Effects of Aggregate, Water/Cement Ratio, and Curing on the Coefficient of Linear Thermal Expansion of Concrete

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A study to determine the coefficient of linear thermal expansion of concrete was conducted using concrete mixtures prepared with three types of coarse aggregates: porous limestone, dense limestone, and river gravel. A Type II portland cement was used at contents of 508, 564, and 752 lb/yd^3 and water/cement ratios of 0.53, 0.45, and 0.33, respectively. The concrete specimens were moist-cured and tested at 28 and 90 days. The concrete made with the porous limestone had the lowest coefficient of linear thermal expansion ($5.42-5.80 \times 10^{-6}$ in.^{2}/°F), whereas the concrete made with river gravel had the highest ($6.49-7.63 \times 10^{-6}$ in.^{2}/°F). The concrete made with dense limestone had an intermediate coefficient ($5.82-6.14 \times 10^{-6}$ in.^{2}/°F). The water-saturated concrete specimens had a lower coefficient of linear thermal expansion than the oven-dried specimens. The coefficient of oven-dried concrete decreased with moist-curing time. No significant difference between the 28-day and 90-day moist-curing was observed in the water-saturated concrete specimens.

The coefficient of linear thermal expansion of concrete is listed in the literature as varying from 4 to 8 millionths/°F (7.2 to 14.4 millionths/°C). Data on Florida concretes, which are made of predominately porous limestone, are lacking. In absence of actual data, a value of 6 millionths/°F is usually assumed. This could result in an error of 30 percent in the coefficient of linear thermal expansion and errors of more than 100 percent in the computed maximum thermal-load-induced stresses in concrete pavements. In view of the aforementioned reasons, the research reported here was started to obtain the needed data to be used in modeling and analysis of concrete pavement response and performance.

The coefficient of linear thermal expansion of concrete has been reported to be affected primarily by factors such as type and amount of aggregate and moisture content, as well as by the type and amount of cement and concrete age (*1–3*). However, the effect of the moisture content on the coefficient of linear thermal expansion applies only to the paste component as reported by one researcher (*4,5*). The variation of the coefficient of linear thermal expansion of cement paste is much greater than that of concrete (*6*). Orchard (*7*) pointed out that the coefficient of linear thermal expansion is not affected by drying wet-cured concrete specimens. Meyers (*8*) observed that the coefficient of linear thermal expansion increases with an increase in the cement content of the concrete mix and that the coefficient is dependent on the quantity of tricalcium silicate in the cement. He reported that cement with low tricalcium silicate had a low volume change with temperature variation. The type of cement does not greatly affect the coefficient of linear thermal expansion of concrete (*7,8*). Orchard (*7*) reported that the time of wet-curing (i.e., in water) has little effect on the coefficient of linear thermal expansion, whereas the time of dry-curing (i.e., in air) has little effect up to 3 months and tends to reduce the coefficient slightly between 3 months and 1 year.

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MATERIALS

The following materials and variables were used to prepare the concrete specimens for the study:

1. Three types of aggregates were used: a porous limestone (Florida Brooksville aggregate), a river gravel, and a dense limestone (Alabama aggregate). The aggregates had a maximum size of ⅜ in. because of the small size of the concrete test specimens. Although a maximum size of ¾ in. might also have been used, the ⅜ in. size was used to minimize the effects of specimen size and facilitate consolidation of the fresh concrete in the specimen molds. The physical properties of the aggregates are presented in Table 1. The fine aggregate used for all mixtures was a fine sand from Goldhead, Florida. The physical properties for the sand are as follows: bulk specific gravity = 2.50, absorption = 0.65 percent, and fineness modulus = 2.23.
2. The cement used was a Type II portland cement. The results of the physical and chemical analyses on the cement follow. Cement contents of 508, 564, and 752 lb/yd^3 were used.

TABLE 1 PHYSICAL PROPERTIES OF COARSE AGGREGATES

	Coarse Aggregates		
Property	Porous Limestone	Dense Limestone	River Gravel
Bulk specific gravity (SSD)	2.50	2.70	2.59
Absorption (%)	2.95	0.5	1.46
Unit weight (lb/ft^3)	92.0	96.82	100.38

The results of the physical tests are as follows:

- Fineness (Blaine air permeability test): 3,970 cm^2/g;
- Soundness (autoclave expansion): − 0.01 percent;
- Time of setting (Gilmore): 2 hr, 45 min (initial); 4 hr, 25 min (final);
- Compressive strength: 1,990 psi (1 day), 3,040 psi (3 days), and 4,190 psi (7 days); and
- Air entrainment: 9.1 percent.

The results of the chemical analyses (in percentages) are as follows:

- Silicon Dioxide (S_iO_2): 21.6,
- Aluminum Oxide (Al_2O_3): 4.5,
- Ferric Oxide (Fe_2O_3): 4.1,
- Magnesium Oxide (MgO): 0.6,
- Sulfur Trioxide (SO_3): 2.9,
- Loss on Ignition: 0.9,
- Insoluble Residue: 0.17,
- Alkalis (percent $Na_2O + O.658K_2O$): 0.36,
- Tricalcium Silicate: 54,
- Dicalcium Silicate: 21,
- Tricalcium Aluminate: 4.8, and
- Tetracalcium Alumino Ferrite: 12.6.

3. The water/cement (w/c) ratios were 0.33, 0.45, and 0.53.
4. The curing durations were 28 days and 3 months.
5. An admixture, Mighty RD1, was used to adjust the slump of the fresh concrete to a target slump of 3 in. This admixture meets all the requirements of ASTM C494 Type G and Type D and is classified as a water-reducer and retarder. A Darex air-entraining admixture was used. It was assumed that the small variation of admixtures used did not have any significant effects on the test results.
6. A Sikadur 32, Hi-Mod, 2-component (A and B), solvent-free moisture-insensitive structural epoxy adhesive was used to secure contact points to the concrete specimens used to determine the coefficient of thermal expansion.

EQUIPMENT

A length comparator, a water tank, and a forced draft oven were used to conduct the study on the coefficient of linear thermal expansion of concrete.

Length Comparator

The length comparator (shown in Figure 1) consists of a sensitive dial micrometer mounted on a sturdy upright support that is attached to a solid triangular base. The dial micrometer is graduated to read to 0.0001 in. The range of the scale is 0.4000 in. The dial has one large and two small count hands with needle pointers. The scale may be rotated to zero at any indication of the large needle pointer, at which point it can then be locked by a set screw. The two smaller count hands with needle pointers on the face of the large dial show the number of revolutions of the larger pointer. One of the count hands shows the reading in 0.010 in., and the other hand shows it in 0.100-in. intervals.

FIGURE 1 Length comparator.

Two anvils are fitted with collars and shaped to meet the measuring studs cast into the ends of the test concrete bars. As supplied by the manufacturer, one of the anvils is movable, whereas the other is stationary. The movable anvil is attached to the end of the indicator spindle; the stationary one is attached to the base with a threaded fastener through the base and a hex lock nut. The threaded fastener could be modified to facilitate adjustment to various heights to accommodate short specimens.

Water Tank

A water tank was constructed and used to saturate and condition the concrete specimens to the specified test temperatures. The rectangular water tank is 4 ft long × 2 ft wide × 1 ft high (see Figure 2). It was fabricated in the laboratory from 0.125-in.-thick steel. The tank was fitted with a heating element, thermometer, thermostat, and pump. Two small hollow rectangular pieces of rods were glued to the bottom of the tank for the specimens to be placed on. This helps to circulate the heated water to all surfaces of the specimens.

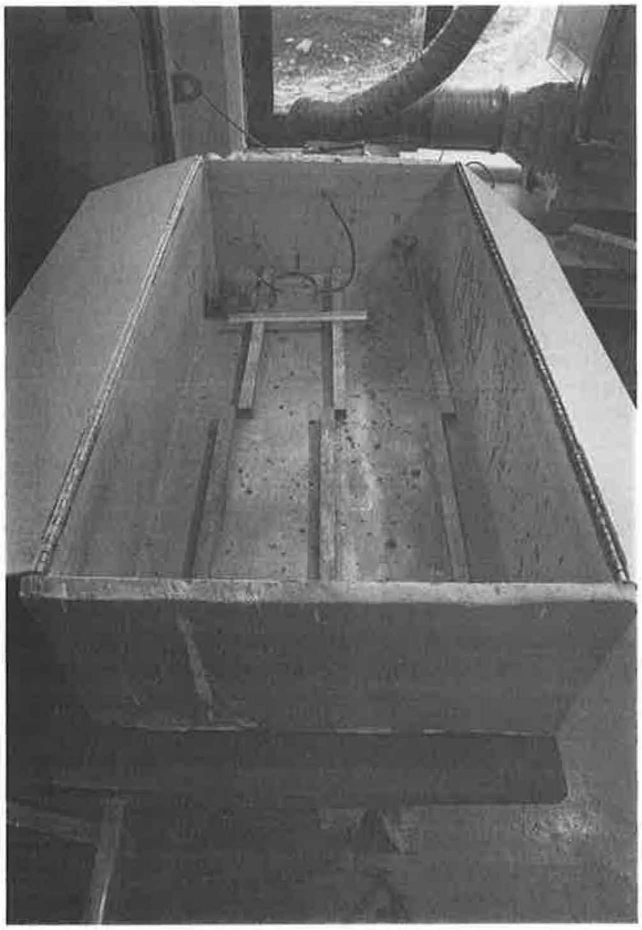

FIGURE 2 Water tank.

Forced Draft Oven

A standard laboratory oven with approximately 2 ft^3 capacity was modified in the laboratory to enable flow of warm air through the oven. The modification was performed by providing a large inlet port on one side of the oven and a small exit port on the top. A flexible aluminum duct was used to connect the two ports. A 375-cfm air booster was installed over the inlet port on the outside of the oven and connected to the duct line (see Figure 3). A thermostat and sensor were also installed to control the temperature of the oven. A small hole was made on the side of the oven so that a thermometer could be inserted to check the temperature inside the oven.

Specimen Molds

A one-compartment mold with inside dimensions of 3 in. × 11.25 in. was used to cast the test specimens. A total of ten molds were used per batch. The thickness of the steel mold is 0.5 in. (see Figure 4). Two 0.375-in.-thick, 3-in. square steel plates with a hole at the center were used to hold the contact points in place. After the concrete had set, the two steel plates were removed, leaving the two contact points embedded in the concrete specimen.

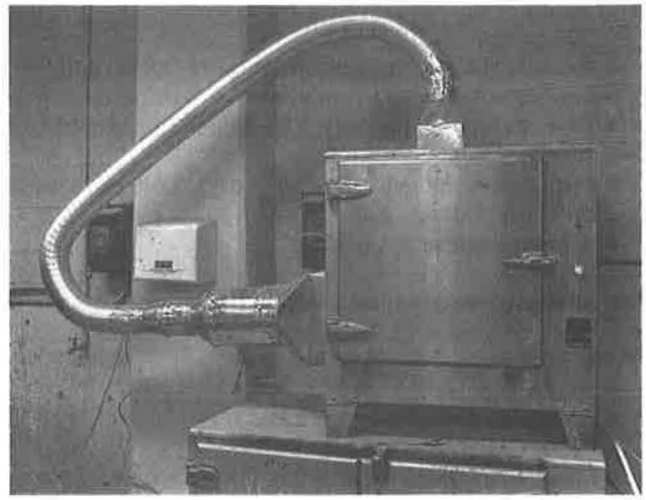

FIGURE 3 Forced draft oven.

TEST SPECIMENS

The test specimens measured 3 in. wide × 3 in. thick × 11.25 in. long. The specimens were obtained from concrete batches. Each batch varied in w/c ratio, type of coarse aggregate used, and cement content. Thermocouples were embedded in a

FIGURE 4 Specimen mold.

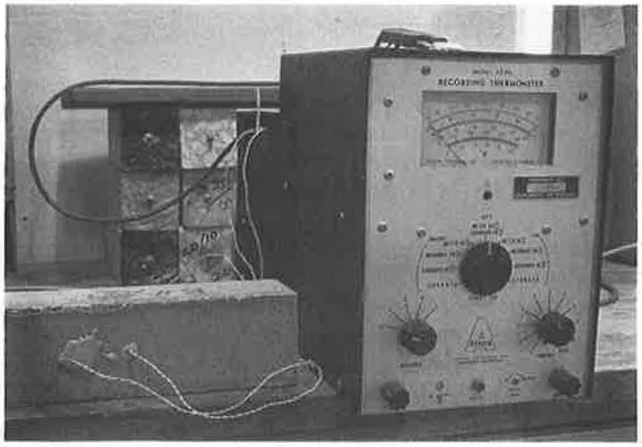

FIGURE 5 Concrete specimen with embedded thermocouples.

portion of the concrete specimens to check the temperatures in the specimen at various stages of the tests. Figure 5 is a photograph of a concrete specimen with embedded thermocouples.

EXPERIMENT DESIGN

A summary of the mix combinations is presented in Table 2. To ensure effective study of the effects of the mix parameters on the coefficient of linear thermal expansion of concrete, a factorial experiment was used. A complete factorial design facilitates statistical analyses and interpretation of the test results. The main factors and their levels under study are as follows:

- Factor A: Aggregate type:
  - –Level 1. Porous limestone,
  - –Level 2. River gravel, and
  - –Level 3. Dense limestone;

TABLE 2 DESIGN FOR TEST ON EFFECTS OF AGGREGATE TYPE, w/c RATIO AT VARIABLE CEMENT CONTENT, AND CURING DURATION

Aggregate	W/C = 0.53		W/C = 0.45		W/C = 0.33	
	(1) 508 lb/cy		564 lb/cy		752 lb/cy	
	(2) 28-day	90-day	28-day	90-day	28-day	90-day
Porous Limestone	X	X	X	X	X	X
River Gravel	X	X	X	X	X	X
Dense Limestone	X	X	X	X	X	X

X = Two replicate batches per cell.
Note:
(1) Cement Content
(2) Curing Durations

- Factor D: Curing duration:
  - –Level 1. 28-day and
  - –Level 2. 90-day; and
- Factor E: Water-Cement ratio:
  - –Level 1. 0.53,
  - –Level 2. 0.45, and
  - –Level 3. 0.33.

The following linear model was used to analyze the full factorial experiment:

$$
\begin{aligned}
Y_{ijklm} &= \mu + A_i + E_j + (AE)_{ij}\, B_{(ij)k} + \delta_{(ijk)} \\
&\quad + D_l + (AD)_{il} + (ED)_{jl} + (AED)_{ijl} \\
&\quad + (BD)_{(ij)kl} + \varepsilon_{(ijkl)m}\; i = 1,2,3; \\
&\quad j = 1,2,3;\; k = 1,2;\; l = 1,2;\; m = 1,2,3
\end{aligned} \tag{1}
$$

where

- Y_{ijklm} = response variable of the mth specimen of the lth level of curing duration, kth batch, jth level of w/c ratio, and ith level of aggregate type;
- μ = overall mean;
- A_i = effect of the ith level of aggregate type;
- E_j = effect of the jth level of w/c ratio;
- $(AE)_{ij}$ = effect of the interaction of the ith aggregate type and the jth w/c ratio;
- $B_{(ij)k}$ = effect of the kth batch nested under the ith aggregate type and jth w/c ratio;
- $\delta_{(ijk)}$ = restriction error caused by subjecting samples from the same batch to different curing conditions;
- D_l = effect of the lth curing duration;
- $(AD)_{il}$ = effect of the interaction of the ith aggregate type with the lth curing duration;
- $(ED)_{jl}$ = effect of the interaction of the jth w/c ratio with the lth curing duration;
- $(AED)_{ijl}$ = effect of the interaction of the lth curing duration, jth w/c ratio, and ith aggregate type;
- $(BD)_{(ij)kl}$ = effect of the interaction of the lth curing duration with the kth batch; and
- $\varepsilon_{(ijkl)m}$ = effect of the mth random error within the lth curing duration, kth batch, jth w/c ratio, and ith aggregate type.

TEST PROCEDURE

Measurement of Length Change

Before length changes of the specimens were measured, a high and low reading for the standard Invar reference bar was obtained. Another high and low reference bar reading was taken at the conclusion of the measurements. This was done because the room temperature might not be constant at the location of the apparatus, and the reading was used to adjust the change in length of the reference bar. The following formula was used to correct length readings of the reference bar, if necessary, taken at temperatures other than the standard temperature:

$$L_{\text{std. temp.}} = L_x - (T_x - \text{Std. temp.})\ G\ \alpha$$

where

$L_{\text{std. temp.}}$ = corrected length reading of the reference bar,
L_x = length reading of the reference bar taken at temperature T_x,
T_x = temperature of the room when length readings were taken,
G = gauge length, and
α = coefficient of linear thermal expansion of the reference bar material.

The coefficient of linear thermal expansion of Invar is 1.6 $\times$ 10^{-6}/°F (0.9 $\times$ 10^{-6}/°C). The correction factor for a 5°F (2.8°C) variation in temperature for the Invar bar is 0.000093.

A few trial runs with specimen embedded with thermocouples confirmed that the desired temperature can be attained within 3 hr of conditioning. However, readings were taken after at least 6 hr of conditioning.

A preliminary study was conducted to determine the reliability of the length comparator. First, the variability of the length readings from cycle to cycle was determined for the various temperatures. Then the number of cycles of readings was determined based on the variability of the data. It was observed that the variability of readings from cycle to cycle is higher when readings are taken at 140°F. For all conditions, the standard deviations are equal to or less than 0.0001 in., which is the sensitivity of the length comparator. This indicates that the method used for the measurement of the length is reliable and its precision is limited only by the precision of the length comparator. Although it could have been sufficient to use only one cycle of measurement, two cycles were used so that the mean length measurement would be more reliable and the variability of the readings could be checked. The standard deviations of the means were much less than 0.0001 in.

A conditioned specimen was brought to the instrument with the dial indicator retracted. It was carefully positioned in the lower anvil, and the indicator was released slowly and carefully to make contact with the upper anvil. The specimen was then rotated slowly while measurement of the length on each of the four sides was read aloud by one person and recorded by another or by cassette recorder. Four readings were made per cycle. A second person or cassette recorder was used to minimize the time the conditioned specimen was exposed to ambient conditions. The direction of the rotation of the specimen in the length comparator for Cycle 1 was opposite of that used for Cycle 2. Opposite directions were used to reduce the effects of the direction of rotation on the results. The specimens were placed in the length comparator with the same end pointed up each time a length measurement was made. The mean of the eight readings (four per cycle) was used as the length reading for the specimen at a given temperature.

Calculation of Coefficient of Linear Thermal Expansion

The coefficient of linear thermal expansion of each of the samples was computed from the following equation:

$$\alpha = \frac{\Delta L/L}{(T_2 - T_1)} \qquad (2)$$

where

α = coefficient of linear thermal expansion of test specimen per degrees Celsius or Fahrenheit,
ΔL = change in length of the specimen from temperature T_1 to T_2,
L = original length of test specimen in inches or centimeters,
T_1 = original temperature of test specimen in degrees Celsius or Fahrenheit, and
T_2 = final temperature of test specimen in Celsius or Fahrenheit.

STATISTICAL METHODS OF ANALYSES

Analysis of Variance

The response variables were analyzed by a statistical method called analysis of variance (ANOVA). The SAS/STAT software developed by the SAS Institute, Inc., was used to perform the analyses. PROC ANOVA procedure was used. The expected mean squares presented in Table 3 enabled the construction of appropriate test statistics. In ANOVA, a P-value indicates the probability of error of the statement that a factor has a significant effect on the measured parameter. A lower P-value for a factor means that such factor has a higher level of significance. A probability of error (α) level of 0.05 was used. A factor is considered to be significant if the P-value of the factor is equal to or less than 0.05. It should be noted that a statistical significance may not necessarily mean a practical significance or importance and vice versa.

Before the analysis of variance, the data were screened visually by scanning and printing of the high and low values of the data. The purpose was to locate and remove outliers. The presence of outliers causes the data to depart from the basic assumptions of ANOVA, which are normal distribution, equal variances, and independent random samples. Outliers were removed before statistical analyses were performed. An assumption of independence among observations was satisfied because measurements were taken in a random order.

The Burr-Foster Q-test was used to check the assumption of homogeneity of variance, which is required in the ANOVA technique. The results of the Burr-Foster Q-test indicated no deviations from the assumptions.

Duncan's Multiple Range Test

The rejection of the null hypothesis after running ANOVA only shows that at least one pair of group means are unequal. In order to determine specifically which pair or pairs of means are unequal, multiple comparison of means was performed using Duncan's test at a significance level of 0.05.

RESULTS OF COEFFICIENT OF LINEAR THERMAL EXPANSION TEST

The mean results of the coefficient of linear expansion test on the test specimens are presented in Table 4. In water-

TABLE 3 EXPECTED MEAN SQUARE ALGORITHM FOR ANOVA MODEL

No. of levels	3	3	2	2	3	Expected Mean Square (EMS)
Type of Treatment*	F	F	R	F	R	
Subscript / Source	i	j	k	l	m	
A_i	0	3	2	2	3	$\sigma_\epsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 36\sigma_A^2$
E_j	3	0	2	2	3	$\sigma_\epsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 36\sigma_E^2$
$(AE)_{ij}$	0	0	2	2	3	$\sigma_\epsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2 + 12\sigma_{AE}^2$
$B_{(ij)k}$	1	1	1	2	3	$\sigma_\epsilon^2 + 6\sigma_\delta^2 + 6\sigma_B^2$
$\delta_{(ijk)}$	1	1	1	2	3	$\sigma_\epsilon^2 + 6\sigma_\delta^2$
D_l	3	3	2	0	3	$\sigma_\epsilon^2 + 3\sigma_{BD}^2 + 54\sigma_D^2$
$(AD)_{il}$	0	3	2	0	3	$\sigma_\epsilon^2 + 3\sigma_{BD}^2 + 18\sigma_{AD}$
$(ED)_{jl}$	3	0	2	0	3	$\sigma_\epsilon^2 + 3\sigma_{BD}^2 + 18\sigma_{EB}^2$
$(AED)_{ijl}$	0	0	2	0	3	$\sigma_\epsilon^2 + 3\sigma_{BD}^2 + 6\sigma_{AED}^2$
$(BD)_{(ij)kl}$	1	1	1	0	3	$\sigma_\epsilon^2 + 3\sigma_{BD}^2$
$\epsilon_{(ijkl)m}$	1	1	1	1	1	σ_ϵ^2

* F = Fixed R = Random

NOTE: See Equation 1 for model.

TABLE 4 MEAN, STANDARD ERROR OF THE MEAN, AND 95 PERCENT CONFIDENCE INTERVAL OF COEFFICIENT OF THERMAL LINEAR EXPANSION RESULTS

Condition	Moist-Curing Duration*	Mean ($x10^{-6}/°F$)	Standard Error of Mean ($x10^{-6}/°F$)	95% Confidence Interval ($x10^{-6}/°F$)
		(a) Porous Limestone		
Water-Saturated	28- and 90-day	5.42	0.04396	5.33, 5.51
Oven-Dried	28-day	5.57	0.08999	5.39, 5.75
	90-day	5.80	0.07389	5.66, 5.94
	28- and 90-day	5.68	0.05983	5.56, 5.80
Water-Saturated and Oven-Dried	28-day	5.52	0.05749	5.41, 5.63
	90-day	5.59	0.05258	5.49, 5.69
	28- and 90-day	5.55	0.03888	5.47, 5.63
		(b) Dense Limestone		
Water-Saturated	28- and 90-day	5.83	0.06828	5.70, 5.96
Oven-Dried	28-day	6.14	0.07403	5.99, 6.29
	90-day	5.83	0.10384	5.63, 6.03
	28- and 90-day	5.99	0.06793	5.86, 6.12
Water-Saturated and Oven-Dried	28-day	6.00	0.06257	5.88, 6.12
	90-day	5.82	0.07198	5.68, 5.96
	28- and 90-day	5.91	0.04873	5.81, 6.01
		(c) River Gravel		
Water-Saturated	28- and 90-day	6.49	0.06904	6.35, 6.63
Oven-Dried	28-day	7.63	0.07606	7.48, 7.78
	90-day	6.77	0.12958	6.52, 7.02
	28- and 90-day	7.20	0.10389	7.00, 7.40
Water-Saturated and Oven-Dried	28-day	7.12	0.11056	6.90, 7.34
	90-day	6.58	0.08293	6.42, 6.74
	28- and 90-day	6.85	0.07547	6.70, 7.00

* Moist-curing duration for water-saturated condition is not significant.

saturated concrete, the curing duration was found to be insignificant by Duncan's Multiple Range Test. Therefore, the results from the two curing durations were combined.

STATISTICAL ANALYSES RESULTS

A Student's *t*-test analysis on the means of the coefficient of linear thermal expansion of water-saturated and oven-dried conditions showed that there is a difference between them. Hence, they were analyzed separately. The ANOVA results for water-saturated specimens are presented in Table 5. The results show that only the effect of aggregate type is significant. The results of the Duncan's test performed on the aggregate type at 5 percent alpha level show that the three aggregates are significantly different from one another (Table 6). River gravel produces the highest coefficient of linear thermal expansion ($6.49–7.63 \times 10^{-6}$/°F) followed by dense limestone ($5.82–6.14 \times 10^{-6}$/°F) and porous limestone ($5.42–5.80 \times 10^{-6}$/F).

The results of ANOVA performed on data obtained from oven-dried results are summarized in Table 7. It is to be noted that, due to the presence of restriction error, the interaction term $B(A^*E)$ was used to test for the significance of factors A, E, and AE, whereas the interaction term $BD(A^*E)$ was used to test for the significance of D, AD, ED, and AED. The error term ε was used to test for the significance of $B(A^*E)$. The ANOVA results indicated that the interaction factor $B(A^*E)$ was highly significant. This meant that it could not be pooled together with the error term ε. The ANOVA results indicated that aggregate type, moist curing duration, and their interaction are highly significant. A comparison of the means of the significant effects by Duncan's multiple range test at 5 percent probability of error level was performed. The results are summarized in Table 8. At the 28-day moist curing duration, each aggregate is are significantly different from the others. At the age of 90 days, concrete made with porous limestone and dense limestone does not show significant difference in the value of the coefficient of linear thermal expansion. However, the river gravel produced a significantly higher value than the other two aggregates.

TABLE 5 RESULTS OF ANOVA ON DATA FROM COEFFICIENT OF LINEAR THERMAL EXPANSION TEST ON WATER-SATURATED CONCRETE SPECIMENS

Source of Variation#	df	SS	MS	F	P
A	2	18.40E-12	9.20E-12	34.10	0.0001**
E	2	0.84E-12	0.42E-12	1.56	0.2616
AE	4	1.43E-12	0.36E-12	1.33	0.3309
B(A*E)	9	2.43E-12	0.27E-12	-	-
D	1	0.22E-12	0.22E-12	0.51	0.4936
AD	2	0.03E-12	0.02E-12	0.04	0.9651
ED	2	0.10E-12	0.05E-12	0.12	0.8875
AED	4	1.46E-12	0.36E-12	0.85	0.5304
BD(A*E)	9	3.87E-12	0.43E-12	5.85	0.0001**
ε	67	4.93E-12	0.07E-12	-	-

R-Square = 0.858281

See Equation (1) for definition of the terms

** Significant at α = 0.01 level.

TABLE 6 GROUPING OF AGGREGATE TYPE BY MEANS OF COEFFICIENT OF LINEAR THERMAL EXPANSION OF WATER-SATURATED CONCRETE FROM DUNCAN'S TEST

Aggregate Type	Mean	Grouping*
River Gravel	6.49×10^{-6}/°F	A
Dense Limestone	5.83×10^{-6}/°F	B
Porous Limestone	5.44×10^{-6}/°F	C

* Note: Means with different letters are significantly different at α = 0.05 level.

TABLE 7 RESULTS OF ANOVA ON DATA FROM COEFFICIENT OF LINEAR THERMAL EXPANSION TEST ON OVEN-DRIED CONCRETE SPECIMENS

Source of Variation#	df	SS	MS	F	P
A	2	43.85E-12	21.93E-12	52.23	0.0001**
E	2	0.10E-12	0.05E-12	0.12	0.8845
AE	4	4.37E-12	1.09E-12	2.60	0.1076
B(A*E)	9	3.78E-12	0.42E-12	-	-
D	1	2.75E-12	2.75E-12	11.08	0.0088**
AD	2	5.17E-12	2.59E-12	10.41	0.0046**
ED	2	0.13E-12	0.07E-12	0.26	0.7799
AED	4	1.91E-12	0.48E-12	1.92	0.1906
BD(A*E)	9	2.24E-12	0.25E-12	2.54	0.0136*
ε	72	7.04E-12	0.10E-12	-	-

R-Square = 0.901342

See Equation (1) for definition of the terms.

* Significant at α = 0.05 level.

** Significant at α = 0.01 level.

TABLE 8 GROUPING OF AGGREGATE TYPE BY MEANS OF COEFFICIENT OF LINEAR THERMAL EXPANSION OF OVEN-DRIED CONCRETE FROM DUNCAN'S TEST

Moist Curing Duration	Aggregate Type	Mean	Grouping*
28 - day	River Gravel	7.63×10^{-6}/°F	A
	Dense Limestone	6.14×10^{-6}/°F	B
	Porous Limestone	5.64×10^{-6}/°F	C
90 - day	River Gravel	6.77×10^{-6}/°F	A
	Porous Limestone	5.85×10^{-6}/°F	B
	Dense Limestone	5.83×10^{-6}/°F	B

* Note: Means at each moist curing duration with the same letter are not significantly different at α = 0.05 level.

CONCLUSIONS

1. Aggregate type has some effect on the coefficient of linear thermal expansion of water-saturated and oven-dried concrete. Under water-saturated conditions, the three aggre-

gates are significantly different from one another. The river gravel has the highest coefficient; porous limestone has the least. Under oven-dried conditions, the three aggregates are significantly different from one another at 28-day moist-cured age. The river gravel produced the highest coefficient, followed by dense limestone; porous limestone had the least. At the 90-day moist-cured age, the porous limestone and dense limestone did not show any significant difference from each other. The river gravel, however, yielded a significantly higher coefficient than the other two aggregates.

2. The w/c ratio and the cement content did not show any effect on the coefficient of linear thermal expansion.

3. The moist-curing duration does effect the coefficient in the oven-dried condition but not in the water-saturated condition. The coefficient of concrete in oven-dried condition is significantly higher at 28-day moist curing than at 90-day moist curing.

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