GDOT Research Project No. 10-04

Final Report

DETERMINATION OF COEFFICIENT OF THERMAL EXPANSION FOR PORTLAND CEMENT CONCRETE PAVEMENTS FOR MEPDG IMPLEMENTATION

Submitted by

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EXECUTIVE SUMMARY

The Coefficient of Thermal Expansion (CTE) is an important parameter in Portland Cement Concrete (PCC) pavement analysis and design as it is directly proportional to the magnitude of temperature-related pavement deformations throughout the pavement service life. Several studies in the past few years have classified the CTE as an extremely sensitive input in the Mechanistic-Empirical Pavement Design Guide (MEPDG) for structural design of rigid pavements, because the CTE affects slab stresses due to initial temperature-induced movements, corner deflections, joint faulting, pavement smoothness, and sawcut timing (ARA 2004).

All testing for this research was performed at the Georgia Pavement Research Center at Southern Polytechnic State University. Concrete samples having various aggregates and sands used in Georgia were tested for their CTEs at 28 days in accordance with the American Association of State Highway and Transportation Officials (AASHTO) T 336-11. Compressive strength tests were also conducted at 28 days for MEPDG inputs. The study investigated the effect of aggregate and sand types, aggregate gradations, percentages of coarse aggregate and fine sand on the CTE of concrete mixtures. Concrete specimens were fabricated in the laboratory to produce different mixes using Type I cement. Mix design variables were 1) coarse aggregate and fine sand types (Granite/Dolomite/Limestone, Manufactured sand/Natural sand) from a single source (quarry) for each type of aggregate, 2) fly ash types and contents (Class C/Class F, High/Low), 3) air-entraining admixture (3%/6%), and 4) aggregate contents (High/Low). For each combination of factors, five specimens from each batch were prepared for the

CTE measurements. Total number of specimens tested for the CTE measurements in this study was 340. In addition, three concrete cylinders from each batch were also prepared and subjected to compressive strength test at 28 days. Total number of specimens subjected to compressive strength test was 204. While preparing each batch, traditional tests on fresh-mixes (air content, slump, and unit weight) were also performed. The measured average CTE of concrete with limestone, granite and dolomite were as follows:

Coarse Aggregate	Average CTE	Standard Deviation
Limestone	3.836 με /°F (6.905 με /°C)	0.44 με /°F (0.792 με /°C)
Granite	4.751 με /°F (8.552 με /°C)	0.4 με /°F (0.72 με /°C)
Dolomite	4.847 με /°F (8.725 με /°C)	0.35 με /°F (0.63 με /°C)

The average CTE of limestone concrete mixtures was relatively lower than concrete mixtures composed of granite or dolomite. The results also showed that concrete composed of high stone volume of limestone with manufactured sand showed the lowest average CTE value of 3.367 με /°F (6.061 με /°C), while the highest average CTE was observed from the concrete made of the low stone volume of dolomite and siliceous natural sand with average CTE of 5.318 με /°F (9.573 με /°C). It was also found that the use of natural sand in concrete mix resulted in the increase of the CTE of concrete, and that an increase in the volume of coarse aggregate decreases the CTE for concretes.

Through other studies on MEPDG sensitive analyses, it can be mentioned that there are essentially no transverse cracking present in the limestone concrete pavements. However, attention is needed when concrete pavement is composed of granite or dolomite with natural sand due to the increase of CTE.

Based on the CTE test results, a multiple regression model was developed to estimate the CTE of granite and dolomite concretes as a function of coarse aggregate and sand types and their contents. The developed model can be used to estimate the CTE of a concrete mixture that is prepared based on typical concrete mix design of class I used by GDOT on PCC pavement. The prediction model gave an overall coefficient of determination R-square over 86% when all the test results were included in the analyses.

For the field validations, five concrete specimens were cored from rigid pavement sections. The specimens were composed of high stone volume of granite as “Gneiss/Amphibolite” and natural sand as “Alluvial/Marine Sand". The measured CTEs for specimens 1 through 5 are as follows:

Sample	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
CTE (με /°F)	4.932	4.998	4.685	5.030	4.909
CTE (με /°C)	8.878	8.996	8.433	9.054	8.836
Average	4.911 με /°F (8.840 με /°C)				

The predicted CTE from the model was 4.967 $\mu\varepsilon/^{o}$F (8.941 $\mu\varepsilon/^{o}$C) for a concrete mixture composed of granite and natural sand. The difference of measured and predicted CTE was 0.056 $\mu\varepsilon/^{o}$F (0.101 $\mu\varepsilon/^{o}$C), and it confirms that the developed model produces very consistent response predictions.

It was observed that fly ash type, fly ash content, and water cement ratio affect the concrete CTE to a certain extent, but those properties did not have as much influence on the concrete CTE as do the coarse aggregate and fine sand types. It is worthy to note that the average CTE of concrete mixtures with C-fly ash was higher than the average CTE of concrete with F-fly ash when both C- and F-fly ash contents were high. The difference between the average CTEs with high contents of F-fly ash and C-fly ash was approximately 0.291 $\mu\varepsilon/^{o}F$ (0.524 $\mu\varepsilon/^{o}C$). It can be concluded that fly ash type and content affect the concrete CTE when high contents of either C- or F-fly ash is used.

INTRODUCTION

Concrete expands as the temperature increases and contracts as the temperature decreases. The Coefficient of Thermal Expansion (CTE) explains this concrete behavior and it is defined by the change in unit length per unit change in temperature. The CTE is an important parameter in Portland Cement Concrete (PCC) pavement design as it is directly proportional to the magnitude of temperature-related pavement deteriorations both during early stage and in the long term. The CTE of concrete affects initial and long term temperature-induced movements such as curling and warping, corner deflections, joint faulting, pavement smoothness, and sawcut timing (ARA 2004).

Previous researchers have mentioned that the CTE value is influenced by aggregate type, aggregate volume, moisture state, and cement paste (Mallela et al. 2005, Tanesi 2007, Won 2005). As aggregates compose 60% to 75% of the concrete volume, the final concrete CTE can be significantly influenced by aggregate volume and raw aggregate CTE. The CTE also varies extensively among aggregates due to mineralogical differences. It has been illustrated that even same aggregate type can provide different CTEs when the mineralogical contents are different (FHWA 2011).

To consider significant effects of CTE on concrete behavior that is directly related to the rigid pavement design, AASHTO's new Mechanistic-Empirical Pavement Design Guide (MEPDG) incorporates the CTE measurement as a significant input parameter (Tran et al. 2008). The MEPDG provides three levels of reliability: Level 1 from actual tests resulting in highest level of reliability; Level 2 from calculations considering the state or regional individual CTEs of the aggregates and the cement paste; and Level 3 from the local database, default values for the region or based on type of coarse aggregate.

Level 1 input is desirable for heavy traffic pavement design since it provides the highest level of reliability for rigid pavement design. Level 2 provides an intermediate level of reliability while Level 3 provides the lowest level of reliability that could be used for the relatively less significant level of pavement design.

An increase in CTE has been found to significantly affect and increase the possibility of cracking, faulting, spalling, and the roughness of jointed plain concrete pavement (ARA 2004). The stresses induced by the concrete expansion and contraction with temperature changes result in transverse cracking, faulting, and joint spalling. To incorporate significant effects of CTE in MEPDG, the Georgia Department of Transportation (GDOT) has funded this study for the CTE database development in order to reduce concrete pavement distresses and improve pavement performance. The developed CTE database for different types of concrete mixes having various coarse aggregates, fine sands, and admixtures used in Georgia can provide the GDOT a better understanding of the variability of CTE values with different source of aggregates and abilities to successfully implement the CTE values into MEPDG.

The objectives of this research, therefore, were to develop a statewide database for CTE input values for the State of Georgia in accordance with the newly adopted CTE testing method (AASHTO T 336-11). A GDOT pavement engineer could then select appropriate CTE inputs considering the location of projects and various mix design variables not only for the structural designs of rigid pavement but also for forensic studies for pavement performance. To accomplish these objectives, the relationships between CTE and mix design variables such as coarse aggregate and sand types, coarse aggregate and fine sand proportions in mixture, and type and proportion of fly ash were investigated.

With the successful implementation of MEPDG, the GDOT will be able to provide accurate designs of rigid pavements minimizing pavement deteriorations and saving to the state of Georgia.

LITERATURE REVIEW

Over a decade, the Federal Highway Administration (FHWA) conducted CTE measurements using more than 1800 sample cores and concrete samples from the Long-Term Pavement Performance Program (LTPP) test sections in accordance with AASHTO TP-60. The FHWA has monitored the results as follows:

TABLE 1

CTE Measurements from LTPP

Coarse Aggregate	Average CTE
Limestone	4.5 με /°F (8.1 με / °C)
Quartzite	7.5 με /°F (13.5 με /°C)

From the LTPP data analysis, it was concluded that PCC with igneous aggregates showed relatively lower CTE compared to PCC made from sedimentary aggregates. It was also found that the CTE value significantly affected MEPDG in terms of percentage of slab cracking, but had less impact on the faulting and international roughness index (IRI) (Mallela et al. 2005, Tanesi 2007). Tanesi (2007) described that if the CTE is 5 με /°F, the change of CTEs of 0.9 με /°F will result in an increase in the percent slabs cracked of approximately 6%, while if the CTE is 6.5με /°F, a change of CTEs of only 0.5 με /°F will have more than double that effect. It was concluded that higher CTE values correspond to a decrease in pavement performance.

Effect of Aggregate Types

Mallela et al. (2005) conducted CTE measurements with 673 cores obtained throughout the United States as part of the LTPP and found that concrete mixtures with igneous aggregates shows relatively lower CTE values than those with sedimentary rock. The CTE values were 5.2 με /°F (9.4 με /°C) for mixtures with igneous aggregates and 6.0 με /°F (10.8 με /°C) for with sedimentary rock, respectively.

Jahangirnejad et al. (2009) conducted experiments on concrete specimens after the average 28 day to measure CTE for concrete cylinders, and it was found that the CTE values of specimens composed of limestone coarse aggregate were relatively less than those for CTEs of specimens composed of gravel, dolomite, and igneous rock. The CTE values of concrete specimens containing limestone showed the lowest CTE values in his study. The results are as follows:

TABLE 2

CTE Measurements by Jahangirnejad et al. (2009)

Coarse Aggregate	CTE value
Limestone	4.44 to 4.51 με /°F (8.0 to 8.11 με /°C)
Dolomite	5.87 to 5.92 με /°F (10.57 to 10.65 με /°C)
Gravel	5.84 με /°F (10.52 με /°C)
Slag	5.71 με /°F (10.27 με /°C)
Igneous Rock	5.41 με /°F (9.73 με /°C)

Similar results were reported by Alungbe et al. (1992) describing that river gravels produced the highest CTE of concrete while limestone rock produced the lowest concrete CTE. It should be noted that the variation over the normal range of cement contents may not be as great as the effect of aggregate type on concrete CTE although the concrete CTE depends on cement content (Mindess, Young, and Darwin, 2002). Neville and Brooks (1987) showed thermal expansion coefficients variation of concrete along with different aggregate types and it is observed that the aggregate type significantly affects the CTE of concrete mixture.

TABLE 3

CTE of concretes made with different aggregates by Neville and Brooks. (1987)

	Linear CTE			
	Air-Cured Concrete		Water-Cured Concrete	
Type of Aggregate	$\mu\varepsilon/^{o}C$	$\mu\varepsilon/^{o}F$	$\mu\varepsilon/^{o}C$	$\mu\varepsilon/^{o}F$
Gravel	13.1	7.3	12.2	6.8
Granite	9.5	5.3	8.6	4.8
Quzrtzite	12.8	7.1	12.2	6.8
Dolerite	9.5	5.3	8.5	4.7
Sandstone	11.4	6.5	10.1	5.6
Limestone	7.4	4.1	6.1	3.4
Portland Stone	7.4	4.1	6.1	3.4
Blast-Furnace Slag	10.6	5.9	9.2	5.1
Foamed Slag	12.1	6.7	9.2	5.1

Effect of Fine Sand Type and Volume on Mortar CTE

Mindess, Young, and Darwin (2002) showed that the CTE of the mortar increases when the siliceous sand volume increases while the CTE of the mortar decreases when the limestone sand volume increases as shown in Figure 1. Figure 1 shows the significant impact of sand type and content in the mixture on the CTE of mortar.

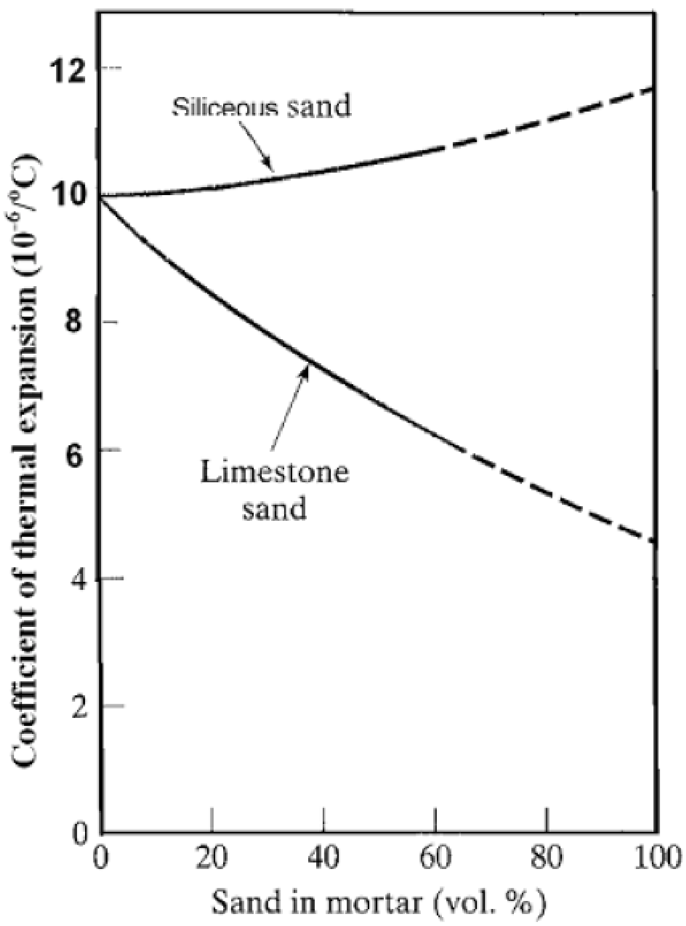

FIGURE 1

Aggregate Volume and Mineralogy Effects on the CTE of Mortar

Effect of Water-Cement Ratio on CTE

Alungbe et al. (1992) studied the effect of water-cement ratio on CTE of concrete and it was found that water-cement ratio did not show any significant effect on the concrete

CTE. The similar results were found by Mindness, Young, and Darwin (2002) from tests conducted on cement pastes with water-cement ratios of 0.4, 0.5, 0.6.

Effect of Concrete Age on CTE

Won (2005) found that the average measured CTE for limestone was 4.44 με /°F (8.0 με /°C) while the CTE containing gravel coarse aggregate ranges from 4.50 to 7.22 με /°F (8.1 to 13.0 με /°C). Won (2005) concluded that there was a linear relationship between percent volume of coarse aggregate in the concrete mixture and the resultant CTE. Based on the recent findings by Won (2005), the effect of the rate of heating and cooling is negligible, and coarse aggregate type and content in the concrete mix has a significant effect on concrete CTE.

Won (2005) also studied the effects of specimen age on CTE and concluded that the CTE values changed very little during the 3 week period, and specimen age has a negligible effect on CTE. This finding confirms previous findings that the age of the concrete has little effect on CTE by Alungbe (1992). However, Jahangirnejad et al. (2009) described that the CTE values at 28 days was significantly lower than the CTE measured at 90 and 180 days for most aggregate types. The CTE differences between 28-day and 180-day measurements were ranging from 0.08 με /°F (0.144 με /°C) to 0.52 με /°F (0.936 με /°C).

Effect of CTE on Pavement Performance

Tanesi et al. (2007) studied the effects of CTE on pavement performance by using the MEPDG software and he found that the CTE affects transverse cracking significantly while faulting and IRI have less impacts. Results showed that increasing the CTE value from 5.5 με /°F (9.90 με / °C) to 6.5 με /°F (11.7 με / °C) turned out to be approximately 32% increase in transverse cracking.

Summary

In summary, the CTE value of concrete mixture is generally influenced by coarse aggregate and sand types, volumetric proportion of coarse aggregate and sand, age of the concrete sample, moisture condition, and water cement ratio. While all these factors affect the CTE values to some degree, previous studies emphasize that aggregate geology and volumetric proportion of coarse aggregate and sand have the most significant effect on CTE, while the other factors have a relatively small effect on the CTE value.

LABORATORY TESTINGS

As previously discussed, researchers have made efforts to study several factors that affect the CTE values of concrete. To properly take those factors into consideration on the CTE measurements of concrete mixtures containing locally available aggregates based on locally selected mix design, it is important to prepare concrete specimens properly.

Concrete Mix Design

The mix designs that are currently used in PCC pavement construction in Georgia have been utilized for this study since the purpose of this study is to develop the database of CTE from actual PCC mixtures. Typical concrete mix design of Class I used by GDOT on PCC pavement is tabulated in Table 4. Table 5 shows mix design variables utilized in this study. Three types of coarse aggregates (Limestone, Granite, and Dolomite), and two types of sands, which are Granite Gneiss Manufactured Sand (MS) and Alluvial/Marine natural sand (NS), were taken into consideration.

TABLE 4

GDOT Concrete Mix Design

Class 1 PCCP Mix Design Properties									
			Cementitious Content		Fine Aggregate Content				
Contractor	Project	Mix No.	Cement	Fly Ash	NS	SM	FM	Stone Vol.	W/C Ratio
APAC	NHS-0005-00(071)(088) 01 Glynn								
	NH-IM-95-1(117)01 Glynn-McIntosh	#1	541	0	1214			11.45	0.471
APAC	NHS-0005-00(071)(088) 01 Glynn								
	NH-IM-95-1(117)01 Glynn-McIntosh	#5	460	102	1166			11.83	0.428
APAC	NHS-0005-00(071)(088) 01 Glynn								
	NH-IM-95-1(117)01 Glynn-McIntosh	#2	460	102	1253			10.93	0.454
Lane	NH-IM-20-2(145)01	#2	478	94	946			12.36	0.499
Lane	NH-IM-20-2(145)01	#3	509	71	917			12.54	0.493
Lane	NH-IM-20-2(145)01	#4	541	0	943			12.75	0.524
McCarthy	csnhs-008-00(232) 01 Troup		460	101	1085			12.26	0.448
Archer Western	HPP-NH-75-1(156)01 Crisp		465	114	1225			11.3	0.424
APAC	CSNHS-M003-00(158)01 Cobb-Douglas		459	102	1085			11.89	0.45
McCarthy	NH-IM-520-1(15)01 Columbia		487	81	1191			10.84	0.499
McCarthy	CSNHS-M003-00(480)01 Fulton	#4B	460	101	1189			12.29	0.386
McCarthy	CSNHS-M003-00(480)01 Fulton	#4	460	101	1086			12.29	0.445
McCarthy	NHS-M002-00(434)01 Coweta	#48	460	101	1189			12.29	0.386
McCarthy	NHS-M002-00(434)01 Coweta	#4	460	101	1086			12.29	0.445
McCarthy	NHS-M002-00(434)01 Coweta	#2	460	162	1026			12.14	0.422
McCarthy	NHS-M002-00(434)01 Coweta	#1	541	0	1062			12.57	0.469
Archer Western	MSL-003-00(161)01 Coweta-Meriwether		465	114	241		960	11.45	0.437
Archer Western	CSNHS-M002-00(965)01 Cobb-Bartow-Cherokee		465	114	231		923	11.67	0.446
Scruggs	NH-75-1(204)01 Cook		487	68	1490			9.99	0.45
Scruggs	NH-75-1(204)01 Cook	#1	487	68	1490			9.99	0.45
	NH-75-1(204)01 Cook	#2	487	68	1550			9.79	0.443
Archer Western	NH-056-1(59)01								
	CSSTP-0007-00(239)01 Fulton-Forsyth	#1 w/F ash	480	110	475	712		10.87	0.438
Archer Western	NH-056-1(59)01								
	CSSTP-0007-00(239)01 Fulton-Forsyth	#2 w/C ash	465	114	241	963		11.28	0.462
Archer Western	NH-75-1(206)01 Cook-Tift								
	CSNHS-0006-00(073)01		465	114	1250			11.42	0.4
Scruggs	FLF-540(11)01 Crawford-Peach		465	110	1435			9.39	0.453
J.A.Long	IM-185-1(326)01 Muscogee		541	0	1245			11.91	0.431
APAC/Lafarge	NH-0075-01(246)01 Bibb		541	0	1293			10.9	0.508
APAC/Lafarge	NH-0075-01(246)01 Bibb		476	84	1304			10.9	0.466

TABLE 5

Mix Design Variables

[1]Coarse aggregate	[2]Fine aggregate	[3,4]Fly Ash Class	[3,4]Fly Ash content	[5]Air Content	[1]Stone Volume	Total
Limestone	MS/NS	C	High	Low	High/Low	4
Granite	MS/NS	C/F	High/Low	High/Low	High/Low	32
Dolomite	MS/NS	C/F	High/Low	High/Low	High/Low	32

Notes:

[1]Coarse aggregate: No. 57 Limestone, Granite, and Dolomite, 2100 lb/yd^3 for high stone volume per cubic yards of concrete, and 1150 lb/yd^3 for low stone volume mixes

[2]Fine aggregate: No. 10 Manufactured Sand (MS) and Natural Sand (NS), 950 lb/yd^3 for high stone volume, and 1900 lb/yd^3 for low stone volume mixes

[3]Cement: Type I Portland cement, 530 lb/yd^3 for low Fly Ash mixes, and 460 lb/yd^3 for high Fly Ash mixes

[4]Fly Ashes: Class C and Class F, 20 lb/yd^3 for low Fly Ash mixes, and 160 lb/yd^3 for high Fly Ash mixes

[5]Air Content: The dosage of admixture depending on the target air content of the mix, 3% air for low and 6% for high air content mixes

*the amount of water depending on the target slump, and 2 inch-slump is target for all mixes

Gradations of raw aggregate and sand delivered are shown in Figures 2 and 3. Raw coarse aggregates and fine sands from quarries satisfy No. 57 and No. 10 grading requirements, separately, in ASTM C33 specification, “Standard Specification for Concrete Aggregates”.

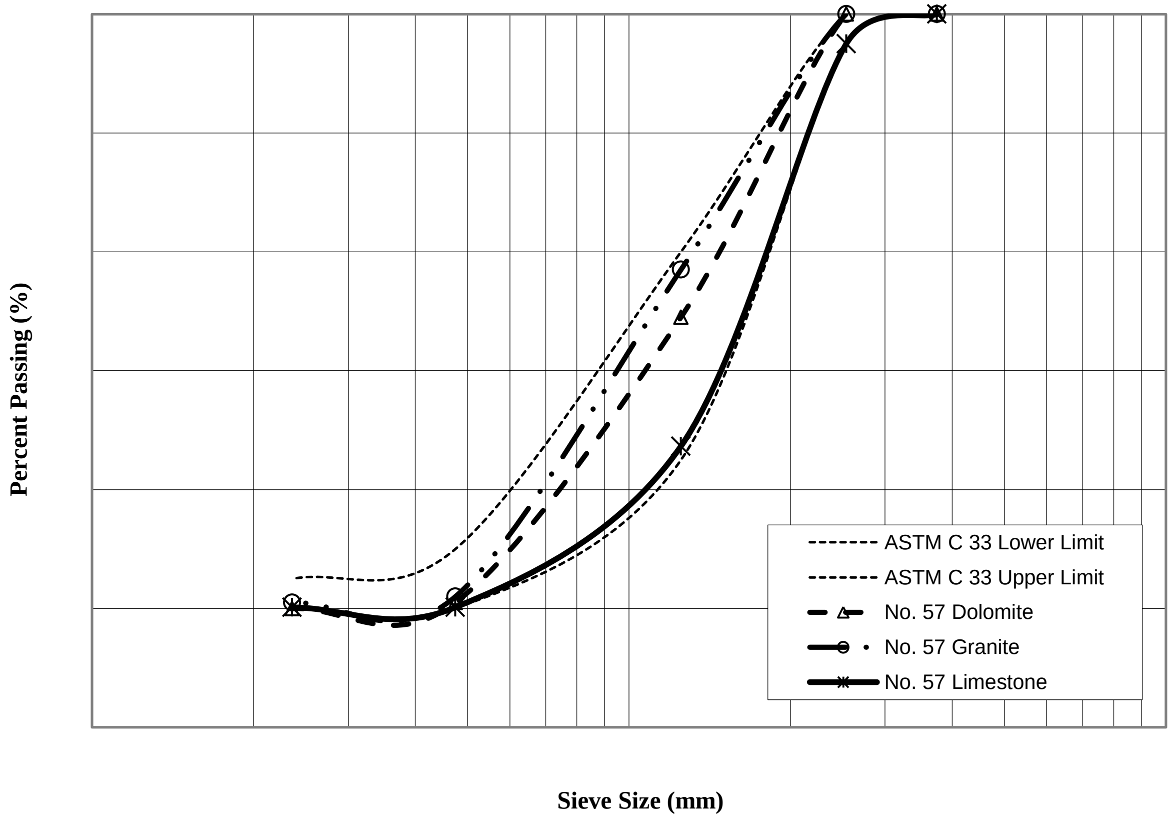

FIGURE 2

No. 57 Gradation of Coarse Aggregates

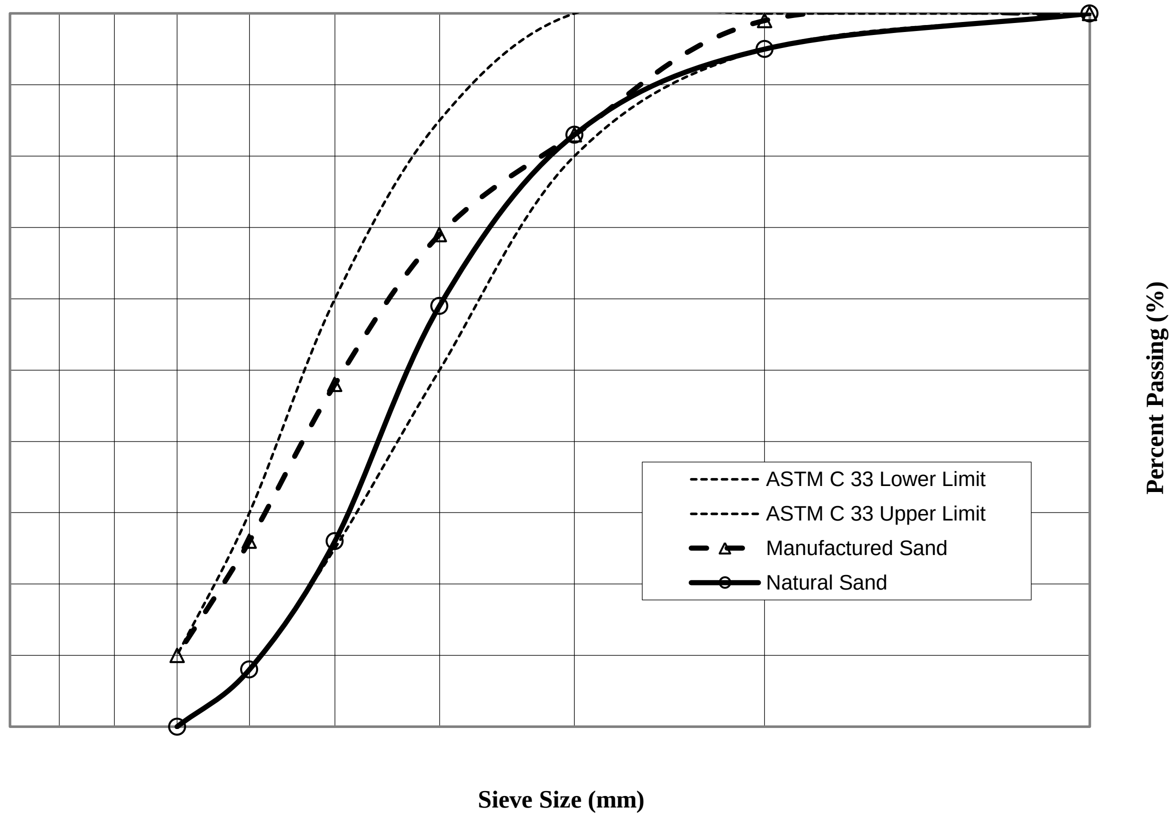

FIGURE 3

Gradation for MS and NS

In summary, the mix designs that are commonly used in PCC pavement construction in Georgia have been utilized for this study to develop the database for the CTE of actual PCC mixture. Mix design variables are 1) coarse aggregate type (Limestone/Granite/Dolomite), 2) fine sand types (MS/NS), 3) fly ash classes (Class C/Class F), 4) fly ash contents (High/Low), 5) air-entraining admixture (3%/6%), and 6) stone volume (High/Low). For each combination of factors, five (5) specimens were prepared from the mixer for the CTE measurement and additional three specimens were prepared for compressive strength test. The total number of specimens tested for the CTEs and compressive strength tests in this study were 340 and 204, respectively.

Concrete Batching and Mixing

Table 6 summarizes CTE identification number, batch number and properties of mixes. To properly account for the effect of aggregate content changes on the CTEs, the slump was held approximately 2-inch on all the concrete mixture designs, by adjusting the amount of water used in the mixes, and thus the water cement ratio varied from 0.5 to 0.6. The concrete mixing procedure was in accordance with AASHTO T 126 using portable drum mixer. While preparing each batch, traditional tests on fresh-mixes (ASTM C 231 Air content using pressure meter, ASTM C 143 Slump test, and ASTM C 31 Molding the Specimens) were also performed. The exact batch weights were adjusted and scaled down to produce enough concrete mixes for all the tests; slump test, air content, five 4”x 8” cylinders for CTE test, and three 6”x 12” cylinders for compressive strength test.

TABLE 6

Concrete Mix Design for Concrete Cylinders

CTE No.	Batch No.	Granite (lb/yd^3)	Dolomite (lb/yd^3)	Limestone (lb/yd^3)	MS (lb/yd^3)	NS (lb/yd^3)	C-Ash (lb/yd^3)	F-Ash (lb/yd^3)	Cement (lb/yd^3)	Air Content	Slump
1	1	2100	0	0	950	0	20	0	530	3%	2"
2	2	2100	0	0	950	0	20	0	530	6%	2"
3	17	2100	0	0	950	0	160	0	460	3%	2"
4	18	2100	0	0	950	0	160	0	460	6%	2"
5	33	2100	0	0	950	0	0	20	530	3%	2"
6	34	2100	0	0	950	0	0	20	530	6%	2"
7	49	2100	0	0	950	0	0	160	460	3%	2"
8	50	2100	0	0	950	0	0	160	460	6%	2"
9	5	2100	0	0	0	950	20	0	530	3%	2"
10	6	2100	0	0	0	950	20	0	530	6%	2"
11	21	2100	0	0	0	950	160	0	460	3%	2"
12	22	2100	0	0	0	950	160	0	460	6%	2"
13	37	2100	0	0	0	950	0	20	530	3%	2"
14	38	2100	0	0	0	950	0	20	530	6%	2"
15	53	2100	0	0	0	950	0	160	460	3%	2"
16	54	2100	0	0	0	950	0	160	460	6%	2"
17	3	1150	0	0	1900	0	20	0	530	3%	2"
18	4	1150	0	0	1900	0	20	0	530	6%	2"
19	19	1150	0	0	1900	0	160	0	460	3%	2"
20	20	1150	0	0	1900	0	160	0	460	6%	2"
21	35	1150	0	0	1900	0	0	20	530	3%	2"
22	36	1150	0	0	1900	0	0	20	530	6%	2"
23	51	1150	0	0	1900	0	0	160	460	3%	2"
24	52	1150	0	0	1900	0	0	160	460	6%	2"
25	7	1150	0	0	0	1900	20	0	530	3%	2"
26	8	1150	0	0	0	1900	20	0	530	6%	2"
27	23	1150	0	0	0	1900	160	0	460	3%	2"
28	24	1150	0	0	0	1900	160	0	460	6%	2"
29	39	1150	0	0	0	1900	0	20	530	3%	2"
30	40	1150	0	0	0	1900	0	20	530	6%	2"
31	55	1150	0	0	0	1900	0	160	460	3%	2"
32	56	1150	0	0	0	1900	0	160	460	6%	2"
33	9	0	2100	0	950	0	20	0	530	3%	2"
34	10	0	2100	0	950	0	20	0	530	6%	2"

TABLE 6 (Continued)

Concrete Mix Design for Concrete Cylinders

CTE No.	**Batch No.**	**Granite** (lb/yd^3)	**Dolomite** (lb/yd^3)	**Limestone** (lb/yd^3)	**MS** (lb/yd^3)	**NS** (lb/yd^3)	**C-Ash** (lb/yd^3)	**F-Ash** (lb/yd^3)	**Cement** (lb/yd^3)	**Air Content**	**Slump**
35	25	0	2100	0	950	0	160	0	460	3%	2"
36	26	0	2100	0	950	0	160	0	460	6%	2"
37	41	0	2100	0	950	0	0	20	530	3%	2"
38	42	0	2100	0	950	0	0	20	530	6%	2"
39	57	0	2100	0	950	0	0	160	460	3%	2"
40	58	0	2100	0	950	0	0	160	460	6%	2"
41	13	0	2100	0	0	950	20	0	530	3%	2"
42	14	0	2100	0	0	950	20	0	530	6%	2"
43	29	0	2100	0	0	950	160	0	430	3%	2"
44	30	0	2100	0	0	950	160	0	430	6%	2"
45	45	0	2100	0	0	950	0	20	530	3%	2"
46	46	0	2100	0	0	950	0	20	530	6%	2"
47	61	0	2100	0	0	950	0	160	460	3%	2"
48	62	0	2100	0	0	950	0	160	460	6%	2"
49	11	0	1150	0	1900	0	20	0	530	3%	2"
50	12	0	1150	0	1900	0	20	0	530	6%	2"
51	27	0	1150	0	1900	0	160	0	460	3%	2"
52	28	0	1150	0	1900	0	160	0	460	6%	2"
53	43	0	1150	0	1900	0	0	20	530	3%	2"
54	44	0	1150	0	1900	0	0	20	530	6%	2"
55	59	0	1150	0	1900	0	0	160	460	3%	2"
56	60	0	1150	0	1900	0	0	160	460	6%	2"
57	15	0	1150	0	0	1900	20	0	530	3%	2"
58	16	0	1150	0	0	1900	20	0	530	6%	2"
59	31	0	1150	0	0	1900	160	0	460	3%	2"
60	32	0	1150	0	0	1900	160	0	460	6%	2"
61	47	0	1150	0	0	1900	0	20	530	3%	2"
62	48	0	1150	0	0	1900	0	20	530	6%	2"
63	63	0	1150	0	0	1900	0	160	460	3%	2"
64	64	0	1150	0	0	1900	0	160	460	6%	2"
65	65	0	0	2100	950	0	160	0	460	3%	2"
66	66	0	0	1150	1900	0	160	0	460	3%	2"
67	67	0	0	2100	0	950	160	0	460	3%	2"
68	68	0	0	1150	0	1900	160	0	460	3%	2"

Appendix A contains the gradations for each of the aggregate and sand source. The nominal maximum aggregate size used in this study was 1" for limestone, 3/4" for granite, and 1/2" for dolomite, separately. Coarse aggregate gradations were performed for each aggregate sample based on the American Society for Testing and Materials (ASTM) C33 specifications. It was found that all coarse aggregates satisfied No. 57 gradation specification. The delivered raw limestone was used to prepare concrete specimens because one of the objectives of this study was to develop the CTE database of concrete composed of locally available aggregate sources. Further, Table 7 summarizes approximate location of aggregate source, primary aggregate classification, and physical properties of the aggregate.

TABLE 7

Aggregate Physical Properties

Aggregates	Coarse Aggregate Location in GA	Aggregate Group	Absorption (%)	Magnesium Sulfate Soundness Loss, %	Specific Gravity		
					Bulk	S.S.D	APP
Granite (118C)	Columbus	II	0.62	0.8	2.677	2.693	2.722
Dolomite (120C)	Adairsville	I	0.64	0.5	2.805	2.823	2.857
Limestone (013C)	Dalton	I	0.63	0.4	2.702	2.719	2.749

Sample Preparation

The concrete samples were subjected to hardening with 4 in. by 8 in. (100 mm by 200 mm) plastic cylinder molds as shown in Figure 4. The samples were trimmed with 4 in. by 7 in. sample size for AASHTO T 336-11 using an electric-power saw blade as shown in Figure 5. Three concrete cylinders from each batch were prepared for the compressive strength tests with sample size of 150-mm (6-in.) in diameter and 300-mm (12-in.) in length as shown in Figure 6. The concrete specimens were moved and cured in the curing room.

FIGURE 4
Concrete Sample Preparation

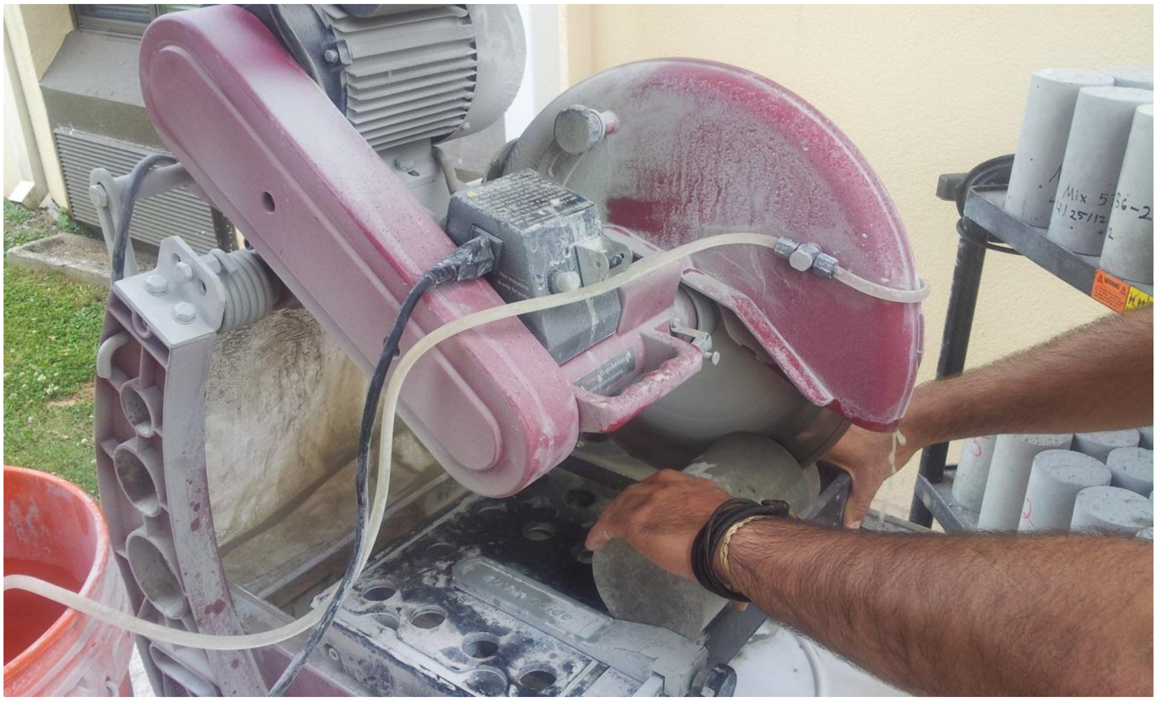

FIGURE 5

Saw-cutting Sample

FIGURE 6

Sample Preparation for compressive strength tests

CTE Measurements

With the previously known effects of the CTE value in concrete pavement design, it was apparent that extensive research would be needed for accurate CTE measurements for successful MEPDG implementation. The AASHTO TP 60 was the provisional standard to determine PCC CTE and it was developed to provide a practical and rapid basis for ascertaining this important material property in the laboratory. This protocol was based on the test method and apparatus developed by researchers at FHWA. In this test procedure, standard specimens are subjected to a uniform increase (10°C to 50°C) and decrease (50°C to 10°C) in temperature. The length change is measured as a result of the heating and cooling cycles, and the CTE is computed as the average change in length of the material for unit change in temperature. The test is repeated until the difference between the CTEs of two consecutive temperature cycle is less that 0.2 $\mu\varepsilon/^{o}F$ (0.3 $\mu\varepsilon/°C$). Because the influence of the moisture condition on the CTE is significant and the maximum value usually occurs at 60 to 70 % relative humidity, a controlled temperature water bath is used to eliminate the effect of the moisture condition variation. The fully saturated condition is a reasonable approach because pavements in the field have an internal relative humidity of 80% or more, except surface (Mallela et al., 2005).

However, recently an error was observed in the AASHTO TP 60 regarding the calibration of the testing equipment which directly affects the determination of the concrete CTE (FHWA 2011, Tanesi et al, 2007). The FHWA recently noticed that AASHTO TP 60 provisional test method uses the incorrect literature value of 9.6 $\mu\varepsilon/^{o}F$ (17.3 $\mu\varepsilon/^{o}C$) for a reference specimen (304 stainless steel) calibration factor determination to account for the apparatus expansion. The use of incorrect CTE values resulted in much higher CTEs than the ones obtained in accordance with ASTM E 228-06, which as widely accepted test method to measure the CTE of metals.

Due to the overestimation of CTE from AASHTO TP 60, AASHTO recently adopted AASHTO T 336-11 as the new standard test method. Therefore, AASHTO T 336-11 was used to measure CTEs of concrete mixture in this study. The testing method of AASHTO T 336-11 remains relatively the same and Figure 7 shows the equipment setup that was used for CTE measurement. Pine Instrument Company's AFCT2 system was purchased for determining the Coefficient of Thermal Expansion (CTE) of concrete samples to meet the requirements of the AASHTO T336-11 protocol in Appendix B. The equipment is designed to test concrete samples over a temperature range of 10°C to 50°C.

FIGURE 7

CTE Measurement Equipment (Courtesy by Pine Instrument)

The frame and two concrete specimens were placed in the water bath with fully saturated condition throughout the test. The protocol was then initiated using AFCT2 software interaction. According to the test procedure the saturated concrete specimen was subjected to a consistent increase in temperature from 50 to 122 ^{o}F (10 to 50 ^{o}C) followed by a consistent decrease in temperature from 122 to 50 ^{o}F (50 to 10 ^{o}C). Length change readings were recorded every 1 minute during the heating and cooling cycles. The heating CTEs are measured when temperature changes from 10 to 50 ^{o}C while the cooling CTEs are measured when temperature changes from 50 to 10 ^{o}C. Then the difference between the heating and cooling CTEs are checked. If the difference between those two CTE values is less than 0.2 $\mu\varepsilon$ / ^{o}F (0.3 $\mu\varepsilon$ / ^{o}C), the software calculates the CTE_{avg} by taking the average of the extension and contraction CTEs. If the difference between the heating and heating CTEs is greater than 0.2 $\mu\varepsilon$ / ^{o}F (0.3 $\mu\varepsilon$ / ^{o}C), the test is repeated until the difference is within the error range. Figure 8 displays an example of sample summary report and the heating and cooling cycle that a concrete specimen would be subjected to. Appendix C displays the CTE results for each specimen during heating and cooling cycle.

Coefficient of Thermal Expansion Report 4/18/2012

Project:	GDOT RP 10-04
Laboratory:	
Technician:	GPRC
Comment:	

		F1	F2	
Specimen Identification		Mix 16/2	Mix 16/3	
Specimen Diameter	mm			
Specimen L_0	mm	179.02	179.66	
Frame S/N		133722	133723	
Frame Cf	mm/mm/°C	20.400E-6	19.722E-6	
FCS Serial No.		102801c	102801e	
FCS CTE	mm/mm/°C	10.296E-6	10.296E-6	
T_1	°C	50.05	50.05	
T_2	°C	10.05	10.05	
T_3	°C	50.05	50.05	
$\Delta T_1 = T_2 - T_1$	°C	-40.00	-40.00	
$\Delta T_2 = T_2 - T_1$	°C	40.00	40.00	
L_1	mm	-0.28300	-0.07597	
L_2	mm	-0.20626	-0.00442	
L_3	mm	-0.28236	-0.07408	
$\Delta L_{m1} = L_2 - L_1$	mm	0.07675	0.07154	
$\Delta L_{m2} = L_3 - L_2$	mm	-0.07610	-0.06966	
$\Delta L_{f1} = Cf^*L_0^*\Delta T_1$	mm	-0.14608	-0.14172	
$\Delta L_{f2} = Cf^*L_0^*\Delta T_2$	mm	0.14607	0.14172	
$\Delta L_{a1} = \Delta L_{m1} + \Delta L_{f1}$	mm	-0.06933	-0.07018	
$\Delta L_{a2} = \Delta L_{m2} + \Delta L_{f2}$	mm	0.06996	0.07206	
$CTE_1 = \Delta L_{a1}/L_0/\Delta T_1$	mm/mm/°C	9.682E-6	9.766E-6	
$CTE_2 = \Delta L_{a2}/L_0/\Delta T_2$	mm/mm/°C	9.771E-6	10.028E-6	
CTE_{avg}	**mm/mm/°C**	**9.727E-6**	**9.897E-6**	

CTE_{avg}	**in/in/°F**	**5.404E-6**	**5.499E-6**	

Test Parameters	
Number of Segments Required	2
Segment CTE Match Tol. (mm/mm/°C)	3.00E-6
Temperature In-Range Tolerance (°C)	1.0
LVDT Stability Tolerance (mm)	0.00025
LVDT Stability Interval (min)	10
LVDT Stability Span (min)	30
Hold Time (Hours)	0

Comments:

FIGURE 8

Sample Summary Report of CTE System

CTE TEST RESULTS AND DISCUSSIONS

Total CTE test results are shown in Appendix C. The results are summarized in Tables 8 through 11and Figures 9 through 14.

Effect of Aggregate Type and Aggregate Gradation on CTE

Figures 9 and 10 show the effect of coarse aggregate and sand types on CTE. The measured average CTE of concrete with limestone, granite and dolomite were as follows:

Coarse Aggregate	Average CTE	Standard Deviation
Limestone	3.836 με /°F (6.905 με /°C)	0.44 με /°F (0.792 με /°C)
Granite	4.751 με /°F (8.552 με /°C)	0.4 με /°F (0.72 με /°C)
Dolomite	4.847 με /°F (8.725 με /°C)	0.35 με /°F (0.63 με /°C)

The average CTE of limestone concrete mixtures was significantly lower than concrete mixtures composed of granite or dolomite. The results also showed that concrete composed of high stone volume of limestone with manufactured sand showed the lowest average CTE value of 3.367 με /°F (6.061 με /°C); while, the highest average CTE was observed from the concrete made of the low stone volume of dolomite and siliceous natural sand with average CTE of 5.318 με /°F (9.573 με /°C). These results are in good agreement with previous studies (FHWA 2011).

It should be also noted that uniform gradation with larger maximum aggregate size were observed when raw granite was delivered compared to dolomite. It is possible that the particle size distribution of aggregate could affect the concrete CTEs. To verify the effect of gradation, additional 10 concrete specimens were prepared. Then, the CTE measurements were conducted on 10 additional concrete specimens composed of granite and MS/NS with same gradation as the dolomite mixtures. Table 8 shows the average CTEs of concrete composed of granite and dolomite with MS and NS when the same gradations in the entire coarse/fine aggregate mixes were used in specimen preparations. In Table 8, the average CTE of concrete mixtures composed of granite is relatively lower than concrete mixture composed of dolomite even if same gradations are used to prepare concrete mixtures. The comparison of Tables 8 and 9 shows that aggregate gradation and type affect the CTE of concrete. Therefore, it can be concluded that aggregate gradation, type and mineralogy have significant impacts on CTE of concrete mixture.

TABLE 8

Comparison of averaged CTE values – Granite vs. Dolomite with same gradations

Coarse Aggregate	Sand Type	Average CTE		Standard Deviation	
		(με/°F)	(με/°C)	(με/°F)	(με/°C)
Granite	MS	4.155	7.479	0.052	0.093
Granite	NS	4.917	8.851	0.043	0.078
Dolomite	MS	4.579	8.242	0.127	0.229
Dolomite	NS	5.150	9.270	0.221	0.398

TABLE 9

Comparison of averaged CTE values – Granite vs. Dolomite with Original Gradations from Quarry

Coarse Aggregate	Sand Type	Average CTE		Standard Deviation	
		(με/°F)	(με/°C)	(με/°F)	(με/°C)
Granite	MS	4.413	7.944	0.117	0.211
Granite	NS	5.089	9.160	0.255	0.458
Dolomite	MS	4.579	8.242	0.127	0.229
Dolomite	NS	5.150	9.270	0.221	0.398

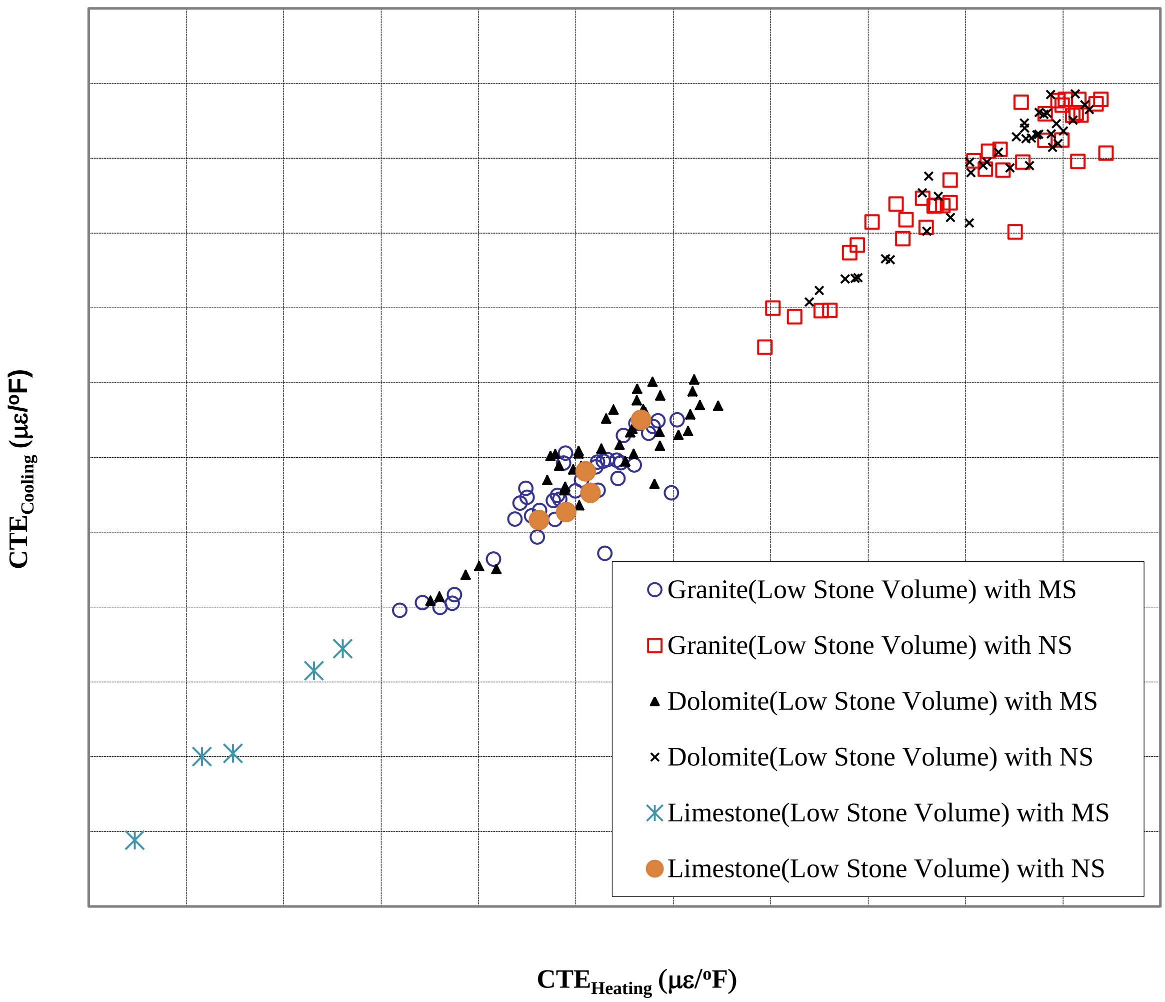

FIGURE 9
Effect of Coarse Aggregate and Sand Types on CTE (Low Stone Volume).

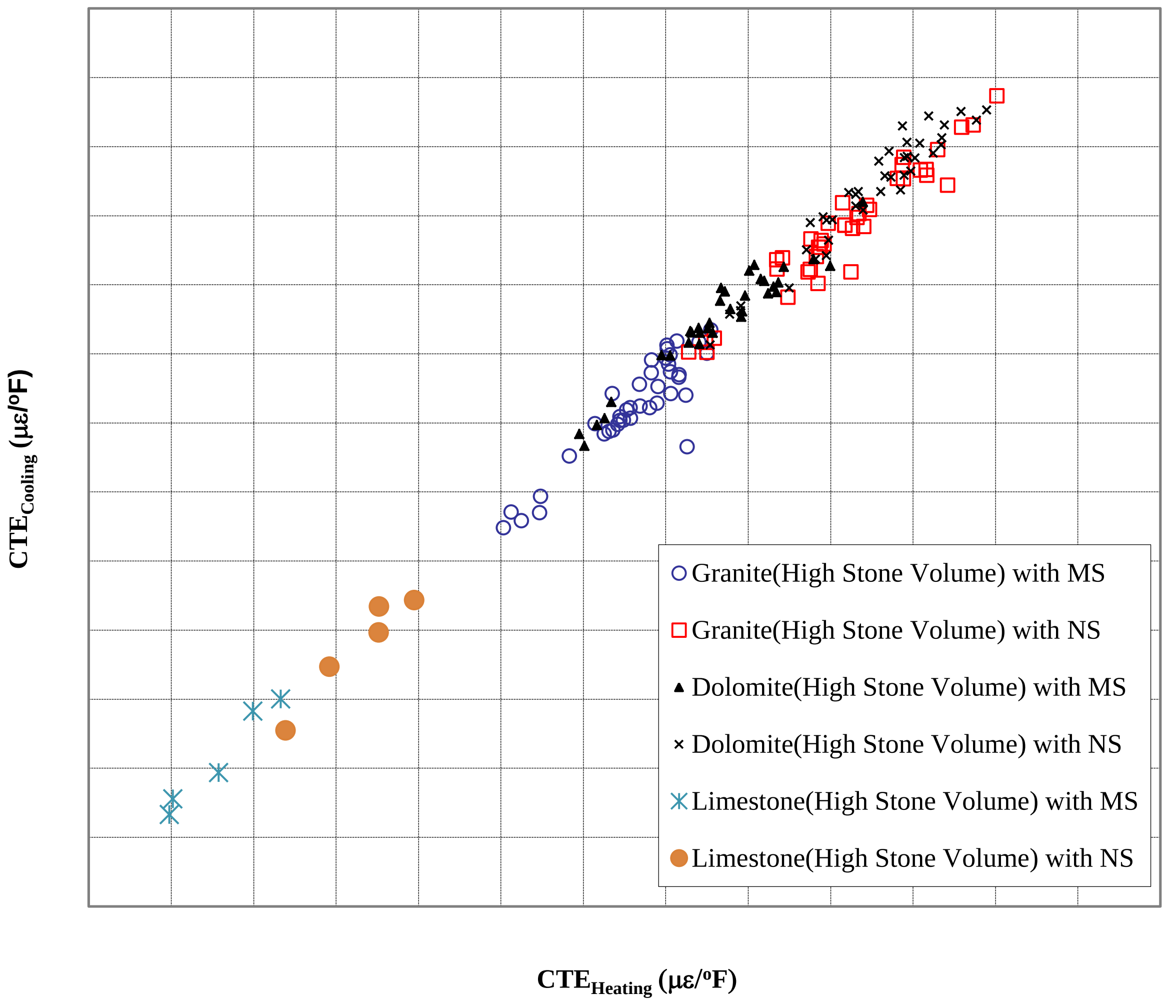

FIGURE 10
Effect of Coarse Aggregate and Sand Types on CTE (High Stone Volume).

Effect of Sand Type on CTE

Figure 11 shows the effect of sand type on concrete CTE. For each aggregate type, the lowest and highest CTEs were observed when concrete specimens were composed of MS and NS, respectively, and the difference between lowest and highest CTEs were more than 0.43 με /°F (0.77 με /°C). It demonstrates the significant effect of mineralogical contents of fine sand on CTE. MS used in concrete specimen was made from granitic and gneissic rocks while NS was made from alluvial marine siliceous rocks. This result confirms the effect of fines on CTE by Mindess, Young, and Darwin (2002).

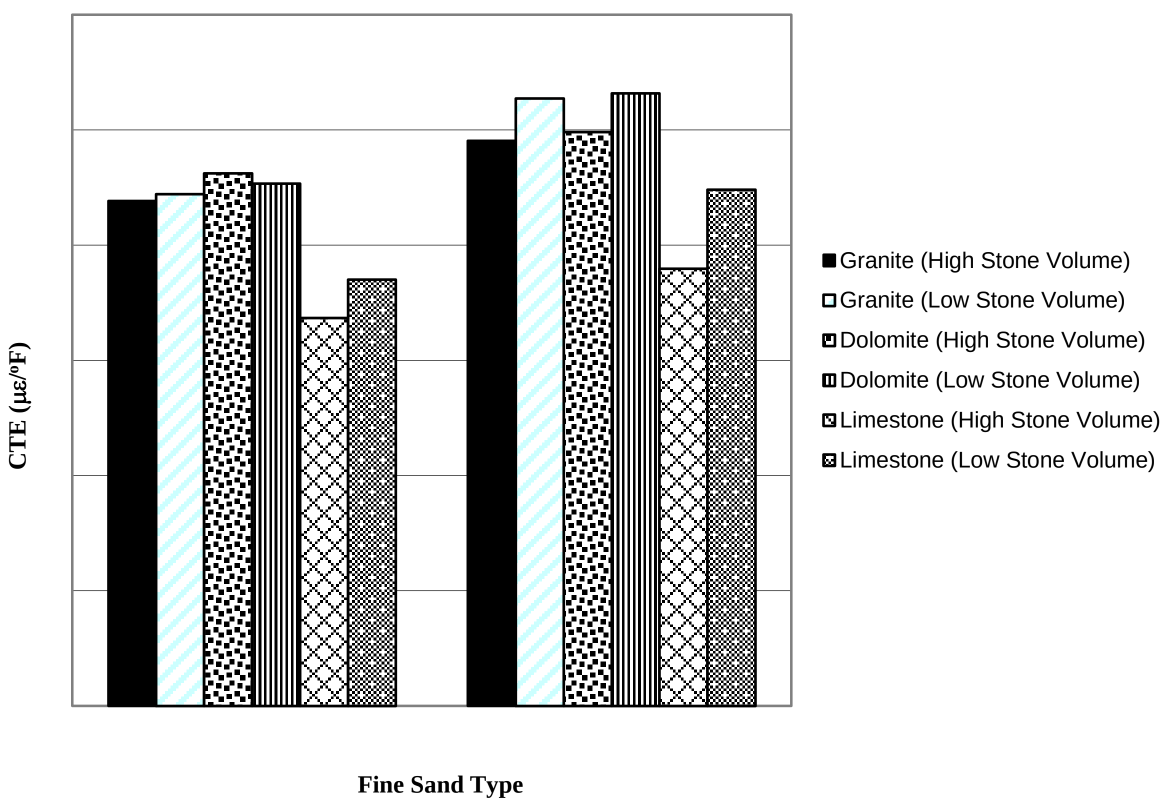

FIGURE 11
Effect of Sand Type on CTE.

Figures 9, 10, and 11 show that the CTE of concrete specimens increases significantly when NS content increases in concrete mixture compared to MS content increases. Generally, the CTEs of high stone volume of concrete mixtures with MS were less than 4.8 με /°F (8.64 με /°C), while the CTEs of high stone volume of concrete mixture with NS was over 4.8 με /°F (8.64 με /°C) except limestone concrete. The CTEs of low stone volume of concrete mixture also follow a similar trend. It demonstrates that sand type significantly affects the CTE of concrete and that an increase of siliceous NS increases the concrete CTE. The average CTE of concrete composed of coarse dolomite and NS increased by 13% compared to the CTE of specimen composed of coarse dolomite and MS, while the average CTE of concrete with coarse granite and NS increased by 15% compared to the CTE of specimen with coarse granite and MS. The average CTE of limestone concrete with NS increased by 17 % compared to the CTE of limestone concrete with MS. It implies that the effect of sand type in concrete mixture on CTE is significant.

Effects of Coarse Aggregate Proportion on CTE

A significant effect of stone volume on CTE was observed when fine aggregate type was NS. The average CTE of concrete composed of granite or dolomite with NS was decreased more than 0.34 με /°F (0.612 με /°C) when high stone volume of coarse aggregate was used. Especially, the average CTE of limestone concrete with NS was decreased about 0.686 με /°F (1.235 με /°C) when high stone volume of coarse aggregate was used. However, there were no significant CTE changes were observed when fine aggregate type was MS as shown in Figures 12 and 13, and Table 10.

TABLE 10
Comparison of averaged CTE values – Stone Volume High vs. Low

Coarse Aggregate	Stone Volume	Sand Type	Average CTE		Standard Deviation	
			(με/°F)	(με/°C)	(με/°F)	(με/°C)
Granite	High	MS	4.384	7.891	0.115	0.208
		NS	4.906	8.831	0.168	0.303
	Low	MS	4.442	7.996	0.119	0.214
		NS	5.272	9.490	0.184	0.332
Dolomite	High	MS	4.623	8.322	0.126	0.228
		NS	4.982	8.967	0.152	0.273
	Low	MS	4.534	8.162	0.120	0.216
		NS	5.318	9.573	0.131	0.235
Limestone	High	MS	3.367	6.06	0.13	0.233
		NS	3.795	6.831	0.193	0.348
	Low	MS	3.701	6.661	0.137	0.247
		NS	4.481	8.067	0.106	0.19

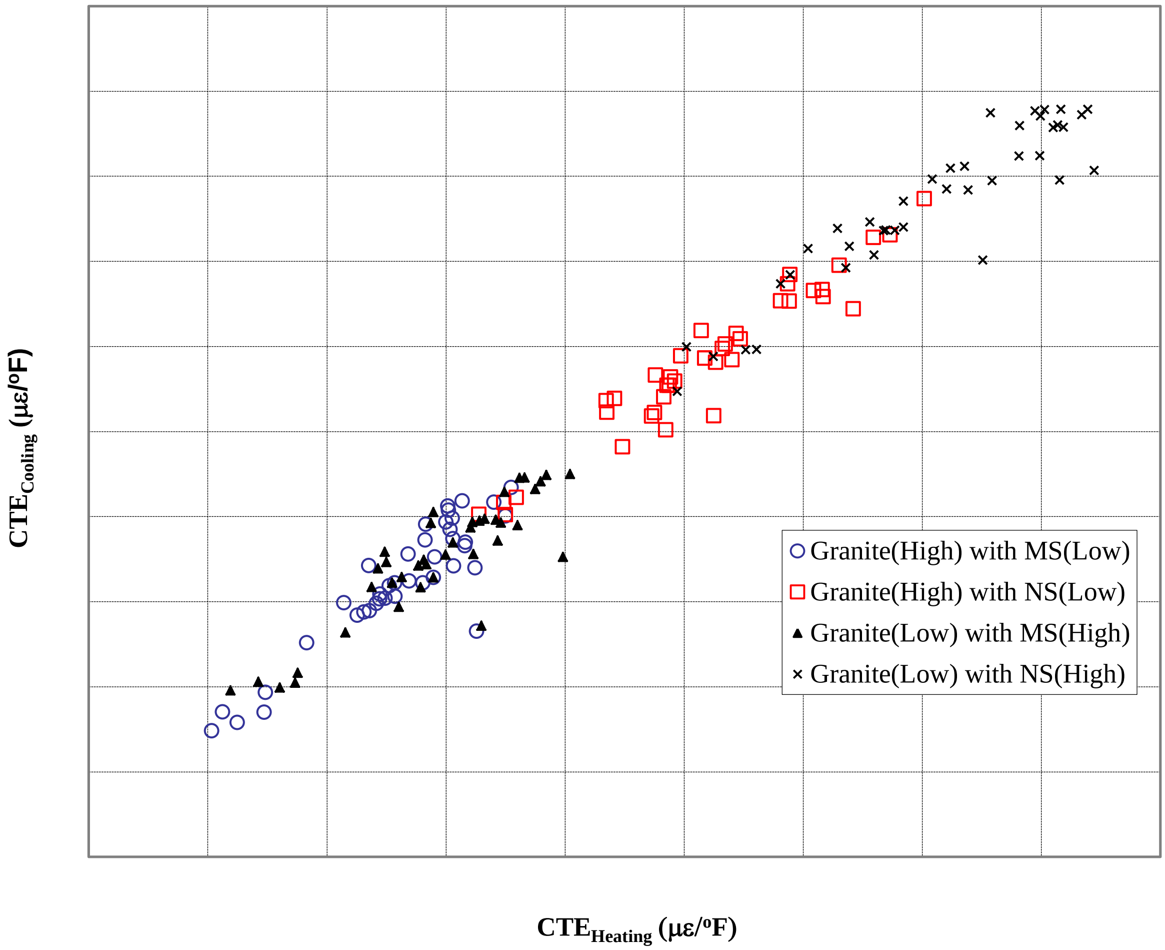

FIGURE 12

Effect of Coarse Aggregate Stone Volume on CTE (Granite)

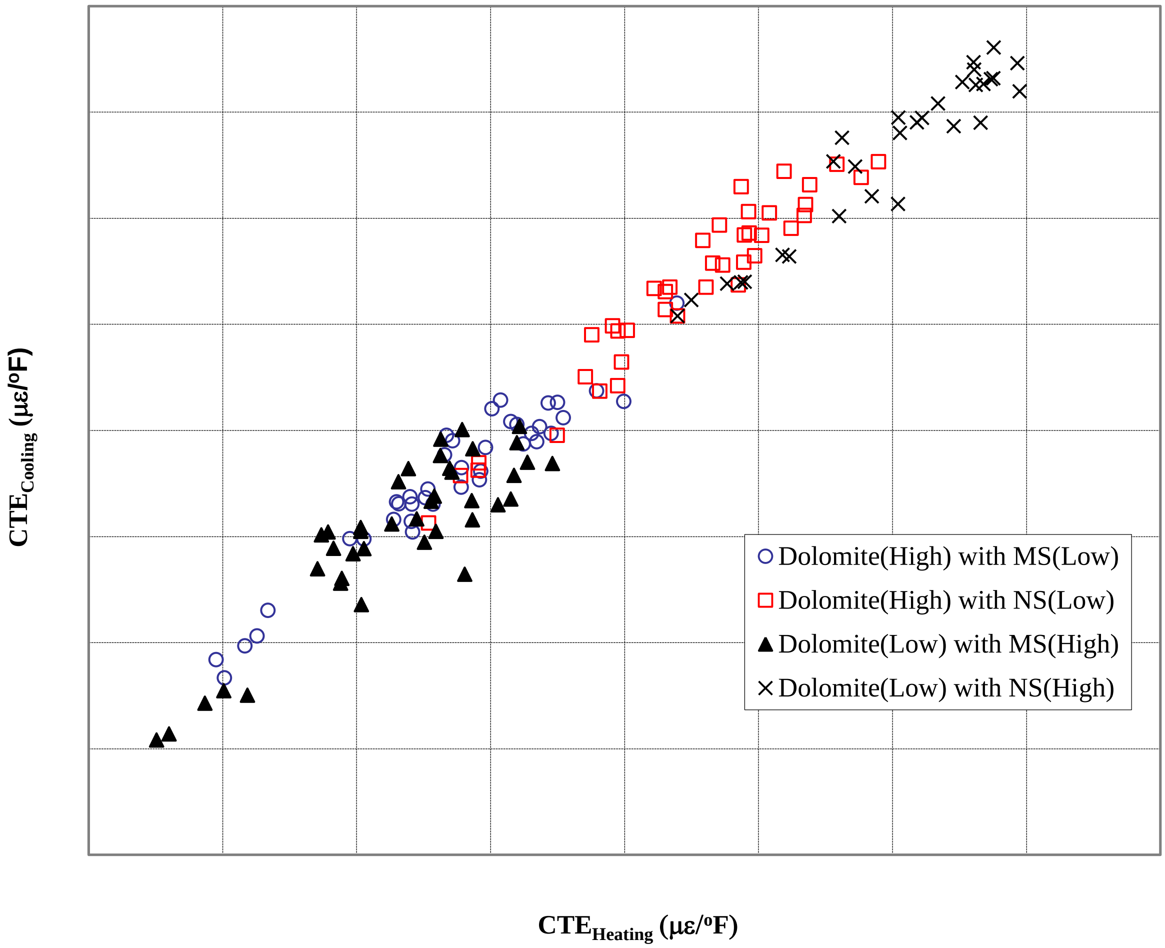

FIGURE 13

Effect of Coarse Aggregate Stone Volume on CTE (Dolomite)

Effects of Fly Ash Types and contents on CTE

Table 11 shows the effect of fly ash type and content. No significant influence on CTE was observed when the fly ash content was low. When the fly ash content is high, however, the average CTE of concrete mixture with C-Fly Ash was higher than the CTEs of concrete with F-fly ash. The difference between the average CTE values with high content of F-fly ash and C-fly ash was approximately 0.291 με/°F (0.524 με/°C).

TABLE 11
Comparison of averaged CTE values – Fly Ash Content High vs. Low

Coarse Aggregate	Volume	Sand Type	Average CTE (με/°F)				Average CTE (με/°C)			
			C-Fly Ash		F-Fly Ash		C-Fly Ash		F-Fly Ash	
			Low	High	Low	High	Low	High	Low	High
Granite	High	MS	4.384	4.481	4.454	4.216	7.892	8.065	8.017	7.590
		NS	5.046	4.990	4.895	4.694	9.082	8.982	8.811	8.448
	Low	MS	4.439	4.593	4.454	4.284	7.990	8.268	8.017	7.710
		NS	5.426	5.429	5.218	5.017	9.766	9.772	9.392	9.030
Dolomite	High	MS	4.735	4.681	4.636	4.440	8.523	8.426	8.345	7.993
		NS	5.128	5.085	4.938	4.776	9.231	9.153	8.889	8.596
	Low	MS	4.640	4.598	4.549	4.351	8.351	8.277	8.189	7.831
		NS	5.456	5.393	5.277	5.147	9.821	9.707	9.499	9.264

Summary

It was found that the CTE of concrete is significantly influenced by aggregate type, stone volume, and sand type as shown in Figure 14. The selection of coarse aggregate, stone volume and sand types provides an approach towards lowering the concrete CTE. Figure 15 shows the average CTE values of concrete mixtures containing different types and stone volumes of aggregate and sand. The lowest CTE was observed from concrete composed of high stone volume of limestone and MS while the highest CTE was observed from concrete composed of low stone volume of dolomite and NS.

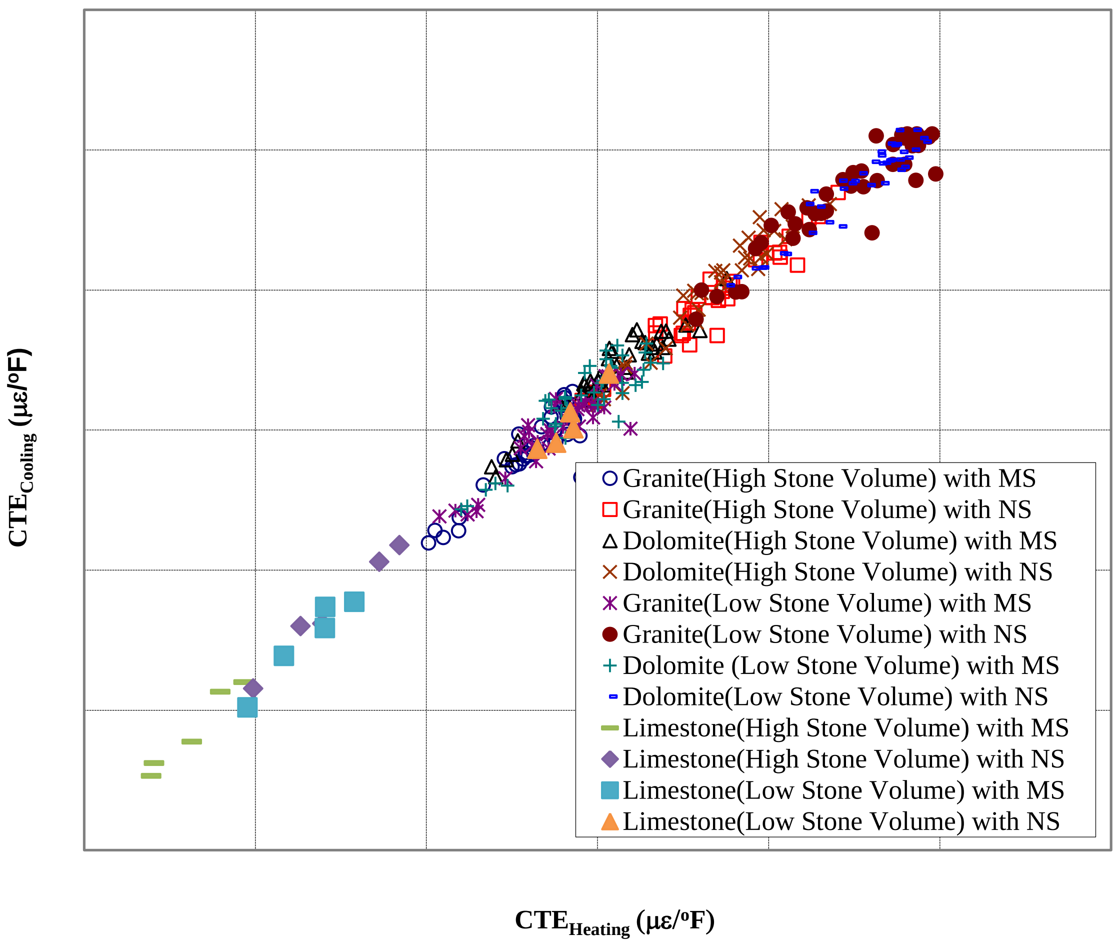

FIGURE 14

CTE Results along with Aggregate and Sand Types with Different Stone Volume

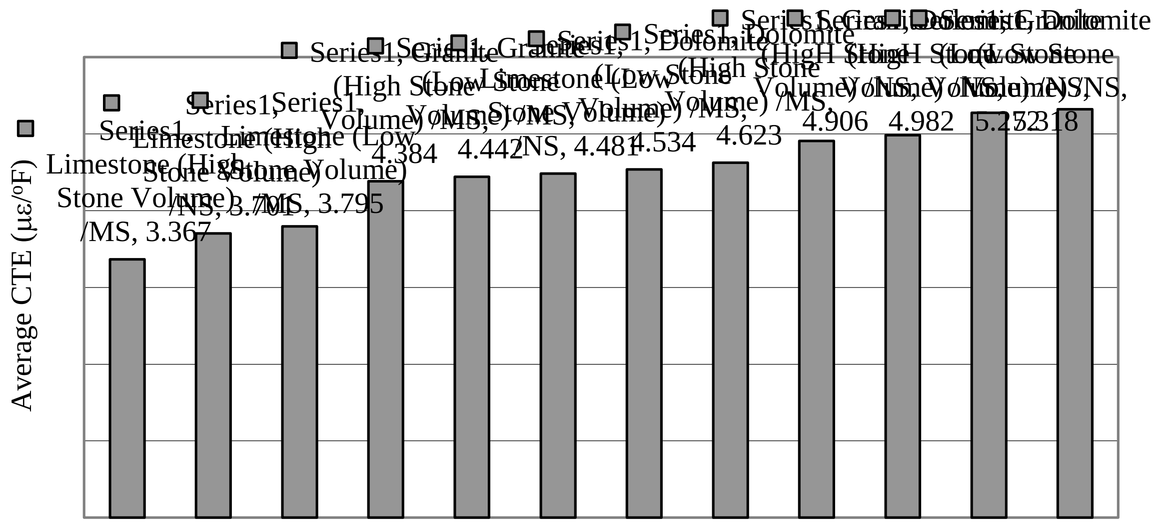

FIGURE 15

Average CTE of Concrete Mixtures along with Aggregate Types and Contents

COMPRESSIVE STRENGTH TEST

Compressive strength tests were conducted with three concrete cylinders from each batch shown in Table 6. Total of 192 compressive strength tests were conducted in accordance with ASTM C 39 and the load at failure was recorded and displayed in Table 12. The average 28-day compressive strength test results are shown in Table 12. It was observed that all compressive strength test results of concrete mixtures containing high stone volume of granite and dolomite satisfy the minimum 28-day compressive strength of 3000 psi required by GDOT. However, most of concrete mixtures containing low stone volume of granite and dolomite didn't satisfy the minimum 28-day compressive strength requirement. The MEPDG allows estimating splitting tensile strength from compressive strength of concrete for the level 2 input. Compressive strength of concrete (f'_c) is converted to modulus of rupture (MR) based on Equation (1):

$$MR = 9.5\sqrt{f_c^{'}}$$

Where, MR = modulus of rupture and f'_c = 28 days compressive strength (psi). MR is then multiplied by 0.67 to estimate 28 days splitting tensile strength of concrete. The estimated splitting tensile strength is shown in Table 12. From Tables 12 and 13, it was generally observed that the concrete mixture with higher compressive strengths showed lower CTE values. The concrete mixture containing high stone volume of coarse aggregate with MS showed the highest average f'_c values as summarized in Table 13. From the test results, it is recommended that GDOT pays close attention to check f'_c requirement and CTE values when low stone volume of dolomite or granite with NS concrete mix is used since the CTEs of those concrete are typically higher than 4.8 $\mu\varepsilon$/°F (8.64 $\mu\varepsilon$/°C) and generally don't satisfy f'_c requirement.

TABLE 12

Mechanical Properties of Specimens

CTE No.	CTE ($\mu\varepsilon/^oF$)	Compressive Strength (psi)	Splitting Tensile Strength (psi)	CTE No.	CTE ($\mu\varepsilon/^oF$)	Compressive Strength (psi)	Splitting Tensile Strength (psi)
CTE 1	4.399	3,250	363	CTE 35	4.710	4,290	417
CTE 2	4.370	3,146	357	CTE 36	4.652	3,275	364
CTE 3	4.438	3,662	385	CTE 37	4.636	3,379	370
CTE 4	4.524	3,400	371	CTE 38	4.636	3,023	350
CTE 5	4.423	3,949	400	CTE 39	4.501	3,078	353
CTE 6	4.485	3,254	363	CTE 40	4.380	3,607	382
CTE 7	4.251	3,494	376	CTE 41	5.109	3,722	388
CTE 8	4.182	3,352	369	CTE 42	5.147	3,220	361
CTE 9	4.926	3,381	370	CTE 43	5.041	3,799	392
CTE 10	5.165	3,016	350	CTE 44	5.129	3,311	366
CTE 11	4.903	3,499	376	CTE 45	4.933	3,520	378
CTE 12	5.077	3,538	379	CTE 46	4.944	3,001	349
CTE 13	4.822	3,445	374	CTE 47	4.816	4,136	409
CTE 14	4.967	3,246	363	CTE 48	4.736	3,235	362
CTE 15	4.694	3,052	352	CTE 49	4.627	3,419	372
CTE 16	4.693	3,075	353	CTE 50	4.653	3,134	356
CTE 17	4.424	3,125	356	CTE 51	4.618	2,580	323
CTE 18	4.454	3,130	356	CTE 52	4.578	2,821	338
CTE 19	4.590	3,307	366	CTE 53	4.555	3,116	355
CTE 20	4.597	3,015	350	CTE 54	4.544	3,104	355
CTE 21	4.425	3,186	359	CTE 55	4.372	2,803	337
CTE 22	4.482	3,040	351	CTE 56	4.330	2,405	312
CTE 23	4.305	3,095	354	CTE 57	5.451	2,399	312
CTE 24	4.262	2,865	341	CTE 58	5.461	2,842	339
CTE 25	5.455	2,090	291	CTE 59	5.399	2,475	317
CTE 26	5.396	2,141	295	CTE 60	5.387	2,202	299
CTE 27	5.419	2,415	313	CTE 61	5.332	2,438	314
CTE 28	5.439	2,578	323	CTE 62	5.222	2,959	346
CTE 29	5.251	1,898	277	CTE 63	5.179	2,065	289
CTE 30	5.184	1,923	279	CTE 64	5.114	2,815	338
CTE 31	5.040	1,385	237	CTE 65	3.367	3,111	355
CTE 32	4.993	1,781	269	CTE 66	3.795	3,192	360
CTE 33	4.691	3,076	353	CTE 67	3.701	3,487	376
CTE 34	4.779	3,002	349	CTE 68	4.481	3,042	351

TABLE 13
Averaged CTE, Compressive Strength, and Splitting Tensile Strength Results

Coarse Aggregate	Stone Volume	Sand Type	Average CTE (με/°F)	Average Compressive Strength (psi)	Splitting Tensile Strength (psi)
Granite	High	MS	4.384	3,438	373
		NS	4.906	3,281	365
	Low	MS	4.442	3,095	354
		NS	5.272	2,026	286
Dolomite	High	MS	4.623	3,341	368
		NS	4.982	3,493	376
	Low	MS	4.534	2,923	344
		NS	5.318	2,524	320
Limestone	High	MS	3.367	3,111	355
		NS	3.701	3,487	376
	Low	MS	3.795	3,192	360
		NS	4.481	3,041	351

MULTIPLE REGRESSION MODEL

The tests provided the information for an extensive database, and this database offered the opportunity to ascertain whether CTE could be predicted from material content of the mixture such as weight of coarse aggregate, fly ash, and cement. Based on the CTE test results, a multiple regression model was developed as given in Equation (2) to estimate the CTE as a function of coarse aggregate and sand types and contents.

Equation (2) is to estimate the CTEs for concrete mixture composed of granite or dolomite with MS or NS. A regression model for limestone concrete was not developed due to the lack of data. Equation (2) gave an overall coefficient of determination R-square over 86% when all the test results were included in the analyses.

$$\begin{pmatrix} CTE_{G/M} \\ CTE_{D/M} \\ CTE_{G/N} \\ CTE_{D/N} \end{pmatrix} = \begin{pmatrix} 5.81 \\ 5.79 \\ 4.57 \\ 4.48 \end{pmatrix} + \begin{pmatrix} -0.000453 & 0 & -0.000459 & 0 \\ 0 & -0.000371 & -0.000429 & 0 \\ -0.000073 & 0 & 0 & 0.000435 \\ 0 & 0.000057 & 0 & 0.000429 \end{pmatrix} \begin{pmatrix} Granite \\ Dolomite \\ MS \\ NS \end{pmatrix} \begin{pmatrix} R^2 = 86.2\% \\ R^2 = 87.9\% \\ R^2 = 86.9\% \\ R^2 = 87.9\% \end{pmatrix} \quad (2)$$

where,

$CTE_{G/M}$= CTE of Concrete Composed of Granite and MS ($\mu\varepsilon/^{o}F$);

$CTE_{D/M}$= CTE of Concrete Composed of Dolomite and MS ($\mu\varepsilon/^{o}F$);

$CTE_{G/N}$= CTE of Concrete Composed of Granite and NS ($\mu\varepsilon/^{o}F$);

$CTE_{D/N}$= CTE of Concrete Composed of Dolomite and NS ($\mu\varepsilon/^{o}F$);

Granite = Granite Content in lb/yd^3 (ranging from 1150 to 2100);

Dolomite = Dolomite Content in lb/yd^3 (ranging from 1150 to 2100);

MS = Manufactured Sand Content in lb/yd^3 (ranging from 950 to 1900); and

NS = Natural Sand Content in lb/yd^3 (ranging from 950 to 1900).

From Equation (2), the CTE decreases when coarse aggregate and MS contents increase. Equation (2) also shows that the CTE increases when NS content increases in the mixture. The CTE results predicted using Equation (2) suggest that high volume of coarse aggregate with MS generally provide better concrete performance with lower CTE than concrete composed of low volume of aggregate with NS. Figure 165 shows the comparisons between the measured average CTE and the CTE predicted using the developed multiple regression model. The data points shown in Figure 16 are centered on the equality line with a high correlation coefficient (R-square) of over 86%. This implies that the prediction model is in good agreement with the CTE measured in the lab and the use of proportion of mixing materials.

With better and more accurate predictions of the CTE, a more structurally adequate rigid pavement can be designed. Since the regression model defines how to estimate the CTE, it provides a tool or guide for the estimation of the CTE of concrete composed of locally available aggregate in Georgia. However, Equation (2) is developed based on the CTE of concrete prepared using single quarry materials and thus, additional CTE database development from different quarry could be useful to validate Equation (2).

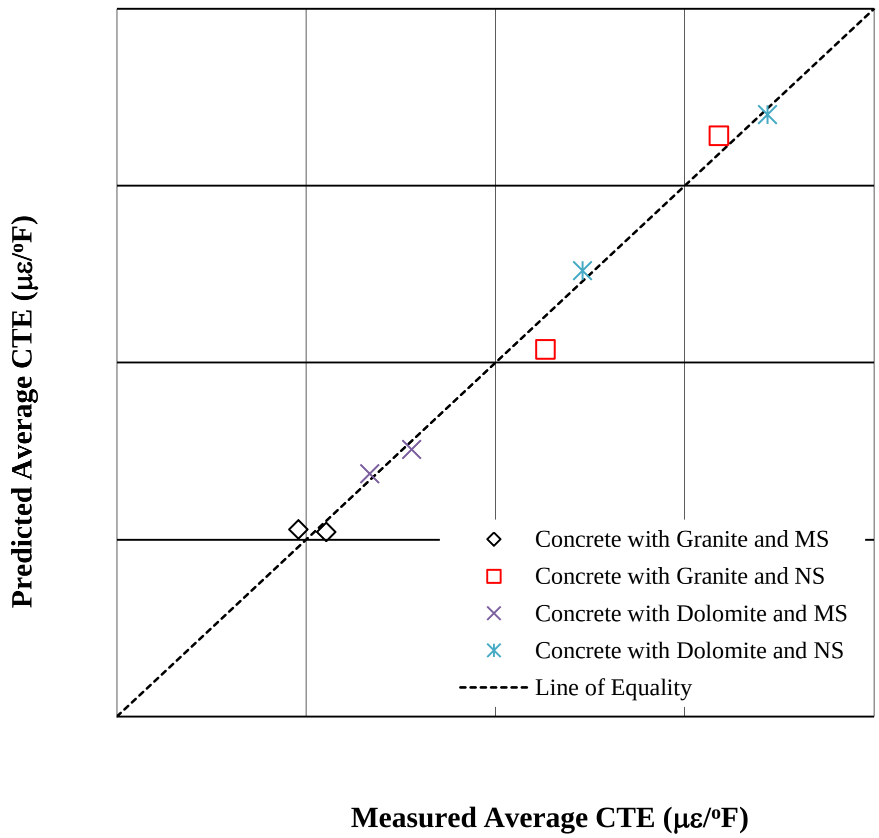

FIGURE 16

Comparison of Measured and Predicted CTEs

FIELD VALIDATIONS

To validate the models that were developed to estimate the CTEs using only aggregate and sand type and contents, five specimens were cored from concrete pavement section newly constructed in 2012 as shown in Figure 17.

FIGURE 17

Cored Specimens from Test Section

These five samples were cored from concrete pavement section because they were mixed with locally available aggregate and sand materials and batched to satisfy the GDOT specification requirement. The specimens were composed of high stone volume of granite as “Gneiss/Amphibolite” and natural sand as “Alluvial/Marine Sand". Concrete properties were obtained from the original mix design in 2012 before the concrete placement and that is the same period of time that laboratory experiments were conducted for this study. These concrete properties are presented in Table 14.

The measured CTEs for specimens 1 through 5 are as follows:

Sample	Specimen 1	Specimen 2	Specimen 3	Specimen 4	Specimen 5
CTE (με /°F)	4.932	4.998	4.685	5.030	4.909
CTE (με /°C)	8.878	8.996	8.433	9.054	8.836
Average	4.911 με /°F (8.840 με /°C)				

The predicted CTE from Equation (1) was 4.967 $\mu\varepsilon/^{o}F$ (8.941 $\mu\varepsilon/^{o}C$) for concrete mixture composed of granite and NS and the difference of measured and predicted CTE was 0.056 $\mu\varepsilon/^{o}F$ (0.101 $\mu\varepsilon/^{o}C$). By considering coefficient of variation of 0.0275 and the prediction error of only 1.1%, it can be concluded that the CTE prediction can be developed using aggregate type and content and the developed model produces very consistent response predictions.

TABLE 14
Concrete Mixture Design of Cored Specimens

Class Concrete	Class 1
Cement (lbs)	460
C-Flyash (lbs)	102
Sand (lbs)	1239
Stone (lbs)	1938
Water (gals)	28.8
Design Air (%)	4.5
Fine Aggregate Ratio	0.4
Stone Size	#57
Design Slump (inches)	1
Max. Water/yd^3	35.8

TIME FACTOR AFFECTING CTE OF CONCRETE

As shown in previous chapters, several researchers have investigated that the concrete CTE is influenced by aggregate type, aggregate volume, moisture state, and cement paste (Mallela et al. 2005, Tanesi 2007, Won 2005). Further, it is revealed that the CTE of concrete varies along with relative humidity (RH) and no capillary menisci exist when the concrete is saturated and the CTE is lower than when the concrete is partially saturated (Yeon et al. 2009).

Yeon et al. (2009) investigated the effect of RH on concrete CTE of concrete and observed that RH affected the CTE of concrete and cement paste. He described that the maximum CTE of both cement paste and concrete was observed at about 70% to 80% RH although there was only 3% difference of concrete CTEs between the measured CTEs at 100% RH and at 70% to 80% RH. Although it seems that RH has little effect on concrete CTE, a controlled temperature water bath is used to eliminate the effect of the moisture condition variation for the concrete CTE measurements. This fully saturated condition is a reasonable approach since pavements in the field have an internal RH of 80% or more, except surface (Mallela et al., 2005).

The variation of concrete CTE along time is frequently observed. Neiville (1992) showed that the measured CTEs of calcareous aggregate and gravel were 7.6 με /°C and 12.8 με/°C at 28 days, respectively and decreased to 6.5 με/°C and 8.4 με/°C after 90 days when concrete curing condition was moist with less than 0.6 water/cement ratio and the concrete temperature was below 260^{o}C. The increasing CTEs of concrete were also observed when the concrete was cured in air.

To identify the effect of concrete age on CTE variation, Won (2005) evaluated the effects of mix design variables, concrete age, and heating and cooling rate on concrete CTE. Won (2005) reported the shortcoming of AASHTO TP 60 and suggested the improved testing method to measure concrete CTE. Based on his research, it was concluded that concrete age had little impact on CTE for up to 3 weeks. Further, it was also stated that the effect of heating and cooling rate had little impact on concrete CTE.

Jahangirnejad et al. (2009) conducted the CTE study of concrete made of coarse aggregate from eight different sources. The test specimens were moist cured for 3, 7, 14, 28, 90, 180, and 365 days prior CTE measurements. It was concluded that aggregate geology, concrete age, and the number of heating and cooling cycles had a significant impact on concrete CTE. Further, it was noticed that for most aggregate types, the concrete CTEs at 28 were significantly lower than the concrete CTEs measured at 90 to 365 days.

To investigate the time factor that affects the concrete CTE, the AASHTO T 336-11 was used to measure the CTE values at 120 days. Five (5) cored concrete specimens from the field were also subjected to CTE measurements at 120 days for the field validation purpose. Two types of coarse aggregates (Granite and Dolomite), and two types of sands which are Granite Gneiss Manufactured Sand (MS) and Alluvial/Marine natural sand (NS) were considered in this study.

For the CTE measurements after 120 days, concrete specimens were selected from eight batches in Table 6 (Batch No.: 18, 20, 22, 24, 26, 28, 30, 32). The selected concrete specimens from the batches were saturated before 48 hours and during the test.

Measured CTE values at 28 and 120 days are tabulated in Table 15. A decreasing tendency of the CTE values was observed on all concrete specimens after 120 days. The highest CTE reduction was observed on granite concrete and the reduction range was from 0.378 με/°C to 0.670 με/°C (0.210 με/°F to 0.372 με/°F). A reduction of CTE ranging from 0.168 με/°C to 0.340 με/°C (0.093 με/°F to 0.189 με/°F) was also observed on dolomite concrete.

TABLE 15
Concrete CTE at 28 and 120 days

CTE No.	**Granite** (kg/m^3)	**Dolomite** (kg/m^3)	**MS** (kg/m^3)	**NS** (kg/m^3)	**Reduction of CTE after 120 days**		**Average CTE at 28 days**		**Average CTE at 120 days**	
					(με/°F)	(με/°C)	(με/°F)	(με/°C)	(με/°F)	(με/°C)
4	1245	0	563	0	0.327	0.589	4.542	8.176	4.215	7.587
12	1245	0	0	563	0.372	0.670	5.076	9.137	4.704	8.467
20	682	0	1127	0	0.226	0.407	4.597	8.275	4.371	7.868
28	682	0	0	1127	0.210	0.378	5.463	9.833	5.253	9.455
36	0	1245	563	0	0.108	0.194	4.679	8.422	4.571	8.228
44	0	1245	0	563	0.189	0.340	5.165	9.297	4.976	8.957
52	0	682	1127	0	0.102	0.184	4.571	8.228	4.469	8.044
60	0	682	0	1127	0.093	0.168	5.371	9.668	5.278	9.500
CORED	1245	0	0	563	0.219	0.394	4.872	8.770	4.653	8.375

For the field validation purpose, five specimens were cored from concrete pavement sections newly constructed in 2012. The specimens were composed of high stone volume of granite as “Gneiss/Amphibolite” and NS as “Alluvial/Marine Sand". Concrete properties were obtained from the original mix design in 2012 before the concrete placement and that is the same period of time that laboratory experiments were conducted for this study. These concrete properties are presented in Table 15 as well. The average CTE value of cored specimens were 8.770 με/°C (4.872 με/°F) at 28 days.

The CTEs of specimens were measured again after 120 days and shown in Appendix D. The average CTEs was 8.375 $\mu\varepsilon/^{o}C$ (4.653 $\mu\varepsilon/^{o}F$) and it confirms the CTE of concrete decreases along with time.

To confirm that the specimen was fully saturated and the RH reached to 100%, additional CTE measurements were conducted on the field cored specimens after 90 days soaking period. The measured CTEs of the specimens that were soaked for 3-month soaking period showed the lower CTE values than the ones measured at 28 days. The difference between average CTEs at 28 days and 90 days was consistent with the results in Table 15.

MEPDG ANALYSIS AND RESULT

To investigate the effects of CTE on JPCP in GA, MEPDG version 1.0 software was used for sensitive analysis. The MEPDG provides concrete performance results in terms of transverse cracking of slabs, faulting, and IRI. As shown in Table 16, the Level 3 default inputs was used in the sensitivity analysis to calculate the % slabs cracked in JPCP as shown in Figure 18:

TABLE 16

MEPDG Input Values

Variable	Default value (units)
JPCP Layer Thickness	10 inches
initial IRI	63 (inch/mile)
limit for terminal IRI	172 (inch/mile)
limit for transverse crackcing	15 (% slabs cracked)
limit for mean joint faulting	0.12 (inch)
reliability for failures	90 (%)
initial two way AADTT	4,000 (vehicles)
number of lanes in design direction	2 (lanes)
percent of trucks in design direction	50 (%)
percent of trucks in design lane	95(%)
traffic growth	4 (% compounded)
pavement base	material=A-1-a, 6 inches
pavement subbase	no default given
pavement subgrade	material=A-2-7, semi infinite
joint spacing	15 (ft)
dowel diameter	1.25 (inch)
dowel bar spacing	12 (inch)
erodibility index of pavement base	very erodable (5)
PCC-base interface	zero friction contact

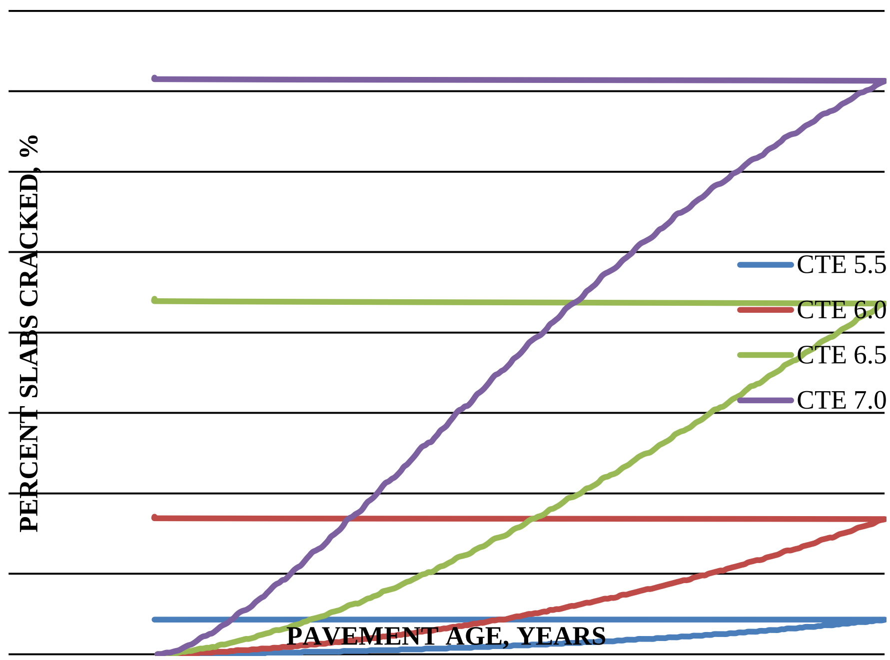

FIGURE 18

Cracking Comparison for Different CTE values

As shown in Figure 18, the CTE values affect the percentage of slabs cracking. When the CTE value increases from 6 to 6.5 με /^{o}F, 45 % increase of slabs cracking was observed. Further, the percentage of slabs cracking increased with increasing AADTT as shown in Figures 19. Figure 20 shows that the percentage of slabs cracking increases dramatically when 18 ft spacing is used instead of 15 ft joint spacing with the CTE value of 6.0 με/ ^{o}F.

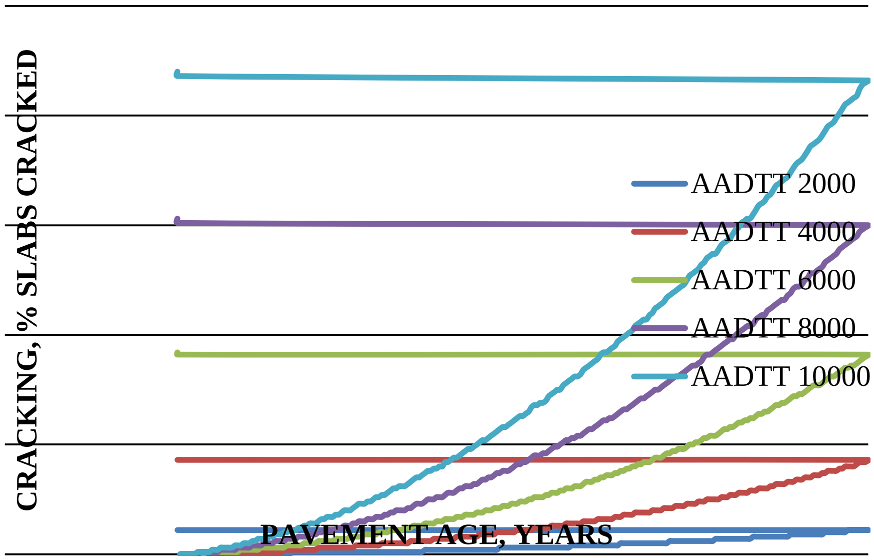

FIGURE 19

Cracking Comparison for Different AADTT

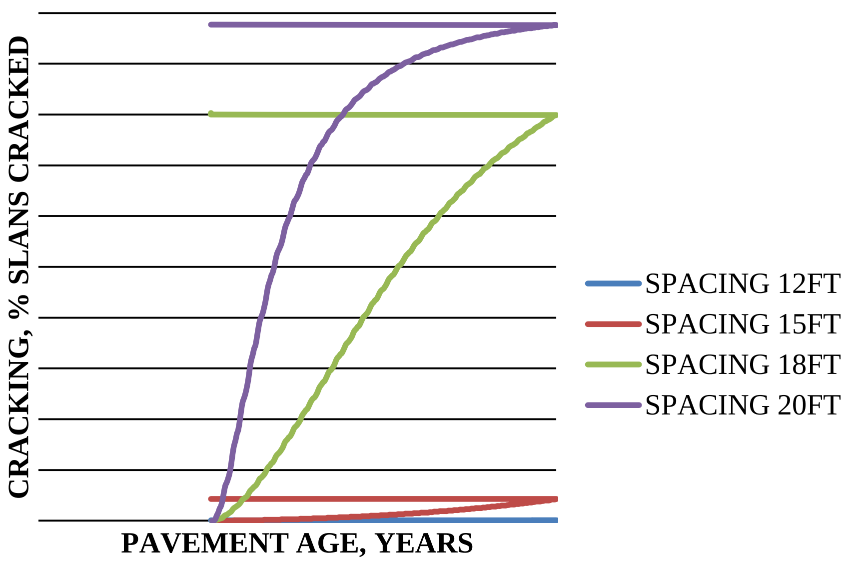

FIGURE 20

Cracking Comparison for Different Joint Spacings

In order to determine how varying CTE affects the performance of concrete pavement, several analyses were completed by keeping all inputs constant, but varying the CTE value from 3.5 to 7.0 με/°F. Figures 21, 22, and 23 show the transverse cracking, faulting, and IRI results by varying the CTE values.

Figure 21 shows that there is essentially no transverse cracking present in the pavement at a CTE value of 3.5 με/°F. However, at a CTE value of 5.5 με /°F the transverse cracking increased to 6 %, and at a CTE value of 7.0 με /°F the transverse cracking increased to 70 %. It can be concluded from this analysis that concrete pavements with CTE values larger than 6.0 με /°F will experience considerable transverse cracking and will ultimately result in poor pavement performance and a shorter design life. Although the effects that varying CTE are not as problematic for faulting and IRI as shown in Figures 22 and 23, it is concluded that the higher the CTE value, the more faulting and roughness will occur.

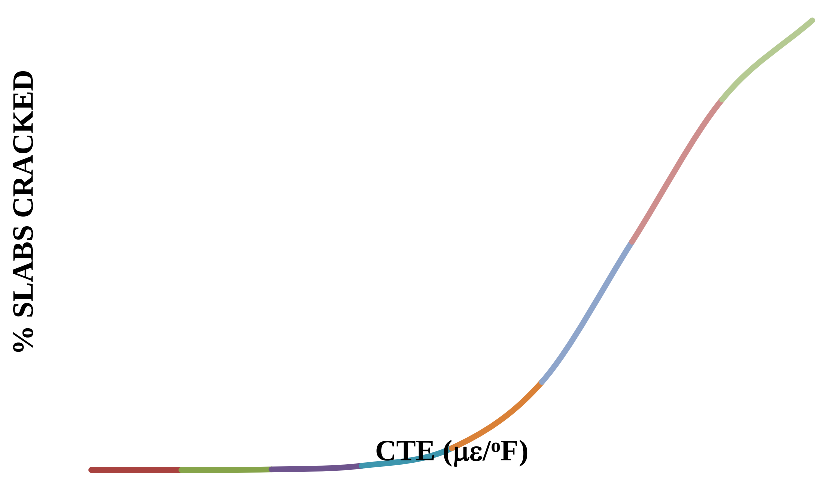

FIGURE 21

% Slabs Cracked along with CTE

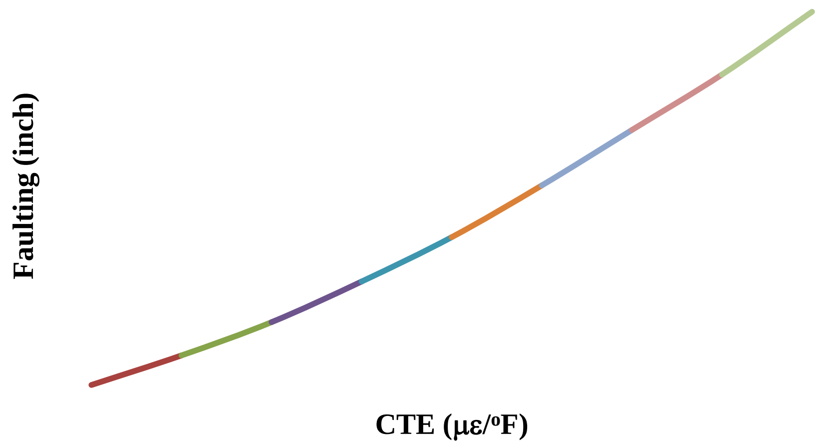

FIGURE 22

Faulting along with CTE

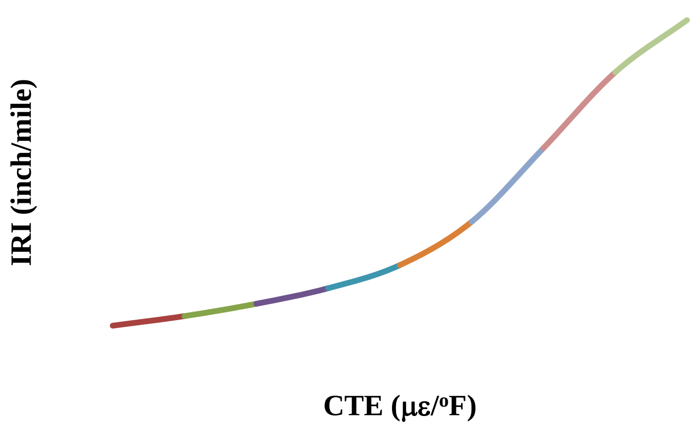

FIGURE 23

IRI along with CTE

SUMMARY AND CONCLUSIONS

This study was developed to measure the CTEs for concretes made with locally available material and mix design used in Georgia for the successful MEPDG implementation and to investigate the variables that affect the CTE of concrete. In order to achieve this, the AASHTO T336-11 was conducted with prepared concrete specimens by varying aggregate types, sand type, stone volume, fly ash type and its contents.

The following conclusions are made based on the laboratory testings:

1. Automated CTE measurement using AFCT2 equipment in accordance with AASHTO T 336-11 reasonably determine the CTE of concrete mixture.
2. Stone Volume of coarse aggregate has significant impact on the CTE. An increase in the volume of coarse aggregate in concrete mixture decreases the CTE of concrete.
3. The CTE of concrete specimens increases when the proportion of natural sand increases in the concrete mixture. Generally, the CTEs of high stone volume of concrete mixture with MS was less than 4.8 $\mu\varepsilon$ /°F while the CTEs of high stone volume of concrete mixture with NS was over 4.8 $\mu\varepsilon$ /°F. It demonstrates that sand type significantly affects the CTE of concrete and that an increase of siliceous natural sand increases the concrete CTE.
4. A multiple regression model was successfully developed to estimate the CTE values of concrete only using coarse aggregate and sand types and contents.

5. Although all of compressive strength test results of limestone concrete satisfied the minimum 28-day compressive strength of 3000 psi, compressive strength test results of granite and dolomite concretes satisfied the minimum 28-day compressive strength of 3000 psi required by GDOT when the mixtures were composed of high stone volume of coarse aggregate.

6. Most of concrete mixtures composed of low stone volume of granite and dolomite showed the 28-day compressive strength less than 3000 psi. This is attributed to the lack of high stone volume and high water-cement ratio. Therefore, it is recommended to use high stone volume mix design to satisfy the minimum 28-day compressive strength requirement.

7. Splitting tensile strength of concrete was estimated from compressive strength results for the MEPDG level 2 input.

8. The concrete mixture with higher compressive strengths generally showed lower CTE values. The concrete mixture containing high stone volume of coarse aggregate with manufacture sand showed the highest average 28-day compressive strength with the lowest average CTE values.

9. The CTE of concrete is significantly influenced by aggregate type, stone volume, and sand type. The selection of coarse aggregate, stone volume and sand types provides an approach towards lowering the concrete CTE. The lowest average CTE of 3.367 $\mu\varepsilon$/°F was observed from the concrete mixture containing high stone volume of limestone with MS while the highest average CTE of 5.318 $\mu\varepsilon$/°F

was observed from the concrete mixture containing low stone volume of dolomite with NS.

10. The measured average CTE of concrete with limestone, granite and dolomite were as follows:

Coarse Aggregate	Average CTE	Standard Deviation
Limestone	3.836 με /°F (6.905 με /°C)	0.44 με /°F (0.792 με /°C)
Granite	4.751 με /°F (8.552 με /°C)	0.4 με /°F (0.72 με /°C)
Dolomite	4.847 με /°F (8.725 με /°C)	0.35 με /°F (0.63 με /°C)

11. CTE values greater than 6.0 με/°F results in large percentages of transverse cracking and thus, decreasing the design life of the pavement. An increase in CTE values has negligible effects on faulting, and an increase in IRI.

12. The MEPDG analysis shows that increasing the joint spacing more than 15 ft of the concrete pavement will result in a significant increment in % slabs cracking.

13. A reduction of CTE was observed on all concrete specimens after 120 days and it has been validated with field cored concrete specimens. It seems that a degree of CTE reduction along time depends on the curing condition of concrete, mix design, and type of aggregate since the highest CTE reduction was observed in granite. Although several factors affect the concrete CTE variations, it is recommend to use the CTE measured at 28 days for rigid pavement design to consider the pavement deteriorations that occurs in the early stage of pavement design life.

RECOMMENDATIONS

Limestone concrete mixtures and concrete mixtures composed of high stone volume of granite and dolomite with MS satisfy the required 3000 psi compressive strength at 28 days with lower CTEs, generally less than 4.8$\mu\varepsilon$ /°F. It is highly recommended to use concrete mixture containing high stone volume of coarse aggregate with MS or NS for rigid pavement construction in Georgia. It is recommended to avoid the mix design using low volume of dolomite or granite with natural sand since it shows a lower compressive strength and higher CTE value.

The 15-ft joint spacing was analyzed in MEPDG and this joint spacing of both dolomite and granite satisfied the specification for all distress types when high stone volume of coarse aggregate was used. Although both MS and NS satisfied the specification for all distress types when high stone volume of aggregate, MS is considered as a better option in concrete mixture since it provides a lower CTE values.

It is recommended to continue measuring CTEs with various aggregate types from different quarries for CTE database development. Further it is recommended to conduct coring concrete samples from the field and run the CTE measurement in the lab for the field validations. Understanding what factors affect the CTE of PCC pavements used on Georgia's roads will aid GDOT in selecting materials that will minimize pavement distresses and increase performance.

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APPENDIX A

AGGREGATE GRADATION

Coarse Aggregates (Granite)	Coarse Aggregate Gradations		
	Sieve size	% passing	ASTM C 33 Specification
	1 ½"	100	100
	1"	100	95-100
	1/2"	57	25-60
	No. 4	2	0-10
	No. 8	1	0-5

Coarse Aggregates (Dolomite)	Coarse Aggregate Gradations		
	Sieve size	% passing	ASTM C 33 Specification
	1 ½"	100	100
	1"	100	95-100
	1/2"	49	25-60
	No. 4	1	0-10
	No. 8	0	0-5

Coarse Aggregates (Limestone)	Coarse Aggregate Gradations		
	Sieve size	% passing	ASTM C 33 Specification
	1 ½"	100	100
	1"	95	95-100
	1/2"	27.3	25-60
	No. 4	0.2	0-10
	No. 8	0.2	0-5

Fine Aggregates (Manufactured Sand)	Fine Sand Gradations		
	Sieve size	% passing	ASTM C 33 Specification
	3/8"	100	100
	No. 4	99	95-100
	No. 16	69	45-95
	No. 50	26	8-30
	No. 100	10	1-10
	No. 200	0	0-3

Fine Aggregates (Natural Sand)	Fine Sand Gradations		
	Sieve size	% passing	ASTM C 33 Specification
	3/8"	100	100
	No. 4	95	95-100
	No. 16	59	45-95
	No. 50	8	8-30
	No. 100	0	1-10
	No. 200	0	0-3

APPENDIX B

AASHTO T 336-11 MANUAL OF CTE MEASUREMENT

APPENDIX C

CTE RESULTS AT 28 DAYS

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 1	1	7.689	7.882	4.272	4.379
	2	7.977	8.157	4.432	4.532
	3	7.651	7.862	4.251	4.368
	4	7.979	8.171	4.433	4.539
	5	8.013	7.795	4.452	4.331
CTE 2	1	8.008	8.063	4.449	4.480
	2	7.720	7.932	4.289	4.407
	3	7.721	7.952	4.289	4.418
	4	7.499	7.747	4.166	4.304
	5	7.943	8.071	4.413	4.484
CTE 3	1	7.765	7.999	4.314	4.444
	2	7.920	8.257	4.400	4.587
	3	7.749	7.987	4.305	4.437
	4	7.933	8.226	4.407	4.570
	5	7.857	8.181	4.365	4.545
CTE 4	1	8.118	8.404	4.510	4.669
	2	7.941	8.186	4.412	4.548
	3	8.065	8.341	4.481	4.634
	4	7.886	8.109	4.381	4.505
	5	8.100	8.282	4.500	4.601
CTE 5	1	7.850	8.000	4.361	4.444
	2	7.969	8.347	4.427	4.637
	3	7.808	8.007	4.338	4.449
	4	7.687	8.254	4.270	4.485
	5	7.882	8.022	4.379	4.457
CTE 6	1	7.926	8.325	4.403	4.625
	2	7.806	8.121	4.337	4.512
	3	7.927	8.306	4.404	4.615
	4	7.859	8.247	4.366	4.582
	5	7.939	8.273	4.411	4.596

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 7	1	7.766	7.943	4.314	4.413
	2	7.289	7.409	4.049	4.116
	3	7.710	7.912	4.283	4.396
	4	7.370	7.452	4.094	4.140
	5	7.736	7.934	4.298	4.408
CTE 8	1	7.374	7.536	4.097	4.187
	2	7.611	7.915	4.228	4.397
	3	7.245	7.454	4.025	4.141
	4	7.672	7.876	4.262	4.376
	5	7.212	7.373	4.007	4.096
CTE 9	1	8.599	8.870	4.777	4.928
	2	9.032	9.236	5.018	5.131
	3	8.765	9.010	4.869	5.006
	4	8.756	8.991	4.865	4.995
	5	8.551	8.720	4.751	4.845
CTE 10	1	9.263	9.472	5.146	5.262
	2	9.366	9.625	5.203	5.347
	3	9.061	9.210	5.034	5.117
	4	9.152	9.159	5.084	5.088
	5	9.212	9.461	5.118	5.256
CTE 11	1	8.785	8.943	4.881	4.968
	2	8.811	9.032	4.895	5.018
	3	8.736	8.933	4.853	4.963
	4	8.630	8.960	4.794	4.978
	5	8.595	8.835	4.775	4.908
CTE 12	1	9.109	9.344	5.060	5.191
	2	8.953	9.265	4.974	5.147
	3	8.958	9.192	4.977	5.106
	4	9.058	9.241	5.032	5.134
	5	8.960	9.304	4.978	5.169

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 13	1	8.542	8.706	4.746	4.837
	2	8.611	8.852	4.784	4.918
	3	8.585	8.646	4.769	4.803
	4	8.730	8.707	4.850	4.837
	5	8.588	8.835	4.771	4.908
CTE 14	1	8.932	9.193	4.962	5.107
	2	8.798	9.054	4.888	5.030
	3	8.692	9.067	4.829	5.037
	4	8.703	8.951	4.835	4.973
	5	8.703	8.951	4.835	4.973
CTE 15	1	8.405	8.770	4.669	4.872
	2	8.100	8.288	4.500	4.604
	3	8.407	8.722	4.671	4.846
	4	8.095	8.340	4.497	4.633
	5	8.579	8.787	4.766	4.882
CTE 16	1	8.133	8.361	4.518	4.645
	2	8.430	8.780	4.683	4.878
	3	8.454	8.575	4.697	4.764
	4	8.554	8.878	4.752	4.932
	5	8.020	8.289	4.456	4.605
CTE 17	1	7.778	7.897	4.321	4.387
	2	8.003	8.122	4.446	4.512
	3	7.843	7.981	4.357	4.434
	4	8.076	8.179	4.487	4.544
	5	7.757	7.999	4.310	4.444
CTE 18	1	8.022	8.262	4.456	4.590
	2	8.027	7.818	4.460	4.343
	3	8.000	8.257	4.445	4.587
	4	7.616	7.790	4.231	4.328
	5	8.274	8.108	4.597	4.505

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 19	1	8.037	8.270	4.465	4.594
	2	8.097	8.385	4.498	4.658
	3	8.143	8.444	4.524	4.691
	4	8.158	8.445	4.532	4.692
	5	8.207	8.429	4.559	4.683
CTE 20	1	8.224	8.456	4.569	4.698
	2	8.137	8.243	4.520	4.579
	3	8.190	8.396	4.550	4.664
	4	8.086	8.254	4.492	4.585
	5	8.295	8.460	4.608	4.700
CTE 21	1	7.715	8.061	4.286	4.478
	2	7.882	8.299	4.379	4.611
	3	7.696	7.982	4.275	4.435
	4	7.941	8.170	4.412	4.539
	5	7.882	8.022	4.379	4.457
CTE 22	1	8.071	8.266	4.484	4.592
	2	7.919	8.118	4.399	4.510
	3	7.875	8.252	4.375	4.585
	4	7.853	8.098	4.363	4.499
	5	7.995	8.234	4.441	4.574
CTE 23	1	7.786	8.024	4.326	4.458
	2	7.269	7.544	4.038	4.191
	3	7.740	8.087	4.300	4.493
	4	7.472	7.619	4.151	4.233
	5	7.861	8.078	4.367	4.488
CTE 24	1	7.418	7.557	4.121	4.198
	2	7.735	8.131	4.297	4.517
	3	7.353	7.581	4.085	4.212
	4	7.837	8.072	4.354	4.484
	5	7.464	7.577	4.147	4.209

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^oC$)	CTE Test #2 ($\mu\varepsilon/^oC$)	CTE Test #1 ($\mu\varepsilon/^oF$)	CTE Test #2 ($\mu\varepsilon/^oF$)
CTE 25	1	9.655	9.933	5.364	5.518
	2	9.861	10.002	5.478	5.557
	3	9.843	9.980	5.468	5.545
	4	9.572	9.700	5.318	5.389
	5	9.880	9.744	5.489	5.413
CTE 26	1	9.788	9.927	5.438	5.515
	2	9.544	9.365	5.302	5.203
	3	9.779	10.002	5.433	5.557
	4	9.489	9.762	5.272	5.423
	5	9.653	9.805	5.363	5.447
CTE 27	1	9.757	9.925	5.420	5.514
	2	9.770	9.937	5.428	5.521
	3	9.775	9.704	5.431	5.391
	4	9.716	9.807	5.398	5.448
	5	9.499	9.662	5.277	5.368
CTE 28	1	9.730	10.002	5.405	5.557
	2	9.702	9.996	5.390	5.553
	3	9.567	9.988	5.315	5.549
	4	9.446	9.753	5.248	5.418
	5	9.718	9.975	5.399	5.542
CTE 29	1	9.250	9.492	5.139	5.273
	2	9.434	9.666	5.241	5.370
	3	9.277	9.491	5.154	5.273
	4	9.391	9.707	5.217	5.393
	5	9.304	9.505	5.169	5.281
CTE 30	1	9.304	9.614	5.169	5.341
	2	9.244	9.490	5.136	5.272
	3	9.104	9.499	5.058	5.277
	4	9.215	9.386	5.119	5.214
	5	9.129	9.332	5.072	5.184

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 31	1	9.140	9.423	5.078	5.235
	2	8.827	8.986	4.904	4.992
	3	8.961	9.302	4.978	5.168
	4	8.648	8.998	4.804	4.999
	5	9.015	9.413	5.008	5.229
CTE 32	1	8.729	8.957	4.849	4.976
	2	8.932	9.265	4.962	5.147
	3	8.859	8.987	4.922	4.993
	4	9.202	9.526	5.112	5.292
	5	8.619	8.810	4.788	4.894
CTE 33	1	8.460	8.735	4.700	4.853
	2	8.443	8.630	4.691	4.794
	3	8.201	8.447	4.556	4.693
	4	8.475	8.682	4.709	4.824
	5	8.071	8.295	4.484	4.608
CTE 34	1	8.390	8.630	4.661	4.795
	2	8.254	8.502	4.586	4.723
	3	8.565	8.774	4.759	4.874
	4	8.412	8.652	4.673	4.807
	5	8.781	9.071	4.878	5.040
CTE 35	1	8.250	8.473	4.583	4.707
	2	8.638	8.739	4.799	4.855
	3	8.368	8.594	4.649	4.774
	4	8.284	8.713	4.602	4.840
	5	8.202	8.513	4.557	4.730
CTE 36	1	8.436	8.733	4.686	4.852
	2	8.126	8.390	4.514	4.661
	3	8.267	8.582	4.593	4.768
	4	8.034	8.391	4.463	4.662
	5	8.178	8.605	4.543	4.780

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^oC$)	CTE Test #2 ($\mu\varepsilon/^oC$)	CTE Test #1 ($\mu\varepsilon/^oF$)	CTE Test #2 ($\mu\varepsilon/^oF$)
CTE 37	1	8.351	8.660	4.639	4.811
	2	8.069	8.390	4.483	4.661
	3	8.335	8.670	4.631	4.817
	4	8.028	8.397	4.460	4.665
	5	8.162	8.623	4.534	4.791
CTE 38	1	7.940	8.271	4.411	4.595
	2	8.404	8.601	4.669	4.778
	3	8.067	8.331	4.482	4.628
	4	8.307	8.743	4.615	4.857
	5	8.105	8.412	4.503	4.673
CTE 39	1	7.682	8.029	4.268	4.461
	2	8.157	8.557	4.532	4.754
	3	7.653	7.943	4.252	4.413
	4	8.064	8.415	4.480	4.675
	5	7.565	7.800	4.203	4.333
CTE 40	1	7.902	8.272	4.390	4.596
	2	7.543	7.862	4.191	4.368
	3	8.020	8.338	4.456	4.632
	4	7.620	7.909	4.233	4.394
	5	9.008	9.301	5.005	5.167
CTE 41	1	9.138	9.473	5.077	5.263
	2	8.975	9.310	4.986	5.172
	3	9.123	9.369	5.068	5.205
	4	8.963	9.303	4.979	5.168
	5	9.323	9.552	5.179	5.306
CTE 42	1	9.211	9.543	5.117	5.302
	2	9.126	9.406	5.070	5.226
	3	8.946	9.133	4.970	5.074
	4	9.088	9.326	5.049	5.181
	5	8.351	8.660	4.639	4.811

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 43	1	8.877	9.208	4.932	5.115
	2	8.974	9.382	4.985	5.212
	3	8.762	9.125	4.868	5.070
	4	8.896	9.336	4.942	5.187
	5	8.750	9.050	4.861	5.028
CTE 44	1	9.069	9.518	5.038	5.288
	2	8.954	9.467	4.974	5.260
	3	9.276	9.498	5.154	5.277
	4	8.850	9.284	4.917	5.158
	5	9.030	9.378	5.017	5.210
CTE 45	1	8.961	9.210	4.978	5.117
	2	8.535	8.822	4.742	4.901
	3	8.859	9.126	4.922	5.070
	4	8.622	8.791	4.790	4.884
	5	8.750	9.111	4.861	5.062
CTE 46	1	8.632	8.872	4.796	4.929
	2	8.990	9.232	4.994	5.129
	3	8.574	8.773	4.763	4.874
	4	8.904	9.201	4.947	5.112
	5	8.783	9.028	4.879	5.016
CTE 47	1	8.623	8.977	4.791	4.987
	2	8.249	8.530	4.583	4.739
	3	8.608	8.994	4.782	4.997
	4	8.459	8.623	4.699	4.791
	5	8.648	8.979	4.804	4.988
CTE 48	1	8.114	8.326	4.508	4.626
	2	8.552	8.964	4.751	4.980
	3	8.200	8.486	4.556	4.714
	4	8.720	9.121	4.844	5.067
	5	8.247	8.505	4.582	4.725

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 49	1	8.231	8.336	4.573	4.631
	2	8.379	8.532	4.655	4.740
	3	8.134	8.298	4.519	4.610
	4	8.358	8.654	4.643	4.808
	5	8.103	8.260	4.502	4.589
CTE 50	1	8.300	8.388	4.611	4.660
	2	8.032	8.466	4.462	4.703
	3	8.147	8.610	4.526	4.783
	4	8.335	8.407	4.630	4.671
	5	8.446	8.528	4.692	4.738
CTE 51	1	8.121	8.400	4.512	4.666
	2	8.232	8.578	4.574	4.765
	3	8.176	8.499	4.542	4.722
	4	8.351	8.598	4.640	4.777
	5	7.940	8.239	4.411	4.577
CTE 52	1	8.170	8.511	4.539	4.729
	2	7.858	8.240	4.366	4.578
	3	8.059	8.510	4.477	4.728
	4	8.014	8.322	4.452	4.623
	5	8.146	8.555	4.525	4.753
CTE 53	1	8.082	8.340	4.490	4.633
	2	7.881	8.138	4.378	4.521
	3	8.230	8.402	4.572	4.668
	4	8.211	8.152	4.562	4.529
	5	8.129	8.417	4.516	4.676
CTE 54	1	7.844	8.295	4.358	4.608
	2	8.204	8.643	4.558	4.802
	3	7.933	8.049	4.407	4.472
	4	8.343	8.487	4.635	4.715
	5	7.877	8.122	4.376	4.512

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 55	1	7.931	8.311	4.406	4.617
	2	7.563	7.757	4.202	4.309
	3	7.826	8.286	4.348	4.603
	4	7.416	7.610	4.120	4.228
	5	7.815	8.171	4.342	4.539
CTE 56	1	7.627	7.742	4.237	4.301
	2	7.911	8.222	4.395	4.568
	3	7.383	7.590	4.102	4.217
	4	7.931	8.298	4.406	4.610
	5	7.513	7.715	4.174	4.286
CTE 57	1	9.677	9.836	5.376	5.465
	2	9.757	9.902	5.421	5.501
	3	9.818	9.953	5.455	5.530
	4	9.661	9.936	5.367	5.520
	5	9.650	9.930	5.361	5.516
CTE 58	1	9.675	10.026	5.375	5.570
	2	9.682	9.771	5.379	5.429
	3	9.766	10.028	5.426	5.571
	4	9.802	9.976	5.445	5.542
	5	9.722	9.850	5.401	5.472
CTE 59	1	9.578	9.889	5.321	5.494
	2	9.696	9.886	5.387	5.492
	3	9.580	9.864	5.322	5.480
	4	9.483	9.749	5.268	5.416
	5	9.624	9.831	5.347	5.462
CTE 60	1	9.584	9.812	5.325	5.451
	2	9.604	9.816	5.336	5.453
	3	9.524	9.672	5.291	5.373
	4	9.631	9.835	5.351	5.464
	5	9.702	9.790	5.390	5.439

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 61	1	8.783	9.028	4.879	5.016
	2	9.597	9.684	5.332	5.380
	3	9.440	9.700	5.244	5.389
	4	9.375	9.408	5.208	5.227
	5	9.548	9.822	5.304	5.457
CTE 62	1	9.217	9.367	5.121	5.204
	2	9.632	9.939	5.351	5.522
	3	9.305	9.434	5.169	5.241
	4	9.260	9.535	5.144	5.297
	5	9.083	9.230	5.046	5.128
CTE 63	1	9.426	9.685	5.237	5.381
	2	8.963	9.144	4.979	5.080
	3	9.380	9.649	5.211	5.361
	4	8.820	9.082	4.900	5.046
	5	9.376	9.701	5.209	5.389
CTE 64	1	9.065	9.235	5.036	5.131
	2	9.225	9.633	5.125	5.352
	3	8.953	9.142	4.974	5.079
	4	9.201	9.552	5.112	5.307
	5	8.916	9.138	4.953	5.077

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 65	1	5.768	5.959	3.204	3.311
	2	6.117	6.417	3.398	3.565
	3	5.967	6.097	3.315	3.387
	4	6.239	6.480	3.466	3.600
	5	5.753	5.877	3.196	3.265
CTE 66	1	6.953	7.253	3.863	4.029
	2	6.290	6.437	3.494	3.576
	3	6.539	6.839	3.633	3.799
	4	6.653	6.855	3.696	3.808
	5	7.059	7.359	3.922	4.088
CTE 67	1	6.451	6.648	3.584	3.693
	2	6.668	6.962	3.704	3.868
	3	6.259	6.316	3.477	3.509
	4	6.822	6.996	3.790	3.887
	5	6.667	6.827	3.704	3.793
CTE 68	1	8.161	8.461	4.534	4.701
	2	7.974	8.109	4.430	4.505
	3	7.784	7.978	4.324	4.432
	4	7.884	8.017	4.380	4.454
	5	7.957	8.212	4.421	4.562

APPENDIX D

CTE RESULTS AT 120 DAYS

CTE No.	Specimen No.	CTE Test #1 ($\mu\varepsilon/^{o}C$)	CTE Test #2 ($\mu\varepsilon/^{o}C$)	CTE Test #1 ($\mu\varepsilon/^{o}F$)	CTE Test #2 ($\mu\varepsilon/^{o}F$)
CTE 4	1	7.467	7.495	4.148	4.164
	2	7.629	7.892	4.238	4.384
	3	7.360	7.684	4.089	4.269
CTE 12	1	8.317	8.514	4.621	4.730
	2	8.502	8.899	4.723	4.944
	3	8.127	8.439	4.515	4.688
CTE 20	1	7.917	8.222	4.398	4.568
	2	7.458	7.654	4.143	4.252
	3	7.812	8.140	4.340	4.522
CTE 28	1	9.146	9.515	5.081	5.286
	2	9.520	9.817	5.289	5.454
	3	9.268	9.471	5.149	5.262
CTE 36	1	8.211	8.502	4.562	4.723
	2	7.850	8.113	4.361	4.507
	3	8.165	8.533	4.536	4.741
CTE 44	1	8.859	9.268	4.922	5.149
	2	8.554	8.790	4.752	4.883
	3	8.912	9.355	4.951	5.197
CTE 52	1	7.713	7.926	4.285	4.403
	2	8.292	8.599	4.607	4.777
	3	7.752	7.985	4.307	4.436
CTE 60	1	9.238	9.446	5.132	5.248
	2	9.626	9.952	5.348	5.529
	3	8.877	9.096	4.932	5.053
DOT (CORED)	1	8.265	8.490	4.592	4.717
	2	8.474	8.890	4.708	4.939
	3	8.013	8.126	4.452	4.514