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Coefficient of Thermal Expansion for Concrete Containing Fly Ash and Slag

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ABSTRACT

Although the Coefficient of thermal expansion (CTE) has been regarded as a fundamental property of concrete, the CTE of ternary mixtures was not studied widely. In this research, twenty-five concrete mixtures were fabricated with various combinations of fly ashes (class C and F), slags (grade 100 and 120 ground granulated blast furnace slag), and Portland cement (Type I). The CTE and compressive strength of both the control mixture and the ternary mixtures were measured at 28 days. All the CTE values of ternary mixtures were larger than that of the control mixture, except for a ternary mixture. The largest CTE value of a ternary mixture was 10.2×10^{-6}/°C, 10% larger than that of the control mixture. The prediction equations of CTE for the eight groups of ternary mixture were introduced and the predicted CTEs had a good agreement with the measured CTEs.

Keywords. Coefficient of thermal expansion, ternary mixtures, slag, fly ash

INTRODUCTION

Supplementary cementitious materials (SCMs) have been commonly used in modern concrete practice to meet the requirement of sustainability for Portland cement concrete (PCC) pavements. There are two main categories of impacts, environmental and economic, that are generally considered to be sustainable. For the environmental impacts, the usage of SCMs reduces the carbon dioxide (CO_2) contributing to the earth's greenhouse-effect by reducing the production of Portland cement. Since SCMs are industrial by-products, use of the SCMs in concrete mixtures reduces landfill disposal. In regarding to economic impacts, using SCMs saves money by replacing the use of Portland cement, the most expensive ingredient in concrete mixtures. In addition, properly used SCMs enhance the durability of a concrete mixture, thus increasing the service life, while decreasing the life-cycle cost.

Ternary-blended cement constitutes a blend of Portland cement, together with two of the following SCMs: fly ash, slag, or silica fume. Ternary-blended cement is used increasingly in the industry at present, thus ASTM provides the specification for ternary-blended cement. Approved in 2009, ASTM C595, the standard specification for blended hydraulic cements, explains a designation for ternary-blended cement (ASTM, 2010). Specifications for ternary-blended cement define the hydraulic cement, consisting of an intimate and uniform blend, produced either by blending Portland cement with 1) two different pozzolans, or 2) slag cement and a pozzolan, or 3) a combination of intergrinding and blending.

The ternary mixtures including fly ash and slag enhance mixture properties in both fresh and hardened concrete. Fly ash slag are broadly used as a cementitious ingredient in hydraulic cement concrete for many reasons including reduction in temperature rise during initial hydration, improved resistance to sulfates, reduced expansion due to alkali-silica reactions (ASR), and contribution to the durability and strength of hardened concrete (ACI,2006 and Mehta, 2005). A large amount of slag can be used for replacement of Portland cement since the chemical compositions of slag are closely related to that of Portland cement (Mehta, 2005). Because of its beneficial effects on the properties of fresh and hardened concrete with lower cost, fly ash has increasingly used as a supplementary material or a component of blended cement. Kashima et al. (1992) found that an adding of fly ash or slag in the concrete mixture reduced heat generation during the hydration process, and potential thermal cracking was reduced correspondingly. Swamy and Laiw (1995) indicated that a concrete mixture containing fly ash and slag presented a better workability than a concrete mixture, including silica fume. Using fly ash and slag in a concrete mixture usually provides lower early-age strength, but high long-term strength in concrete rather than ordinary Portland cement concrete. Kelham et al. (1995) studied the development of compressive strength at various ages for cement pastes and mortars. The compressive strength increases after 7 days, when slag was added to the mixture. However, the compressive strength did not develop until 28 days when fly ash was added. Khatri and Sirivivatnanon (2001) investigated and noted that the most effective replacement of fly ash for chloride resistance durability in aggressive and moderate environments was 40% and 30%, respectively.

Although the coefficient of thermal expansion (CTE) has been regarded as a fundamental property of concrete, the CTE of ternary mixture has never been widely studied. Chung and Shin studied the sensitivity analysis of CTE values on PCC pavement distresses, using mechanistic-empirical pavement design guide (MEPDG) (Chung and Shin, 2011). This study noted that a 10% overestimated CTE from an accurate CTE value in a jointed plain concrete pavement (JPCP) having a joint spacing of 15 ft. excessively predicted the percent slab cracking by 188%, and the mean joint faulting by 38%. Thus, the characteristics of CTE in the ternary mixtures should be studied, with accurate measurements of CTE considered essential in correctly predicting critical distress in PCC pavements.

OBJECTIVES

The objectives of this research were to characterize the CTE and compressive strength of ternary mixtures containing slag and fly ash and to develop CTE prediction equations at various proportions of SCMs. The research also provided a guideline for choosing an optimal combination of types or proportions of SCMs, which are favorable to CTE.

EXPERIMENTAL INVESTIGATION

Concrete Mixture Design

Twenty-five concrete mixtures, including one control mixture and twenty-four ternary mixtures with various combinations of fly ashes (class C and F), slags (grade 100 and 120 ground granulated blast furnace slag (GGBFS)), and Portland cement (Type Ⅰ), were fabricated. The mixtures were named by the proportions of different cementitious materials. TI stands for Type Ⅰ Portland cement, S for slag, and FA for fly ash (C for class C fly ash and F for class F fly ash), respectively. The six ternary mixtures presented in Table 1 can be separated into two groups. The first three ternary mixtures have 30% slag-replacements with the proportion of Portland cement, decreasing from 50% to 30%, and the next three ternary mixtures have 50% slag-replacement with the proportion of Portland cement, decreasing from 30% to 10%. The six ternary mixtures shown in Table 1 were repeated four times with combinations of two fly ashes and slags, such as the combination of class C fly ash with grade 100 slag, class C fly ash with grade 120 slag, class F fly ash with grade 100 slag, and class F fly ash with grade 120 slag. The percentage of coarse aggregate and fine aggregate was kept close to 60% and 40%. A Kentucky limestone (Three Rivers Quarry in Kentucky) and siliceous sand (A 133 TXI Dennis Mills) were used for coarse and fine aggregates for all the mixtures. A constant water-to-cementitious (w/cm) ratio of 0.45 was used for the mixtures, in order to minimize the effect of cement paste. Daravair 1440 and WRDA 35 were used as admixtures to provide desirable air content and workability. The numbers in the table present the percent of the mixing proportion by weight.

Table 1. Concrete Mixture Designs

Mixtures	100TI	50TI30S 20FA	40TI30S 30FA	30TI30S 40FA	30TI50S 20FA	20TI50S 30FA	10TI50S 40FA
Type Ⅰ Portland cement	100	50	40	30	30	20	10
Slags	0	30	30	30	50	50	50
Fly ashes	0	20	30	40	20	30	40

TI is Type I Portland cement; S is slags (grade 100 and 120 GGBFS), FA is fly ashes (class C and F fly ash)

CTE and Compressive Strength Tests

HM-251, manufactured by Gilson/Challenge technology, was used to measure the CTE of concrete specimens. The HM-251 strictly conforms to AASHTO T 336-09 standard method (2009). Duplicated specimens were fabricated for CTE testing, while three replicated specimens were fabricated for a compressive strength test at 28 days to reduce experimental variability.

Characteristics of SCMs

In this research, two different sources of fly ash and ground granulated blast furnace slag were used. Fly ashes are divided into two classes, class C and F, based on the composition of the inorganic fractions. Slags are subdivided into three grades: grade 80, 100, and 120, as determined by the slag activity index. The slag activity index represents the ratio of the average compressive strength of the slag-reference cement cubes to the average compressive strength of the reference cement cubes, multiplied by 100. The higher grade of slag implies the increased levels of reactivity or faster strength development. The grade 100 and 120 slags were selected for further analysis. Since SCMs exhibit a significant variation in chemical and physical properties among the sources, the X-ray fluorescence (XRF) analyses were performed; the results are presented in Table 2. ASTM 618 (2005) specifies the limitations of chemical requirements for fly ashes. The minimum percentage of summation of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide is 50% for class C fly ash and 70% for class F fly ash. The maximum percentage of sulfur trioxide (SO_3) and loss of ignition for both fly ashes are 5% and 6%, respectively. The amount of carbon in fly ash can vary over a wide range. Thus, ASTM 618 limits the use of fly ash in concrete to 6% loss on ignition (LOI). The high amount of carbon is not necessary due to NOx control since higher amount of coal burning can result incomplete burning. All of the chemical compositions of fly ashes in Table 2 satisfy the aforementioned requirements. The class C fly ash was obtained from Headwaters Inc., Westlake, Louisiana; the class F fly ash was obtained from Headwaters Inc., Tatum, Texas; the grade 100 slag was obtained from Holcim Inc., Theodore, Alabama; and the grade 120 slag was obtained from BuzziUnicem, New Orleans, Louisiana.

Table 2. Chemical Compositions of SCMs

Oxide	Type I Portland Cement	Class C Fly Ash	Class F Fly Ash	Grade 100 GGBFS	Grade 120 GGBFS
SiO_2	20.24	35.04	60.74	38.59	34.77
Al_2O_3	4.45	19.30	19.41	7.61	10.73
Fe_2O_3	3.47	5.32	7.93	0.76	0.56
CaO	63.28	24.98	5.33	38.61	40.52
MgO	3.82	5.48	1.84	13.00	11.99
Na_2O	0.22	1.95	0.77	0.25	0.29
K_2O	0.44	0.46	1.19	0.38	0.38
TiO_2	0.28	1.36	1.01	0.36	0.60
SO_3	2.62	2.81	0.37	0.38	0.41
LOI	1.10	0.60	0.60	0.20	0.20

EXPERIMENTAL TEST RESULTS

Compressive Strength of Ternary Mixtures

The compressive strength of a control and ternary mixtures at 28 days are shown in Figure 1. The variation of compressive strength for ternary mixtures ranges from 2,650 to 8,580 psi, depending on the combination of fly ashes and slags. The variation of compressive strength fluctuated because the strength development of ternary mixtures is highly time-dependent. The ternary mixture combinations of class C fly ash with grade 120 slag, generally, show a higher strength than other combinations, except for an extreme combination (10TI_50G120S_40C). Per Louisiana DOTD specification, the average compressive strength for PCC pavement shall not be less than 4,000 psi at 28 days. Thus, all of the four extreme combinations by replacing 50% slag and 40% fly ash (10TI50S40FA) did not satisfy the strength requirements.

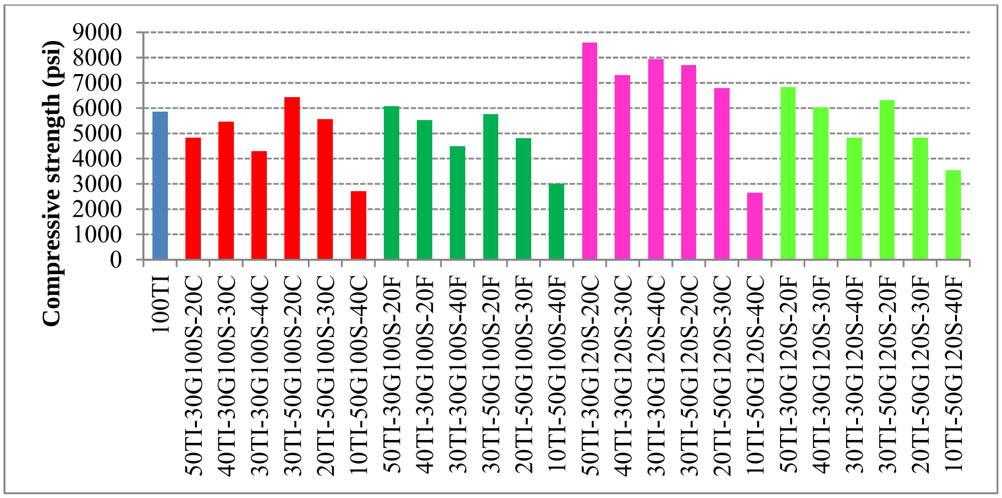

Figure 1. Compressive strength at 28 days.

Figure 2 shows the CTE values of a control and twenty-four ternary mixtures. As shown in Figure 2, all the CTE values of ternary mixtures were larger than that of the control mixture, except for a ternary mixture (30TI-30G100S-40C). The largest CTE value of a ternary mixture (50TI-30G120S-40F) was $10.2 \times 10^{-6}/°C$, 10% larger than that of the control mixture. The CTE of ternary mixtures decreases gradually, as proportions of fly ashes (Class C and F) increase from 20% to 40%. That means the proportions of Type I Portland cement decrease from 50% to 30% for 30% slag-replacement, and decrease from 30% to 10% for 50% slag-replacement. Overall, the combination of class F fly ash with grade 120 slag results in higher CTE values than the combination of class C fly ash with grade 100 slag.

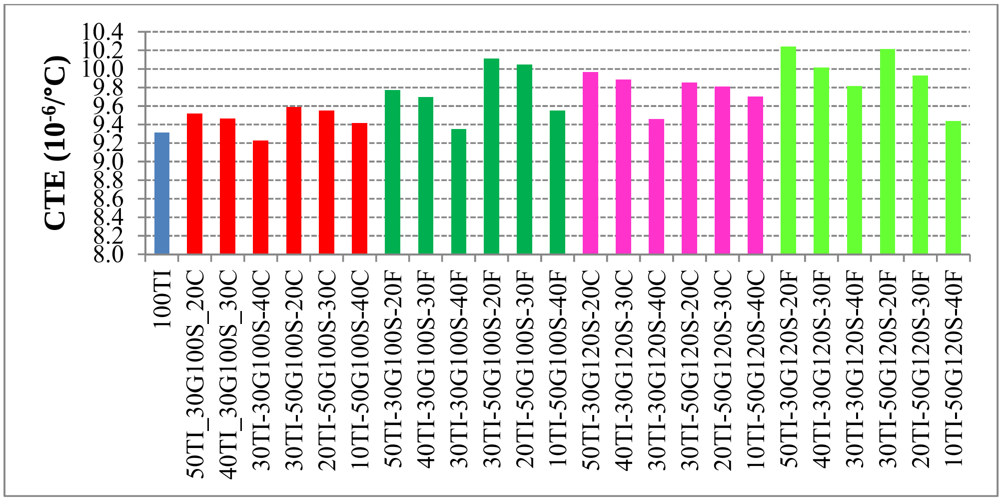

Figure 2. CTE values of a control and ternary mixtures.

Statistical Analysis Method (ANOVA)

An analysis of variance (ANOVA) was employed to validate the influence of SCMs on the CTE values. An ANOVA is a statistical method used to compare the group means among each group (Devore, 2004). Twenty-four ternary mixtures can be divided into four groups with respect to the combinations of two fly ashes and slags, distinguished by different colors in Figure 2. Furthermore, those four groups can be divided into two separated groups by the proportions of slag, such as 30% and 50% slag-replacement. Therefore, eight groups were generated, based on the types of fly ashes and slags, together with the replacement of slag as well. The mean values of these eight groups, each group consisting of three ternary mixtures, were comparable to that of a control mixture. One-way ANOVA was utilized to investigate the significance and duplicated samples of each ternary mixture were tested. The required assumptions, such as (1) residuals (deviations) are normally distributed; (2) observations are independent; and (3) variances are homogeneous, were checked before the analysis. Once the null hypothesis is rejected in the analyses, it means that at least one group mean is not equal; a multiple comparison (Tukey's procedure) was conducted to determine particularly which means are differed from the mean of control mixture. Alpha (α) is a probability error level, fixed by 0.05 in the analyses.

The results of the ANOVA analyses are presented in Table 3. As mentioned earlier, twenty-four ternary mixtures were categorized into eight groups. Each group includes three ternary mixtures. The group name is determined by the types and proportions of slag, as well as the types of fly ash. For example, 30G100S-C means that a ternary mixtures group contains 30% of grade 100 slag and class C fly ash. Mean values of each group were shown in the first column of the ANOVA analyses. The letters in the Tukey grouping indicate that the same letter is not significantly different within the 95% confidence level. For example, there are three letters in the Tukey grouping: A, B, and C. Since the letter of control group is C, any group that does not include letter C in the Tukey grouping has a significantly different mean value, compared to the mean value of the control mixture. Three groups of ternary mixtures (50G100S-F, 30G120S-F, and 50G120S-F) show a statistical significance. The denominator of those three groups is a ternary mixture that contains class F fly ash. The dominant chemical composition of class F fly ash is silicon dioxide (SiO_2), which contributes to high CTE values (9.9-12.8×10^{-6}/°C) in quartz sand and gravel.

Table 3. Results of ANOVA Analysis

Grouping of SCM combinations		Strength			ANOVA analyses		
		Compressive strength at 28 days			Mean value (10^{-6}/°C)	Tukey grouping	Significance
		psi	MPa				
100TI	100TI	5,860	40.4	Pass	9.311	C	-
30G100S-C	50TI-30G100S-20C	4,830	33.3	Pass	9.403	CB	No
	40TI-30G100S-30C	5,460	37.6	Pass			
	30TI-30G100S-40C	4,280	29.5	Pass			
50G100S-C	30TI-50G100S-20C	6,430	44.3	Pass	9.518	CBA	No
	20TI-50G100S-30C	5,550	38.3	Pass			
	10TI-50G100S-40C	2,710	18.7	N.G			
30G100S-F	50TI-30G100S-20F	6,070	41.9	Pass	9.607	CBA	No
	40TI-30G100S-30F	5,500	37.9	Pass			
	30TI-30G100S-40F	4,490	31.0	Pass			
50G100S-F	30TI-50G100S-20F	5,740	39.6	Pass	9.904	BA	Yes
	20TI-50G100S-30F	4,790	33.0	Pass			
	10TI-50G100S-40F	3,000	20.7	N.G			
30G120S-C	50TI-30G120S-20C	8,580	59.2	Pass	9.768	CBA	No
	40TI-30G120S-30C	7,300	50.3	Pass			
	30TI-30G120S-40C	7,930	54.7	Pass			
50G120S-C	30TI-50G120S-20C	7,680	53.0	Pass	9.787	CBA	No
	20TI-50G120S-30C	6,780	46.7	Pass			
	10TI-50G120S-40C	2,650	18.3	N.G			
30G120S-F	50TI-30G120S-20F	6,830	47.1	Pass	10.025	A	Yes
	40TI-30G120S-30F	6,000	41.4	Pass			
	30TI-30G120S-40F	4,830	33.3	Pass			
50G120S-F	30TI-50G120S-20F	6,310	43.5	Pass	9.950	BA	Yes
	20TI-50G120S-30F	4,820	33.2	Pass			
	10TI-50G120S-40F	3,530	24.3	N.G			

CTE PREDICTION EQUATIONS

Figure 3 shows a trend of normalized CTE values, the CTE of ternary mixtures were divided by the CTE of control mixture, with the increased fly ashes proportions in a 30% slag-replacement. Regardless of the combination of SCMs, the CTE values decrease gradually, as proportions of fly ashes increase. The largest normalized CTE values occur with a combination of class F fly ash with grade 120 slag, while the smallest normalized CTE values occur with a combination of class C fly ash with grade 100 slag. The prediction equations and R^2 values of CTE for 30% slag-replacement ternary mixtures are presented in Table 4.

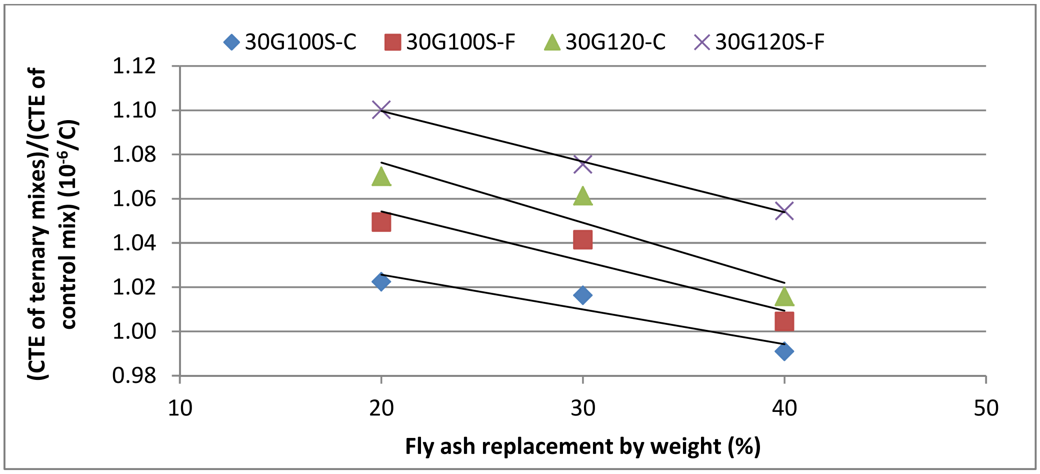

Figure 3. CTE prediction of 30% slag-replacement.

Figure 4 shows a trend of normalized CTE values, with regard to increased fly ashes proportions in a 50% slag-replacement. The ternary combinations, including class C fly ash, show a similar trend to a 30% slag-replacement in Figure 3. The normalized CTE values of the ternary combination that includes class F fly ash decrease sharply as the proportions of fly ash increase. The prediction equations and R^2 values of CTE for 50% slag-replacement ternary mixtures are presented in Table 4.

The prediction equations of CTE for eight groups of ternary mixtures are presented in Table 4. The X values are the proportions of both fly ashes (20 to 40%), and the range of R^2 values are between 0.841 and 0.998. These equations should be used with caution, when the proportions and sources of SCMs differ from Table 4.

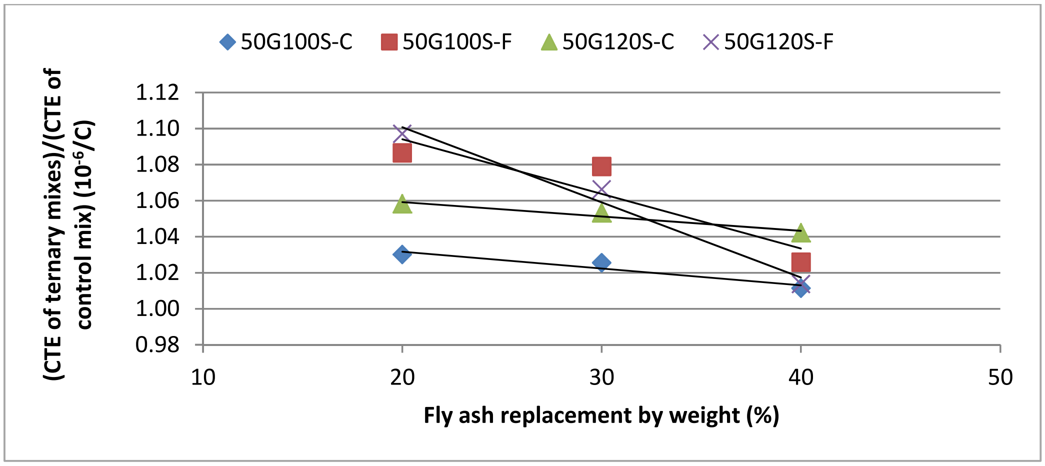

Figure 4. CTE prediction of 50% slag-replacement.

Table 4. CTE Prediction Equations of Ternary Mixtures

Grouping of SCM combinations	equations	R^2
30G100S-C	CTE = (-0.0016X + 1.0571) × 9.311	0.890
30G100S-F	CTE = (-0.0022X + 1.0992) × 9.311	0.879
30G120S-C	CTE = (-0.0027X + 1.1307) × 9.311	0.868
30G120S-F	CTE = (-0.0023X + 1.1453) × 9.311	0.998
50G100S-C	CTE = (-0.0009X + 1.0503) × 9.311	0.920
50G100S-F	CTE = (-0.003X + 1.1547) × 9.311	0.841
50G120S-C	CTE = (-0.0008X + 1.0753) × 9.311	0.957
50G120S-F	CTE = (-0.0042X + 1.1841) × 9.311	0.978

Figure 5 shows the comparison between the predicted CTE by the equation in Table 4, with measured CTE values. The predicted CTE shows a good agreement with the measured CTE, since the R^2 value is 0.918 and the maximum percentage difference between the two CTEs is 1.3%.

SUMMARY AND CONCLUSION

Supplementary cementitious materials have been commonly used in modern concrete practice to satisfy the requirement of sustainability for PCC pavements. Although CTE has been regarded as a fundamental property of concrete, the CTE of ternary mixtures has not been studied widely. This research was performed to characterize the CTE of ternary mixtures with various combinations of fly ashes and slags and to draw the following findings. The variation of compressive strength at 28 days for ternary mixtures ranged from 2,650 to 8,580 psi, depending on the combination of fly ash and slag. The compressive strength of all the extreme combinations (10TI50S40FA) does not meet the strength requirement for Louisiana DOTD specification. All the CTE values of ternary mixtures are larger than that of the control mixture, except for a ternary mixture (30TI-30G100S-40C). The largest CTE value of a ternary mixture (50TI-30G120S-40F) was 10.2×10^{-6}/°C, found to be 10% larger than that of the control mixture. From the results of ANOVA analyses, the mean CTE values of three ternary groups (50G100S-F, 30G120S-F, and 50G120S-F) were significantly different than that of control mixture in the 95% confidence level. The denominator of those three groups is ternary mixtures containing class F fly ash. The dominant chemical composition (silicon dioxide (SiO_2)) was found to contribute to high CTE values ($9.9\text{-}12.8 \times 10^{-6}$/°C) in quartz sand and gravel. The prediction equations of CTE for eight groups of ternary mixture were introduced; the ranges of R^2 values are between 0.841 and 0.998. The predicted CTE has a good agreement with the measured CTE, because the R^2 value is 0.918 and the maximum percentage difference between the two CTEs is 1.3%.

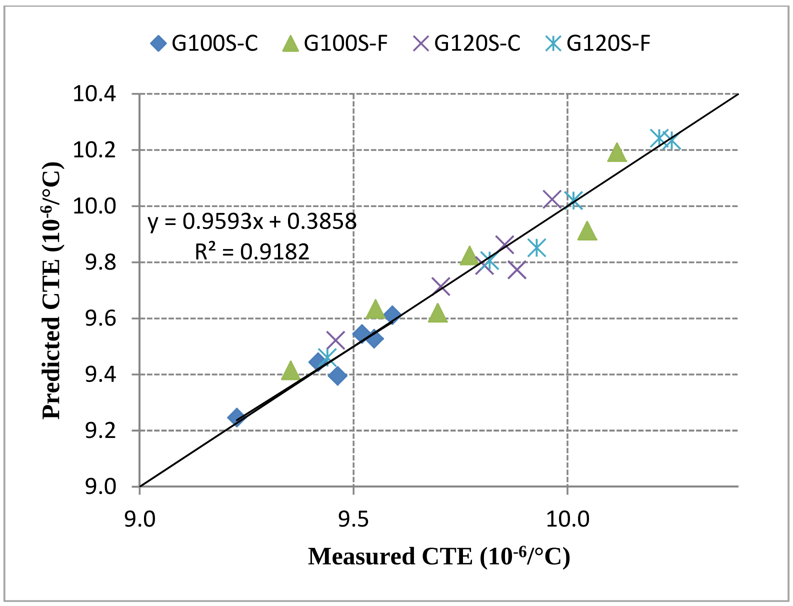

Figure 5. Measured CTE vs. predicted CTE

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