.0645
$\Delta La_7=\Delta Lm_7+\Delta Lf_7$	mm	-0.0357	-0.0482	-0.0620
$\Delta La_8=\Delta Lm_8+\Delta Lf_8$	mm	0.0354	0.0505	0.0640
$\Delta La_9=\Delta Lm_9+\Delta Lf_9$	mm	-0.0355	-0.0484	-0.0621
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	$5.21\text{x}10^{-6}$	$9.59\text{x}10^{-6}$	$12.28\ \text{x}10^{-6}$
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	$5.08\text{x}10^{-6}$	$6.20\text{x}10^{-6}$	$8.19\ \text{x}10^{-6}$

Table A - 34 continued...				
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	$5.13x10^{-6}$	$7.82x10^{-6}$	$9.63\ x10^{-6}$
$CTE_3=\Delta La_3/L_0/\Delta T_3$	mm/mm/°C	$5.10x10^{-6}$	$6.69x10^{-6}$	$8.67\ x10^{-6}$
$CTE_4=\Delta La_4/L_0/\Delta T_4$	mm/mm/°C	$5.08x10^{-6}$	$7.43x10^{-6}$	$9.29\ x10^{-6}$
$CTE_5=\Delta La_5/L_0/\Delta T_5$	mm/mm/°C	$5.10x10^{-6}$	$6.83x10^{-6}$	$8.79\ x10^{-6}$
$CTE_6=\Delta La_6/L_0/\Delta T_6$	mm/mm/°C	$5.04x10^{-6}$	$7.28x10^{-6}$	$9.16\ x10^{-6}$
$CTE_7=\Delta La_7/L_0/\Delta T_7$	mm/mm/°C	$5.07x10^{-6}$	$6.86x10^{-6}$	$8.81\ x10^{-6}$
$CTE_8=\Delta La_8/L_0/\Delta T_8$	mm/mm/°C	$5.03x10^{-6}$	$7.18x10^{-6}$	$9.10\ x10^{-6}$
$CTE_9=\Delta La_9/L_0/\Delta T_9$	mm/mm/°C	$5.05x10^{-6}$	$6.89x10^{-6}$	$8.82\ x10^{-6}$
$CTE_{avg8,9}$	mm/mm/°C	$5.04x10^{-6}$	$7.04x10^{-6}$	$8.96\ x10^{-6}$
CTE_{avg}	in/in/°F	$2.80x10^{-6}$	$3.91x10^{-6}$	$4.98\ x10^{-6}$

Table A - 35: Properties of concrete cores taken from slab number 1 along SC-80.

SC 80, Slab 1, specimens 1-1, 1-2, 1-3				
Specimen ID	unit	1-1	1-2	1-3
Core depth	in.	10”	9-3/4”	9-3/4”
Unit Weight	lbs/ft^3	151.77	150.56	153.95
	g/cc	2.431	2.412	2.466
W_{SSD}	g	3443.1	3433.6	3510.3
W_{SUB}	g	2030.4	2013.5	2090.4
Volume, V	cc	1416.24	1423.66	1423.46
Length, 1	mm	177.40	178.41	178.46
2	mm	177.01	177.89	178.35
3	mm	177.27	178.01	177.56
4	mm	177.89	178.06	177.98
Average Length , $L_{\varnothing}$	mm	177.393	178.093	178.088
Frame Correction, C_f	mm/mm/°C	17.417 x10^{-6}	16.256x10^{-6}	18.709x10^{-6}
Temperature, T_0	°C	22.62	22.62	22.62
T_1	°C	50.15	50.15	50.15
T_2	°C	10.31	10.31	10.31
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	27.53	27.53	27.53
$\Delta T_1=T_2-T_1$	°C	-39.84	-39.84	-39.84
$\Delta T_2=T_3-T_2$	°C	39.83	39.83	39.83
Length measured, L_0	mm	0.1023	0.1424	0.1012
L_1	mm	0.0608	0.1071	0.0601
L_2	mm	0.1250	0.1602	0.1299
L_3	mm	0.0626	0.1086	0.0617
$\Delta Lm_0=L_1-L_0$	mm	-0.0415	-0.0352	-0.0411
$\Delta Lm_1=L_2-L_1$	mm	0.0642	0.0531	0.0699
$\Delta Lm_2=L_3-L_2$	mm	-0.0624	-0.0516	-0.0683
$\Delta Lf_0=C_f*L_{\varnothing}*\Delta T_0$	mm	0.0851	0.0797	0.0917
$\Delta Lf_1=C_f*L_{\varnothing}*\Delta T_1$	mm	-0.1231	-0.1153	-0.1327
$\Delta Lf_2=C_f*L_{\varnothing}*\Delta T_2$	mm	0.1231	0.1153	0.1327
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0435	0.0445	0.0506
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0589	-0.0622	-0.0629
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0607	0.0637	0.0644
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	8.92x10^{-6}	9.07x10^{-6}	10.32x10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	8.33x10^{-6}	8.77x10^{-6}	8.86x10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	8.59x10^{-6}	8.98x10^{-6}	9.09x10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	8.46x10^{-6}	8.87x10^{-6}	8.97x10^{-6}

Table A - 35 continued...				
CTE_{avg}	in/in/°F	$4.70x10^{-6}$	$4.93x10^{-6}$	$4.98x10^{-6}$
Compressive Strength	psi.	4,689	6,351	7,268

Table A - 36: Properties of concrete cores taken from slab number 2 along SC-80.

SC 80, Slab 2, specimens 2-1, 2-2, 2-3				
Specimen ID	unit	2-1	2-2	2-3
Core depth	in.	10-3/4”	10-1/4”	10”
Unit Weight	lbs/ft^3	148.12	148.29	149.54
	g/cc	2.373	2.375	2.395
W_{SSD}	g	3375.9	3373.9	3406.8
W_{SUB}	g	1956.6	1957.1	1988.1
Volume, V	cc	1422.86	1420.35	1422.26
Length, 1	mm	178.00	178.09	177.94
2	mm	177.97	178.37	178.77
3	mm	178.50	178.22	178.58
4	mm	178.40	177.96	177.88
Average Length , $L_{\emptyset}$	mm	178.218	178.160	178.293
Frame Correction, C_f	mm/mm/°C	17.417 x10^{-6}	16.256x10^{-6}	18.709x10^{-6}
Temperature, T_0	°C	23.25	23.25	23.25
T_1	°C	50.15	50.15	50.15
T_2	°C	10.32	10.32	10.32
T_3	°C	50.14	50.14	50.14
$\Delta T_0=T_1-T_0$	°C	26.90	26.90	26.90
$\Delta T_1=T_2-T_1$	°C	-39.83	-39.83	-39.83
$\Delta T_2=T_3-T_2$	°C	39.82	39.82	39.82
Length measured, L_0	mm	0.1050	0.1424	0.1020
L_1	mm	0.0669	0.1085	0.0624
L_2	mm	0.1244	0.1579	0.1290
L_3	mm	0.0673	0.1088	0.0631
$\Delta Lm_0=L_1-L_0$	mm	-0.0381	-0.0339	-0.0396
$\Delta Lm_1=L_2-L_1$	mm	0.0575	0.0494	0.0666
$\Delta Lm_2=L_3-L_2$	mm	-0.0571	-0.0491	-0.0659
$\Delta Lf_0=C_f*L_{\emptyset}*\Delta T_0$	mm	0.0835	0.0779	0.0897
$\Delta Lf_1=C_f*L_{\emptyset}*\Delta T_1$	mm	-0.1236	-0.1154	-0.1329
$\Delta Lf_2=C_f*L_{\emptyset}*\Delta T_2$	mm	0.1236	0.1153	0.1328
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0454	0.0440	0.0501
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0661	-0.0660	-0.0663
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0665	0.0662	0.0669
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	9.47x10^{-6}	9.18x10^{-6}	10.46x10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.31x10^{-6}	9.30x10^{-6}	9.33x10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.38x10^{-6}	9.34x10^{-6}	9.43x10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.34x10^{-6}	9.32x10^{-6}	9.38x10^{-6}

Table A - 36 continued…				
CTE_{avg}	in/in/°F	5.19×10^{-6}	5.18×10^{-6}	5.21×10^{-6}
Compressive Strength	psi.	6,883	4,976	5,213

Table A - 37: Properties of concrete cores taken from slab number 3 along SC-80.

SC 80, Slab 3, specimens 3-1, 3-2, 3-3				
Specimen ID	unit	3-1	3-2	3-3
Core depth	in.	9-3/4”	9-3/4”	9-3/4”
Unit Weight	lbs/ft^3	147.91	148.68	149.34
	g/cc	2.369	2.382	2.392
W_{SSD}	g	3375.0	3391.8	3412.3
W_{SUB}	g	1954.1	1971.2	1989.4
Volume, V	cc	1424.46	1424.16	1426.47
Length, 1	mm	178.13	178.35	177.66
2	mm	178.78	178.31	178.22
3	mm	178.74	178.91	178.90
4	mm	178.27	178.23	178.94
Average Length , $L_\varnothing$	mm	178.480	178.450	178.430
Frame Correction, C_f	mm/mm/°C	17.417 x10^{-6}	16.256x10^{-6}	18.709x10^{-6}
Temperature, T_0	°C	23.93	23.93	23.93
T_1	°C	50.13	50.13	50.13
T_2	°C	10.36	10.36	10.36
T_3	°C	50.13	50.13	50.13
$\Delta T_0=T_1-T_0$	°C	26.20	26.20	26.20
$\Delta T_1=T_2-T_1$	°C	-39.77	-39.77	-39.77
$\Delta T_2=T_3-T_2$	°C	39.77	39.77	39.77
Length measured, L_0	mm	0.1072	0.1477	0.0931
L_1	mm	0.0694	0.1146	0.0541
L_2	mm	0.1288	0.1658	0.1214
L_3	mm	0.0702	0.1152	0.0547
$\Delta Lm_0=L_1-L_0$	mm	-0.0378	-0.0331	-0.0390
$\Delta Lm_1=L_2-L_1$	mm	0.0594	0.0512	0.0674
$\Delta Lm_2=L_3-L_2$	mm	-0.0585	-0.0506	-0.0668
$\Delta Lf_0=C_f*L_\varnothing*\Delta T_0$	mm	0.0815	0.0760	0.0875
$\Delta Lf_1=C_f*L_\varnothing*\Delta T_1$	mm	-0.1236	-0.1154	-0.1328
$\Delta Lf_2=C_f*L_\varnothing*\Delta T_2$	mm	0.1236	0.1154	0.1328
$\Delta La_0=\Delta Lm_0+\Delta Lf_0$	mm	0.0436	0.0429	0.0484
$\Delta La_1=\Delta Lm_1+\Delta Lf_1$	mm	-0.0643	-0.0641	-0.0654
$\Delta La_2=\Delta Lm_2+\Delta Lf_2$	mm	0.0651	0.0648	0.0660
$CTE_0=\Delta La_0/L_0/\Delta T_0$	mm/mm/°C	9.33x10^{-6}	9.17x10^{-6}	10.36x10^{-6}
$CTE_1=\Delta La_1/L_0/\Delta T_1$	mm/mm/°C	9.05x10^{-6}	9.04x10^{-6}	9.22x10^{-6}
$CTE_2=\Delta La_2/L_0/\Delta T_2$	mm/mm/°C	9.17x10^{-6}	9.12x10^{-6}	9.30x10^{-6}
$CTE_{avg1,2}$	mm/mm/°C	9.11x10^{-6}	9.08x10^{-6}	9.26x10^{-6}

Table A - 37 continued…				
CTE_{avg}	in/in/°F	$5.06x10^{-6}$	$5.05x10^{-6}$	$5.14x10^{-6}$
Compressive Strength	psi.	5,334	5,177	5,428

Table A - 38: Coefficient of thermal expansion of 28-day specimens using Tex-428-A Method

Specimen ID	CTE	
	$x10^{-6}$ mm/mm/°C	$x10^{-6}$ in/in/°F
MX1-28-1	8.547	4.748
MX1-28-2	8.610	4.784
MX1-28-3	8.743	4.857
MX2-28-1	9.422	5.234
MX2-28-2	9.446	5.248
MX2-28-3	9.321	5.178
MX3-28-1	8.889	4.938
MX3-28-2	8.889	4.939
MX3-28-3	8.772	4.873
MX4-28-1	8.494	4.719
MX4-28-2	8.800	4.889
MX4-28-3	8.637	4.799
MX5B-28-1	9.358	5.199
MX5B-28-2	9.381	5.211
MX5B-28-3	9.218	5.121
MX6-28-1	10.082	5.601
MX6-28-2	10.030	5.572
MX6-28-3	9.065	5.036
MXA-1	11.761	6.534
MXA-2	11.716	6.509
MXA-3	11.625	6.458
MXB-1	11.739	6.522
MXB-2	11.713	6.507
MXB-3	11.344	6.302

Table A - 39: Coefficient of thermal expansion of 90-day specimens using Tex-428-A Method

Specimen ID	CTE	
	x10^{-6} mm/mm/°C	x10^{-6} in/in/°F
MX1-90-1	8.777	4.876
MX1-90-2	8.805	4.892
MX1-90-3	8.573	4.763
MX2-90-1	9.898	5.499
MX2-90-2	9.944	5.524
MX2-90-3	9.747	5.415
MX3-90-1	8.757	4.865
MX3-90-2	8.790	4.883
MX3-90-3	8.919	4.955
MX4-90-1	9.533	5.296
MX4-90-2	9.461	5.256
MX4-90-3	9.120	5.066
MX5B-90-1	10.083	5.601
MX5B-90-2	10.035	5.575
MX5B-90-3	9.628	5.349
MX6-90-1	9.585	5.325
MX6-90-2	9.528	5.293
MX6-90-3	9.720	5.400