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Coefficient of Thermal Expansion in Concrete Pavement Design

This TechBrief describes the coefficient of thermal expansion (CTE) of concrete, its role in the behavior of concrete pavements, and recommendations for how to determine its value for concrete pavement design and analysis purposes. The sensitivity of concrete pavement performance prediction models in the Mechanistic-Empirical Pavement Design Guide to the CTE is discussed. Laboratory tests and other methods for determining or estimating the CTE are described, and the results of CTE laboratory tests on cores from Long-Term Pavement Performance pavement sections are summarized. Practical guidelines are provided for determining or estimating CTE and for taking into account the effect of CTE on a concrete slab's response to temperature changes when designing and constructing concrete pavements.

Introduction

Concrete expands when its temperature increases and contracts when its temperature decreases. The measure of how concrete changes in volume in response to temperature change is called the coefficient of thermal expansion (CTE) of concrete, defined as the change in unit length per degree of temperature change. The CTE of a concrete paving mixture depends on the aggregate type and degree of saturation.

Since coarse aggregate makes up the bulk of the volume of concrete, the most influential factor in the CTE of the concrete is the CTE of the coarse aggregate. Quartz has the highest CTE of the coarse aggregate types commonly used in concrete pavement construction, and the CTEs of other commonly used coarse aggregate types depend largely on their quartz content. Typical values for the CTE of concrete depending on the type of aggregate used are shown in table 1.

Coarse aggregate has the most effect on the CTE value, but fine aggregate is also a factor. Natural sands are typically high in silica (high CTE), and manufactured crushed limestone fine aggregates are lower in CTE.

The CTE of cement paste is quite sensitive to moisture content, but the CTE of concrete is less so, due to the mitigating influence of the coarse aggregate

Table 1. Coefficient of Thermal Expansion (CTE) of Concrete by Aggregate Type (LTPP Standard Date Release 25.0)

Primary Aggregate Class	Average CTE (/°F x 10^{-6})	Standard Deviation (s) (/°F x 10^{-6})	Average CTE (/°C x 10^{-6})	Standard Deviation (s) (/°C x 10^{-6})	Sample Count[1]
Andesite	4.32	0.42	7.78	0.75	52
Basalt	4.33	0.43	7.80	0.77	141
Chert	6.01	0.42	10.83	0.75	106
Diabase	4.64	0.52	8.35	0.94	91
Dolomite	4.95	0.40	8.92	0.73	433
Gabbro	4.44	0.42	8.00	0.75	8
Gneiss	4.87	0.08	8.77	0.15	3
Granite	4.72	0.40	8.50	0.71	331
Limestone	4.34	0.52	7.80	0.94	813
Quartzite	5.19	0.50	9.34	0.90	131
Rhyolite	3.84	0.82	6.91	1.47	7
Sandstone	5.32	0.52	9.58	0.94	84
Schist	4.43	0.39	7.98	0.70	30
Siltstone	5.02	0.31	9.03	0.56	21
				Total Sample Count	2,251

1. A total of 2,991 CTE values are available in LTPP Standard Data Release 25.0 (January 2011); 628 CTE values were not used due to aggregate class not defined or only one sample available for the primary aggregate type, and 112 CTE outlier values were also not included in the table.

(Powers and Brownyard 1947; Yeon et al. 2009). The CTE of concrete is highest at a relative humidity of about 70 percent (U.S. Army COE 1981) and 20 to 25 percent lower when the concrete is fully saturated.

How CTE Influences Concrete Pavement Behavior

Changes in concrete volume in response to temperature change are responsible for several aspects of concrete pavement behavior. Daily and seasonal cycles of temperature change in a concrete slab cause cyclic opening and closing of joints and cracks. To minimize transverse cracking, a jointed pavement constructed with a concrete with a high CTE may need a shorter joint spacing than a pavement constructed with a concrete with a lower CTE, which would increase the initial construction cost.

During daytime, when the top of a concrete slab warms up more than the bottom of the slab, the concrete will expand at the top of the slab more than at the bottom. If this differential deformation is not restrained (by dowels at the transverse joints, tie bars at the longitudinal joints, or both, and the slab's own weight), the slab will curl downward. If, on the other hand, daytime downward curling of the slab is restrained along the slab's edges, the result will be higher bearing stresses between the concrete and the dowels.

Similarly, during nighttime, when the top of a concrete slab cools down more than the bottom of the slab, the concrete will contract at the top of the slab more than at the bottom. If this differential deformation is not restrained (by dowels at the transverse joints, tie bars at the longitudinal joints, or both), the slab will curl upward. If, on the other hand, nighttime upward curling of the slab is restrained along the slab's edges, the result will be higher bearing stresses between the concrete and the dowels.

If the base layer below the slab is sufficiently soft that the slab can curl upward or downward and still remain in full contact with the base layer in the middle of the slab and along its edges, the stress induced in the slab by a traffic load will not be much different than if the slab were flat and in full contact with the base layer. However, if the base layer below the slab is sufficiently stiff that when the slab curls upward or downward in response to a temperature gradient through its depth, a portion of the slab curls out of contact with the base, the stress induced in the slab by a traffic load will be greater than if the slab were flat and in full contact with the base. This is particularly a concern with nighttime (upward) curling, when reduced support at slab edges and corners will result in increased edge and corner stresses under traffic loads.

The CTE of concrete also has an influence on the performance of continuously reinforced concrete pavement (CRCP). The steel content of CRCP is designed to achieve a crack spacing that is fairly uniform and within the range of about 3 to 6 ft (1 to 2 m). Too short a crack spacing may increase the likelihood of punchouts, and too long a crack spacing may increase the likelihood of steel ruptures. If the CTE of the concrete is higher than is assumed (or implicit) in the design of the steel, the desired crack spacing and uniformity may not be achieved. It is important to determine the concrete CTE (based on past experience or new testing) during the design phase, to adjust the design to achieve the desired level of performance, and to require that the CTE value be verified during construction.

Test Methods for Determining CTE

The AASHTO test method for determining the CTE of concrete is T 336-11. This laboratory test involves measuring the change in length of a saturated concrete core or cylinder, 4 in. (10 mm) in diameter, while it is subjected to an increase in temperature from 50 °F to 122 °F (10 °C to 50 °C) and then a decrease in temperature back to 50 °F. The concrete sample and test apparatus are completely submerged in a water bath to maintain saturation of the concrete during the test. Although the CTE of concrete at 100 percent saturation is not as high as at a somewhat lower moisture content, the laboratory test is run on saturated samples so that the moisture content is controlled. CTE testing equipment from two vendors and a concrete specimen mounted in the CTE test apparatus are shown in figure 1.

The measurements during the expansion (heating) and contraction (cooling) segments of the test are adjusted to account for the effect of the temperature changes on the test apparatus itself, and the CTE of the concrete is calculated for each of the two test segments as the change in the length of the sample per degree of temperature change, divided by the sample length. The testing sequence is repeated if necessary until the CTE values from the expansion and contraction segments of the test are within 0.20 millionths per °F (0.3 millionths per °C) of each other. The CTE of the concrete is then calculated as the average of the two consecutive CTE values obtained, one from the expansion segment of the test and one from the contraction segment of the test.

The U.S. Army Corps of Engineers has a similar test method for determining the CTE of concrete (U.S. Army COE 1981). This test method, CRD-C 39-81, directs that the test be conducted over a temperature range of 40 to 140 °F (5 to 60 °C). The Corps of Engineers test method directs that when the length change in the concrete test specimen is measured between only two temperatures, a single value of the CTE should be reported, but that when length change measurements are made at various temperatures, the curve of CTE versus temperature should be presented and the calculated CTE values for the different temperature intervals should be stated.

Mechanistic–Empirical Pavement Design Guide Recommendations for Determining CTE

For Level 1 design—the level that requires the greatest accuracy in inputs and is considered appropriate for the most important projects—the Mechanistic–Empirical Pavement Design Guide (MEPDG) recommends laboratory testing of concrete samples to determine the CTE (AASHTO 2008).

Many States have begun to characterize their typical portland cement concrete mixtures using their

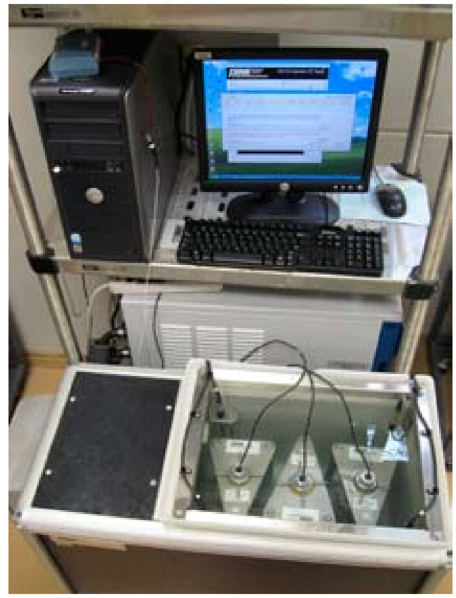

Figure 1. Measuring the CTE of concrete. Testing equipment in use at the FHWA concrete laboratory and, at left, a concrete specimen mounted for testing.

typical aggregates and storing these CTE values in a database. They will use these values, based on the project location, as a CTE input. By definition, these values are not a Level 1 input, but they are a more realistic input than a Level 2 or 3 input.

For Level 2 design—the level that is considered appropriate for routine, real-world projects—the MEPDG recommends that the concrete CTE be estimated as the average of the CTE values of the aggregate and cement paste, weighted with respect to their volumetric proportions in the mix.

For Level 3 design—the level that requires the least accuracy in inputs—the MEPDG permits the use of a typical value of CTE. The value to be used should be the typical value for the concrete made with the type of aggregates to be used in the project. Table 1 provides the range of concrete CTE values obtained from laboratory tests of cores from the Long-Term Pavement Performance (LTPP) program. It should be noted that these values are based on aggregates from across the United States and Canada. These CTE values may vary significantly across regions, depending on the mineralogy.

Information on typical concrete CTE ranges for different aggregate types is also available in the MEPDG (ARA-ERES 2004) based on the uncorrected LTPP CTE data and from other sources (Mindess and Young 1981; Kosmatka et al. 2002; Jahangirnejad et al. 2008).

How CTE Influences Performance Prediction With the MEPDG

The MEPDG identifies the CTE as one of the concrete material inputs required for critical response computations. The value used for the CTE of concrete has a significant effect on the prediction of slab cracking and, to a lesser extent, joint faulting in the MEPDG (Malella et al. 2005). Both of these distresses play a role in the MEPDG's prediction of pavement roughness. Higher CTE values correspond to

CTE Testing and MEPDG Distress Models

The new Mechanistic-Empirical Pavement Design Guide (MEPDG) models for JCPs were developed using the LTPP database. One of the LTPP data parameters used was the concrete CTE. The concrete CTE data used for the original concrete pavement distress model development were found to be in error (Crawford et al. 2010) due to an error in the test procedure used to determine the CTE data. The test procedure used was the AASHTO TP 60-00 (AASHTO 2005) test method, and its use resulted in determination of higher CTE values. The TP 60 test method recommends a value of 17.3 x 10^{-6}/°C for the 304 stainless steel specimen used to calibrate the CTE test frame, but the CTE of the 304 stainless steel specimen determined according to ASTM E 228 is 15.0 x 10^{-6}/°C, use of which results in a lower CTE for concrete by the same proportion.

The method for determining the CTE of the stainless steel specimen used to calibrate the CTE frame has been addressed in the new AASHTO T 336 test method (AASHTO 2011; Tanesi et al. 2010). Use of the new test method results in lower CTE values than those determined using the TP 60-00 test method. The CTE values in the LTPP Standard Data Release 24.0 and later have been corrected to conform to the T 336 test method and are the ones reported in table 1.

As of August 2011, the concrete pavement distress models incorporated in the recently released (July 2011) version of the DARWin-ME™ software (incorporating the MEPDG Version 1.1 distress models) are based on the CTE values determined using the TP 60-00 test method. As a result, Darwin ME users are advised to use the uncorrected CTE values, as listed in table 11-5 of the *Mechanistic-Empirical Pavement Design Guide: A Manual of Practice* (Interim Edition) published by AASHTO in 2008, or to use CTE data determined using the TP 60-00 test method. If the available CTE data were determined using the T 336 procedure, then the CTE values should be adjusted for use with DARWin-ME by adding the difference between the assumed CTE of the calibration bar, 17.3 x 10^{-6}/°C, and the ASTM E 228 CTE value for the 304 stainless steel calibration specimen. The difference should be approximately 1.5 x 10^{-6}/°C.

greater predicted amounts of slab cracking, greater joint faulting, and greater pavement roughness.

Recommendations

The MEPDG provides the opportunity to quantify the effect of concrete CTE on the predicted performance of JCP and CRCP. The MEPDG's prediction of JCP slab cracking is sensitive to the input CTE, and to a lesser extent, so is the MEPDG's prediction of joint faulting. Both of these distresses play a role in the MEPDG's prediction of pavement roughness.

Given the sensitivity of several of the MEPDG's concrete pavement distress models to the concrete CTE input, for Level 1 design, the CTE should be determined (using the AASHTO T 336-11 test method) by conducting tests on cylinders with the same aggregate type and mixture design as will be used in the construction of the pavement.

For Level 3 design, the data provided in table 1 should be used. These are the average CTE values obtained from laboratory testing of hundreds of cores from LTPP concrete pavement sections and are also the typical midrange values of CTE of concrete reported in several sources.

As noted in the boxed text, it is important that if the DARWin-ME™ software (incorporating the MEPDG Version 1.1 distress models) is used, then adjustments to the CTE values should be made if these values were determined using the AASHTO T 336 method or if CTE values from table 1 are used.

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