Task 6: Material Thermal Input for Iowa Materials

National Concrete Pavement Technology Center

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16. Abstract

The present research project was designed to determine thermal properties, such as coefficient of thermal expansion (CTE) and thermal conductivity, of Iowa concrete pavement materials. These properties are required as input values by the Mechanistic-Empirical Pavement Design Guide (MEPDG).

In this project, a literature review was conducted to determine the factors that affect thermal properties of concrete and the existing prediction equations for CTE and thermal conductivity of concrete. CTE tests were performed on various lab and field samples of portland cement concrete (PCC) at the Iowa Department of Transportation and Iowa State University. The variations due to the test procedure, the equipment used, and the consistency of field batch materials were evaluated.

The test results showed that the CTE variations due to test procedure and batch consistency were less than 5%, and the variation due to the different equipment was less than 15%. Concrete CTE values were significantly affected by different types of coarse aggregate. The CTE values of Iowa concrete made with limestone+graval, quartzite, dolomite, limestone+dolomite, and limestone were 7.27, 6.86, 6.68, 5.83, and 5.69 microstrain/^{o}F (13.08, 12.35, 12.03, 10.50, and 10.25 microstrain/^{o}C), respectively, which were all higher than the default value of 5.50 microstrain/^{o}F in the MEPDG program. The thermal conductivity of a typical Iowa PCC mix and an asphalt cement concrete (ACC) mix (both with limestone as coarse aggregate) were tested at Concrete Technology Laboratory in Skokie, Illinois. The thermal conductivity was 0.77 Btu/hr•ft•^{o}F (1.33 W/m•K) for PCC and 1.21 Btu/hr•ft•^{o}F (2.09 W/m•K) for ACC, which are different from the default values (1.25 Btu/hr•ft•^{o}F or 2.16 W/m•K for PCC and 0.67 Btu/hr•ft•^{o}F or 1.16 W/m•K for ACC) in the MEPDG program. The investigations onto the CTE of ACC and the effects of concrete materials (such as cementitious material and aggregate types) and mix proportions on concrete thermal conductivity are recommended to be considered in future studies.

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TASK 6: MATERIAL THERMAL INPUT FOR IOWA MATERIALS

Final Report
February 2008

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EXECUTIVE SUMMARY

Thermal properties of concrete materials, such as coefficient of thermal expansion (CTE), thermal conductivity, and heat capacity, are required by the Mechanistic-Empirical Pavement Design Guide (MEPDG) program as the material inputs for pavement design. However, a limited amount of test data is available on the thermal properties of concrete in Iowa. The default values provided by the MEPDG program may not be suitable for Iowa concrete, since aggregate characteristics have significant influence on concrete thermal properties. The present research investigates some thermal properties of Iowa pavement concrete.

The project includes six tasks:

- Task 1: Conducting a literature survey on concrete thermal properties
- Task 2: Determining variations in the CTE measurements
- Task 3: Performing the CTE tests for portland cement concrete (PCC) made with different aggregates
- Task 4: Analyzing the CTE test results
- Task 5: Studying the thermal conductivity of PCC
- Task 6: Investigating the thermal properties of asphalt cement concrete (ACC)

The following conclusions are drawn based on the present study:

1. The CTE variations due to test procedure and batch consistency were less than 5%, and the variation due to the different equipment used was less than 15%.
2. Concrete CTE values were significantly affected by different types of coarse aggregate. The CTE values of Iowa concrete made with limestone+graval, quartzite, dolomite, limestone+dolomite, and limestone were 7.27, 6.86, 6.68, 5.83, and 5.69 microstrain/^{o}F (13.08, 12.35, 12.03, 10.50, and 10.25 microstrain/^{o}C), respectively. These values are higher or slightly higher than the default value of 5.50 microstrain/^{o}F in the MEPDG program.
3. The thermal conductivity was 0.77 Btu/hr•ft•^{o}F for PCC and 1.21 Btu/hr•ft•^{o}F for ACC, which are different from the default values of 1.25 Btu/hr•ft•^{o}F for PCC and 0.67 Btu/hr•ft•^{o}F for ACC in the MEPDG program. (The tests were performed at Concrete Technology Laboratory in Skokie, Illinois.)
4. A literature review on the factors that affect the thermal properties of concrete and the existing prediction equations for concrete CTE and thermal conductivity is summarized in the report. The prediction equations generally contain the parameters of concrete materials (especially aggregate), mix proportion (water-to-cement ratio), moisture condition, and age.
5. The investigation into the CTE of ACC and the effects of concrete materials (such as cementitious material and aggregate types) and mix proportions on concrete thermal conductivity are recommended to be considered in future studies.

1. INTRODUCTION

1.1. Problem Statement

The thermal properties of portland cement concrete (PCC) and asphalt cement concrete (ACC) or hot mix asphalt (HMA), such as thermal conductivity, coefficient of thermal expansion (CTE), and heat capacity, are required as inputs by the new Mechanistic-Empirical Pavement Design Guide (MEPDG). Previous research on the MEPDG conducted in Iowa (Coree et al. 2005) has indicated that CTE, thermal conductivity, and Poisson's ratio of concrete are either sensitive or extremely sensitive to pavement design results. Heat capacity significantly influences ACC performance. However, a very small amount of test data is available on the thermal properties of Iowa PCC and ACC materials. In the present research, necessary tests were conducted with Iowa concrete materials to provide engineers with basic thermal input values for the MEPDG in Iowa.

1.2. Objectives

The main objectives of this research were to study the thermal properties of typical Iowa concrete materials and to investigate the effects of Iowa aggregates on those concrete thermal properties. The research was designed to help better implement the MEPDG in Iowa.

1.3. Tasks Conducted

The following tasks were conducted in this research:

Task 1: Conducting a Literature Survey on Concrete Thermal Properties

The investigators conducted a literature survey and searched for (1) commonly used concrete thermal properties and their typical values, (2) factors that affect these thermal properties, and (3) existing equations for predicting the CTE of concrete. The results of the literature review are summarized in the present report.

Task 2: Assessing Variations of CTE Measurements

The CTE of PCC was determined according to AASHTO TP 60, Standard Test Method for the Coefficient of Thermal Expansion of Hydraulic Cement Concrete. This test is relatively new to researchers at the Iowa Department of Transportation (Iowa DOT) and Iowa State University (ISU). To assess the reliability of the test results, the following variations were studied before the test equipment and the procedure were used to determine the CTE values of Iowa concrete made with various aggregates:

1. Variation in the AASHTO TP60 test procedure. Three core samples were tested with given equipment, each sample was tested three times, and the variation of the repeated test results was analyzed.

2. Variation resulting from different equipment. Six core samples with different types of aggregate were tested with two pieces of CTE equipment at ISU and the Iowa DOT, respectively. The test results were compared.
3. Variation resulting from field batch materials. Twelve concrete core samples were collected by the Iowa DOT from two field projects and tested at ISU, and the standard deviation of the test results was studied.

Task 3: Performing the CTE Tests for PCC Made with Different Aggregates and Mix Proportions

CTE tests for over a dozen PCC samples made with various mix proportions were conducted at the Iowa DOT. These concrete samples were mainly made with limestone. The investigators analyzed the Iowa DOT data and performed additional CTE tests for 12 more concrete samples made with quartzite.

Task 4: Analyzing CTE Test Results

All CTE data obtained from Tasks 1–3 above were analyzed, and appropriate CTE values were then recommended for the MEPDG design of Iowa pavement concrete.

Task 5: Studying Thermal Conductivity of PCC

Previous study on MEPDG parameter sensitivity at ISU has shown that thermal conductivity is a very sensitive parameter in pavement design. Since both the Iowa DOT and ISU have no equipment for the test, it was proposed that samples of typical Iowa concrete mixes be sent to Concrete Technology Laboratory (CTL) in Skokie, Illinois, for thermal conductivity testing.

The heat capacity of PCC is not a sensitive parameter for pavement design, and therefore it was proposed that it be studied in the future.

Task 6: Investigating Thermal Properties of HMA

Very little information is available on the CTE of ACC or HMA, and no recommendation on test methods is provided in the MEPDG documentation. With agreement from the project manager at the Iowa DOT (April 21, 2006), the investigators decided to focus the present study on the major thermal properties of PCC and to further investigate the thermal properties of ACC in the future.

Considering that both the thermal conductivity and heat capacity of ACC are far more important for pavement design than the CTE of ACC, the investigators sent one typical Iowa ACC mix to CTL for thermal conductivity testing, thus providing a typical input value for the MEPDG Level 3 ACC pavement design. The heat capacity of ACC has not been tested due to the difficulty in finding a proper agent who uses a proper method to test it.

2. RESULTS FROM LITERATURE SURVEY

A literature review has indicated that the thermal properties of concrete are more complex than those of many other materials because concrete is a composite material and its components have different thermal properties. Table 1 shows that the thermal properties (CTE, conductivity, and specific heat) of concrete and its constituents vary largely. The properties may change even more with the environment to which concrete is exposed, since the concrete thermal properties also significantly depend on the moisture content and porosity of the concrete.

Table 1. Thermal properties of concrete and concrete constituents (adopted from Mindess et al. 2003)

	CTE, $10^{-6}/^oF$ ($10^{-6}/^oC$)	Thermal conductivity, Btu/ft•h• ^oF (W/m•k)	Specific heat, Btu/lb• ^oF (J/kg• ^oC)
Aggregate			
Granite	4.0-5.0 (7-9)	1.8 (3.1)	0.19 (800)
Basalt	3.3-4.4 (6-8)	0.8 (1.4)	0.20 (840)
Limestone	3.3 (6)	1.8 (3.1)	---
Dolomite	4-5.5 (7-10)	2.1 (3.6)	---
Sandstone	6.1-6.7 (11-12)	2.3 (3.9)	---
Quartzite	6.1-7.2 (11-13)	2.5 (4.3)	---
Marble	2.2-4.0 (4-7)	1.6 (2.7)	---
Cement paste			
w/c=0.4	10-11 (18-20)	0.75 (1.3)	---
w/c=0.5	10-11 (18-20)	0.7 (1.2)	---
w/c=0.6	10-11 (18-20)	0.6 (1.0)	0.38 (1600)
Water	---	0.3 (0.5)	1.0 (4200)
Air	---	0.02 (0.03)	0.25 (1050)
Concrete	4.1-7.3 (7.4-13)	0.9-2.0 (1.5-3.5)	0.2-0.28 (840-1170)

2.1. Coefficient of Thermal Expansion

The CTE is defined as the change in unit length of a material in response to a degree of temperature change. The stresses on pavement due to drying shrinkage and curling/warping, caused by temperature or moisture differences, are very sensitive to this parameter. The CTE of concrete is therefore very important for optimizing joint design for jointed plain concrete pavement (JPCP) and designing reinforcement for continuously reinforced concrete pavement (CRCP).

Factors that influence concrete CTE have been studied for many years. These factors include water-to-cement ratio (w/c), cement type, aggregate type, aggregate fraction, temperature, and the humidity condition of the specimen (Emanuel and Hulsey 1977; Kim et al. 2003).

Concrete CTE can be predicted from the CTE of cement paste and aggregate. Neville (1996) reported that the CTE of cement paste generally varies from 11 to 20 microstrain/^oC (6–12 microstrain/^{o}F), and the CTE of concrete decreases with the increase of aggregate content (see Table 2).

Table 2. Influence of aggregate content on CTE (adopted from Neville 1996)

Cement/sand ratio	CTE at 2 years, $10^{-6}/^oC$ ($10^{-6}/^oF$)
1:0 (paste)	18.5 (10.3)
1:1	13.5 (7.5)
1:3	11.2 (6.2)
1:6	10.1 (5.6)

Table 3 gives some CTE values for concrete made with different types of aggregate and used in dams. The CTE values of concrete containing quartzite and some siliceous aggregates are around 13 microstrain/^{o}C (7.2 microstrain/^{o}F) at normal temperatures; the CTE values of some limestone aggregate concretes can be lower than 6 microstrain/^{o}C (3.33 microstrain/^{o}F) for comparable conditions. As seen in Table 3, there is a wide range of CTE values for concrete, and therefore it is important to select a proper value for concrete pavement design.

Table 3. CTE of concrete used in dams (Scanlon and McDonald 1994)

Dam	Aggregate type	Concrete CTE, $10^{-6}/^oC$ ($10^{-6}/^oF$)
Hoover	Limestone and granite	9.5 (5.3)
Hungry Horse	Sandstone	11.2 (6.2)
Grand Coulee	Basalt	7.9 (4.4)
Table Rock	Limestone and chert	7.6 (4.2)
Greers Ferry	Quartz	12.1 (6.7)
Dworshak	Granite-gneiss	9.9 (5.5)
Libby	Quartzite and argillite	11.0 (6.1)
Jupia (Brazil)	Quartzite	13.6 (7.5)

Yao and Zheng (2007) showed that, for a given amount of water, the CTE of concrete decreased with w/c ratio. However, for a given paste content, CTE increased with w/c ratio. In addition, the CTE of concrete increased significantly at an early age but became a stable value after 28 days due to the effect of cement hydration.

The CTE of concrete is generally higher in dry conditions than in wet conditions (Figure 1). (Although Figure 1 refers to neat cement pastes, the trend is similar to that of concrete.) Neville (1996) found that for the same concrete the CTE was 11 x$10^{-6}/^oC$ in winter and 13 x$10^{-6}/^oC$ in summer. Concrete age can also affect CTE test results. Concrete that is aged 6 months or older may reach 80% of its maximum CTE (Neville 1996).

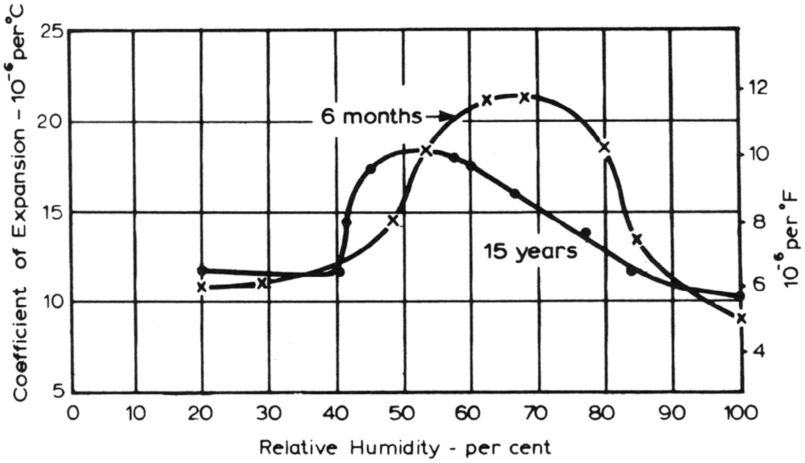

Figure 1. Coefficient of thermal expansion of neat cement paste at different ages (adopted from Neville 1996)

Different models and equations have been developed to predict concrete thermal properties, especially CTE, based on concrete composition. Based on Ziegeldorf et al. (1978), if both cement paste and aggregate could expand freely in concrete, the CTE of concrete can be computed as the volumetric average of the expansion coefficients of it constituents:

$$\alpha_c = \alpha_{paste} \cdot \beta_{paste} + \alpha_{aggregate} \cdot \beta_{aggregate} \quad \text{(Equation 1)}$$

Where, α is CTE, β is volume fraction, and the subscript *c* represents concrete.

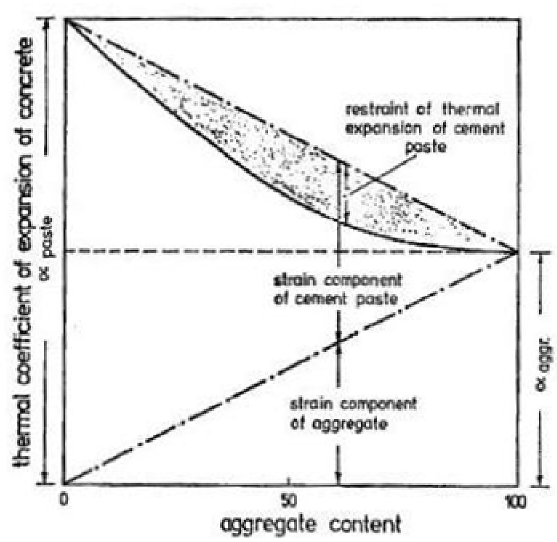

Figure 2. Relationship between thermal expansion of concrete and thermal expansion of its components (adopted from Ziegeldorf et al. 1978)

Actually, cement paste deformation in conventional concrete is restrained by aggregate, since aggregate generally has a much higher elastic modulus and a very low thermal expansion. Therefore, the actual CTE of concrete (α_c) is smaller than that expressed by Equation 1 (see Equation 2 and Figure 2). According to Dettling (Ziegeldorf et al. 1978), the more realistic concrete CTE value is related to the volume fraction of coarse aggregate and the CTE of coarse aggregate:

$$\alpha_c = (\alpha_{paste} - \alpha_{CA})(100 - x)^{3/2}(1/1000) + \alpha_{CA} \qquad \text{(Equation 2)}$$

Where, x is the volume fraction of coarse aggregate and $\alpha_{C,}$ α_{paste}, and α_{CA} are the CTE values of concrete, paste, and coarse aggregate, respectively.

Yang et al. (1990) used a model based on the weighted average of the CTE of cement paste, fine aggregate, and coarse aggregate to express the CTE of concrete:

$$\alpha = \frac{\alpha_p E_p V_p + \alpha_s E_s V_s + \alpha_g E_g V_g}{E_p V_p + E_s V_s + E_g V_g} \qquad \text{(Equation 3)}$$

Where, α_p, α_s, and α_g are the CTE of cement paste, fine aggregate, and coarse aggregate; E_p, E_s, and E_g are the elastic modulus of cement paste, fine aggregate, and coarse aggregate; V_p, V_s, and V_g are the volume proportion of cement paste, fine aggregate, and coarse aggregate (V_p+V_s+V_g=1).

Emanuel and Hulsey (1977) developed an empirical equation for concretes of various mixes, ages, and moisture contents, where the correction factors were used for the consideration of moisture and age and the volume proportion of paste, fine aggregate, and coarse aggregate:

$$\alpha_c = f_T[f_M f_A \beta_P \alpha_S + \beta_{FA}\alpha_{FA} + \beta_{CA}\alpha_{CA}] \qquad \text{(Equation 4)}$$

Where, f_M and f_A are the correction factors for moisture and age, respectively; f_T is the correction factor for temperature alternations; α_c, α_s, α_{FA}, and α_{CA} are the CTE values of concrete, cement paste, fine aggregate, and coarse aggregate; and β_P, β_{FA}, and β_{CA} are the volume proportion of paste, fine aggregate, and coarse aggregate, respectively (β_P+β_{FA}+β_{CA}=1.0). A correction factor can be used for estimating concrete CTE under different exposure conditions (Figure 3). Generally, the correction factor is 1.0 for concrete under a controlled/constant environment condition, while it is 0.86 for concrete exposed to an outside exposure condition.

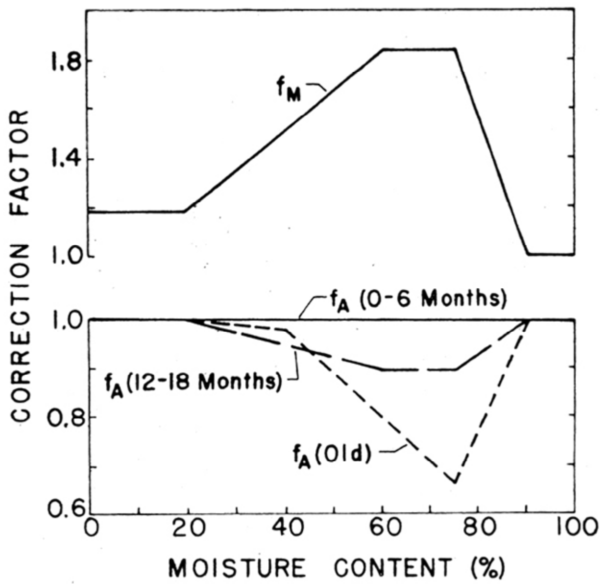

Figure 3. Correction factor for moisture and age (adopted from Emanuel and Hulsey 1977)

2.2. Thermal Conductivity of Concrete

Thermal conductivity represents the ability of a material to transfer heat. It is defined as the ratio of the rate of heat flow to the temperature gradient of a material. The thermal conductivity of PCC or ACC governs the rate at which heat flows into, through, or out of a concrete structure. For normal-weight PCC, thermal conductivity is widely influenced by the mineralogical character of the aggregates, water content, air void content and structure, and the temperature and moisture condition of concrete (Scanlon and McDonald 1994; Kim et al. 2005). The amount of free water in concrete has a major influence on thermal conductivity. Table 1 shows that, while water is a relatively poor conductor of heat as compared to aggregate, water's thermal conductivity is much higher than air; therefore, thermal conductivity significantly decreases with a reduction in moisture content. The mineralogical character of the aggregates largely determines the thermal conductivity of concrete. The effects of moisture and aggregate type on thermal conductivity values are shown in Table 4.

Table 4. Thermal conductivity of concrete with different moisture conditions (adopted from Scanlon and McDonald 1994)

	Moisture conduction	Conductivity W/m•K	Conductivity Btu•in/h•ft^2•^{o}F
Limestone concrete	Moisture	2.2	15.0
	50% RH	1.7	11.0
	Dry	1.4	10.0
Sandstone concrete	Moisture	2.9	20.0
	50% RH	2.2	15.0
	Dry	1.4	10.0
Quartz gravel concrete	Moisture	3.3	23.0
	50% RH	2.7	19.0
	Dry	2.3	16.0
Expanded shale concrete	Moisture	0.85	5.9
	50% RH	0.79	5.5
	Dry	0.62	4.3

Kim et al. (2003) developed an equation to predict the thermal conductivity of concrete according factors that include aggregate volume fraction, fine aggregate fraction, w/c ratio, temperature, and moisture content in concrete:

$$\begin{aligned} k_c &= k_{ref}[0.293+1.01AG]\times[0.8(1.62-1.54w/c)+0.2R_h] \\ &\times[1.05-0.0025T]\times[0.86+0.0036S/A] \end{aligned} \qquad \text{(Equation 5)}$$

Where, AG is aggregate volume fraction, S/A is fine aggregate volume fraction, R_h is average relative humidity, k_c is the thermal conductivity of concrete, and k_{ref} is the referenced thermal conductivity measured from specimens at a condition of AG=0.70*,* w/c=0.4*,* S/A=0.4*,* T=20^{o}C*,* and R_h=100%.

According to Campbell-Allen and Thorne's model, the thermal conductivity of concrete can be expressed as follows (Khan 2002):

$$k = k_m(2M - M^2)\frac{k_m k_a (1-M)^2}{k_a M + k_m(1-M)} \qquad \text{(Equation 6)}$$

Where, M=1-(1-p)$^{1/3}$, p is the volume of mortar per unit volume of concrete, k is thermal conductivity, and subscripts *m* and *a* refer to mortar and aggregate, respectively.

2.3. Specific Heat of Concrete

Specific heat is the amount of energy (such as heat) required for raising the temperature of one gram of a material by one degree (Celsius). The specific heat of PCC/ACC depends on the specific heats of its components. The mineralogy of aggregates has little influence on the specific heat of concrete due to the minimal variation in the specific heat of rocks. However, the specific heat of PCC strongly depends on w/c ratio and water content (see Table 5), and the specific heat of ACC is strongly related to the binder content.

Table 5. Specific heats of pastes, concretes, and mortars (adopted from Mindess and Young 1981)

Material	Agg./c	w/c	Temp. (^oC)	Specific Heat J/kg•^oC	Specific Heat Btu/lb•^oF
Neat paste	-	0.25	21	1140	0.27
	-	0.25	65	1680	0.40
	-	0.60	21	1600	0.38
	-	0.60	65	2460	0.58
Mortar	1:1	-	21	1720	0.41
	1:2	-	21	1180	0.28
	1:6	-	21	1100	0.26
Concrete	-	-	-	800-1200	0.20-0.28

2.4. Other Thermal Properties

The surface shortwave absorptivity of the pavement directly correlates with the amount of solar energy that is absorbed by the pavement surface. The absorptivity of a material depends on surface composition, color, and texture. A material having a lighter and more reflective surface generally tends to have a lower shortwave absorptivity and vice versa. The diffusivity represents the rate at which temperature changes take place in a material. Thermal diffusivity is numerically defined as thermal conductivity divided by the product of specific heat and density. The thermal diffusivity of concrete is determined largely by the mineralogical characteristics of the coarse aggregate. The range of typical diffusivity values in ordinary concrete is between 0.003 and 0.006 m^2/h (0.02 to 0.06 ft^2/h), depending on the type of aggregate used (Mindess et al. 2003).

3. EXPERIMENTS AND TEST METHODS

Using the equipment available at the Iowa DOT and ISU, this study focused on measuring the CTE of PCC. Samples of a typical Iowa PCC mix and a typical Iowa ACC mix were prepared at ISU but tested for thermal conductivity at CTL in Skokie, Illinois.

3.1. CTE Test

The CTE of concrete in the present study was determined according to the standard test method AASHTO TP60-00. The test method determines the CTE of a cylindrical concrete specimen, maintained in a saturated condition, by measuring the length change of the specimen over a specified temperature range (10°C to 50°C). The test apparatus is shown in Figure 4.

Figure 4. Test setup for CTE

The measured length change is corrected for any length change in the previously determined measuring apparatus. The CTE is then calculated from the corrected length change divided by the temperature change and the specimen length:

$$CTE = (\Delta L_a / L_0) / \Delta T \qquad \text{(Equation 7)}$$

Where, ΔL_a = length change of specimen, L_0 = initial measured length of specimen, and ΔT = temperature change.

3.2. Thermal Conductivity of Concrete

In the MEPDG documentation, the ASTM E1952 test method is recommended for testing thermal conductivity of PCC and ACC. The project investigators reviewed ASTM E1952 and found that this test method is specified for homogeneous materials (such as ceramic or glass) having thermal conductivity in the range of 0.10 to 1.0 W/(K • m), and tested samples of only 10 to 100 milligrams in size. Concrete is not only an inhomogeneous material but also contains large particles. The default thermal conductivity values in the M-E PDG are 2.16 and 1.16 W/(K • m) for PCC and ACC, respectively. The investigators also learned that researchers at Arizona

State University (ASU) are developing a new test method for concrete thermal conductivity measurement. Considering that this test method is under development and not a standard test method yet, the investigators selected a more commonly used, standard test method, ASTM C 177, for the thermal conductivity measurements of Iowa PCC and ACC in the present research.

The thermal conductivity of concrete was tested at CTL according to ASTM C177-04 (ASTM 2004). The test was performed using an apparatus, as shown in Figure 5. In the test, two concrete specimens were placed between flat steel plates. The steel plates were heated internally by special electrical resistance heaters. Temperatures were monitored by thermocouples at each surface of the specimens. The heat transferred through the specimens was equal to the power supplied to the heater. Thermal equilibrium was established when temperature and voltage readings were steady. The thermal conductivity was defined as the rate of heat flow through the material per unit thickness per degree of temperature difference across the thickness.

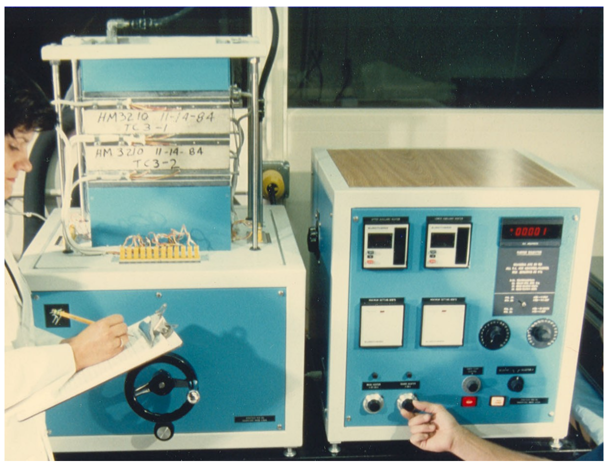

Figure 5. Test setup for thermal conductivity measurement

4. TEST RESULTS AND DISCUSSION

4.1. Variations in the CTE Measurements

1. Variation due to the AASHTO CTE Test Procedure

Core samples made with three different aggregates (quartzite, limestone, and limestone-dolomite) were collected from the field by the Iowa DOT. Each sample was tested three times to determine variations in the AASHTO CTE test procedure. The test results are shown in Table 6.

Table 6. Variations in CTE from repeated tests

Core #	Aggregate type	α_c, 10^{-6}/°C (10^{-6}/°F)	Avg., 10^{-6}/°C (10^{-6}/°F)	STDEV, 10^{-6}/°C (10^{-6}/°F)	Rel. STDEV, %
3-7196	Quartzite	12.714 (7.064) 12.409 (6.894) 12.467 (6.926)	12.530 (6.961)	0.162 (0.090)	1.3
5-0260	Limestone	11.418 (6.343) 11.277 (6.265) 11.324 (6.291)	11.339 (6.300)	0.072 (0.040)	0.6
54-0004	Limestone + Dolomite	11.866 (6.592) 11.897 (6.609) 11.666 (6.481)	11.810 (6.561)	0.125 (0.070)	1.1

Table 6 shows that the standard deviation of the three tests is less than 0.20 microstrain/°C (0.10 microstrain/°F), or less than 1.5%, which indicates a good repeatability value for the CTE test procedure.

2. Variation due to Different Test Equipment

Selected samples were also tested at both the Iowa DOT and ISU to study the variation in CTE due to different equipment. Prior to the CTE tests, both test devices at the Iowa DOT and ISU were calibrated with a standard steel bar. The calibration values (CTE of the standard bar) from the Iowa DOT and ISU were 19.359 and 17.876 microstrain/°C (10.755 and 9.931 microstrain/°F), respectively; the value from the steel bar producer was 18.540 microstrain/°C (10.300 microstrain/°F).

The test results from both ISU and the Iowa DOT are shown in Table 7. The table illustrates that the standard deviations of the average values obtained from the two devices range from 0.048 to 1.412 microstrain/°C (0.027 to 0.784 microstrain/°F), all within 15%. This indicates that the test results from the Iowa DOT and ISU are in good agreement.

Table 7. Variations in CTE resulting from the use of different equipment

Core #	Aggregate	CTE, $10^{-6}/^oC$ ($10^{-6}/^oF$) IA DOT	ISU PCC	STDEV	Rel. STDEV, %
Core 3-7174	Quartzite	12.469 (6.927)	12.730 (7.072)	0.185 (0.102)	1.46
Core 3-7186	Quartzite	12.745 (7.081)	12.812 (7.118)	0.048 (0.027)	0.37
Core 3-7051	Quartzite	12.179 (6.766)	12.319 (6.844)	0.099 (0.055)	0.81
Core 3-7091	Quartzite	12.236 (6.798)	12.743 (7.080)	0.359 (0.199)	2.87
Core 5-0260	Limestone	9.343 (5.190)*	11.339 (6.300)**	1.412 (0.784)	13.65
Core 54-0004	Limestone + Dolomite	10.772 (5.984)*	11.810 (6.561)**	0.734 (0.408)	6.50

* Average of two testing data, ** Average of three testing data

3. Variation Due to Batch Material Consistency

In order to study the variation in CTE tests resulting from batch mixing/production, core samples were taken from two field sites (Cedar Valley Corp. and Irving F. Jensen), both of which used Quartzite as coarse aggregate. Six samples from each site were collected and tested for CTE. The test results are shown in Table 8.

Table 8. Thermal coefficient of Iowa core samples

	Core #	CTE, $10^{-6}/^oC$ ($10^{-6}/^oF$)	Mean, $10^{-6}/^oC$ ($10^{-6}/^oF$)	STDEV, $10^{-6}/^oC$ ($10^{-6}/^oF$)	Rel. STDEV
Cedar Valley Corp.	3-7174	12.730 (7.072)	12.765 (7.092)	0.179 (0.100)	1.40
	3-7176	12.923 (7.179)			
	3-7186	13.031 (7.240)			
	3-7177	12.579 (6.988)			
	3-7175	12.600 (7.000)			
	3-7180	12.728 (7.071)			
Irving F. Jensen	3-7201	13.031 (7.239)	12.514 (6.952)	0.466 (0.259)	3.72
	3-7204	12.645 (7.025)			
	3-7200	12.817 (7.121)			
	3-7199	11.884 (6.602)			
	3-7198	11.993 (6.663)			
	3-7196	12.714 (7.064)			

A statistical analysis was performed to study the distribution of the measured thermal coefficients. For the Cedar Valley Corp. and Irving F. Jensen samples, the results showed a mean CTE of 12.765 and 12.514 microstrain/^oC (7.092 and 6.952 microstrain/^oF) with a standard deviation of 0.179 and 0.466 microstrain/^oC (0.100 and 0.259 microstrain/^oF), respectively. This indicates that the degree of variation of CTE test results within the given projects was limited.

4.2. CTE for PCC with Different Aggregate

The Iowa DOT performed CTE tests for concrete with various aggregate types. These data were collected (Table 9), and more tests were performed at ISU on additional field samples collected by the Iowa DOT (see Table 6). A total of 28 concrete samples made with commonly used Iowa aggregate were tested.

Table 9. Summary of CTE values for PCC with different types of aggregate

	CTE, $10^{-6}/^oC$ ($10^{-6}/^oF$)	Test location	# of data	Avg. CTE, $10^{-6}/^oC$ ($10^{-6}/^oF$)	Stdev, $10^{-6}/^oC$ ($10^{-6}/^oF$)
Dolomite	12.190 (6.772) 11.012 (6.118) 13.447 (7.471) 12.939 (7.188)	Iowa DOT	4	12.03 (6.68)	1.060 (0.589)
Limestone	9.844 (5.469) 11.479 (6.377) 9.423 (5.235)	Iowa DOT	3	10.25 (5.69)	1.086 (0.603)
Quartzite	12.179 (6.766) 12.236 (6.798) 11.21 (6.228) 10.545 (5.858) 12.730 (7.072) 12.923 (7.179) 13.031 (7.240) 12.579 (6.988) 12.600 (7.000) 12.728 (7.071) 13.031 (7.239) 12.645 (7.025) 12.817 (7.121) 11.884 (6.602) 11.993 (6.663) 12.714 (7.064)	Iowa DOT and ISU	16	12.35 (6.86)	0.680 (0.378)
Limestone + Gravel	11.740 (6.522) 14.429 (8.016)	Iowa DOT	2	13.08 (7.27)	1.901 (1.056)
Limestone + Dolomite	10.882 (6.045) 10.612 (5.896) 10.01 (5.561)	Iowa DOT	3	10.50 (5.83)	0.446 (0.248)
		Total	28	11.32 (6.29)	1.525 (0.847)

Table 9 indicates that the order of CTE values for concrete made with different aggregates, from high to low, is quartzite, dolomite, and limestone. Concrete made with limestone as a coarse aggregate has a lower thermal coefficient ($10.25x10^{-6}/^oC$ or $5.69\ x10^{-6}/^oF$) compared to concrete made with either dolomite ($12.03x10^{-6}/^oC$ or $6.68x10^{-6}/^oF$) or quartzite ($12.35\ x10^{-6}/^oC$ or $6.86\ x10^{-6}/^oF$). These results are consistent with those reported in the literature (Tables 1 and 3).

In the MEPDG, the default input value for CTE is 9.9 microstrain/^{o}C (5.5 microstrain/^{o}F), which only matches the value of Iowa concrete made with limestone. This study clearly suggests that the MEPDG should use a different value for concrete made with aggregates other than limestone.

In the present study, more CTE data were obtained from the Long-Term Pavement Performance (LTPP) database (LTPP-TST_PC03). These data are presented in Appendix A. Due to a lack of complete information on the concrete materials, these LTPP data could not be used to study the effect of concrete materials on CTE.

4.3. Study of Thermal Conductivity of Concrete

A typical Iowa PCC pavement mix (C-3WR-C20), with limestone as coarse aggregate, was selected for thermal conductivity testing. The detailed mix design of the concrete can be found in Appendix B, Table 11. The fresh concrete had a unit weight of 143.8 pcf, with a slump of 2.25 in., air content of 5.5%, and a seven-day compressive strength of 4209 psi. Three concrete plates, with dimensions of 12 in.x12 in.x1.5 in. (see Figure 6), were prepared at ISU and then sent to CTL for testing. The thermal conductivity of the PCC concrete was reported as 9.25 Btu•in/hr•ft^{2}•^{o}F (see Appendix C).

In the MEPDG, the default thermal conductivity value for PCC is 15 Btu•in/hr•ft^{2}•^{o}F (1.25 Btu•/hr•ft•^{o}F), which is about 50% higher than the typical Iowa pavement mix with limestone as coarse aggregate.

(a) Mold for sample preparing **(b) Thermal conductivity test sample**

Figure 6. Preparation of PCC thermal conductivity samples

A typical Iowa ACC mix with limestone as coarse aggregate was also selected for thermal conductivity testing. The detailed mix design of ACC can be found in Appendix D, Table 12. Four ACC concrete plates, with dimensions of 15 in. x 8 in. x 2 in. (Figure 7), were made using a roller compactor at ISU's asphalt lab and then sent to CTL for testing. The ACC had design air voids of 4%, voids in the mineral aggregate of 14.4%, and voids filled with asphalt of 72.3%. See Appendix E.

(a) Roller compactor **(b) Thermal conductivity test sample**

Figure 7. Preparation of ACC thermal conductivity samples

In the MEPDG, the default thermal conductivity value for ACC is 8.04 Btu•in/hr•ft^2•^{o}F (0.67 Btu•/hr•ft•^{o}F), which is about 45% lower than the typical Iowa pavement mix with limestone as coarse aggregate.

Concerns were raised regarding the difference in the thermal conductivity values between the tested Iowa PCC and ACC values and the MEPDG default values. Discussions were held among the research team and Iowa DOT members on the effects and sensitivities of the thermal conductivity on pavement performance predicted by MEPDG. With inputs from experts at FHWA, the investigators learned that research has shown that as thermal conductivity increases, faulting and cracking of PCC decrease. Cracking is more sensitive to thermal conductivity when compared to faulting. It is therefore very important to have accurate thermal conductivity value for proper use of MEPDG.

However, as mentioned previously, no proper, standard thermal conductivity test method is currently available for pavement concrete. The thermal conductivity tests of Iowa concrete presented above were done outside, for one PCC mix and one ACC mix only, and it is difficult to assess the accuracy of the data. Although commonly used for concrete testing, ASTM C177 is also specified for homogeneous materials. The sample size, 12 in. x12 in. x 1 in. (30 cm x 30 cm x 2.5 cm), seems too thin to simulate field pavement concrete condition. Thus, the test method may also be unable to provide a "correct or true" thermal conductivity value. It is reported that the ASU test method requires a regular size cylinder sample and has some advantages over the C177. The investigators have learned that FHWA is interested in getting the necessary equipment to study the thermal conductivity test method proposed by ASU, but no one knows when this will take place.

As a result, the investigators suggest using the default thermal conductivity values, rather than the tested values obtained from CTL, in MEPDG until this issue is addressed by the MEPDG developers and a new test method is developed and standardized in the future.

5. SUMMARY OF FINDINGS

1. Variations in CTE measurements resulting from test procedures, equipment used, and batch consistency were investigated. The standard deviation due to the AASHTO CTE test procedure ranged from 0.072 to 0.162 $x10^{-6}/^{o}C$ (0.04 to 0.09 $x10^{-6}/^{o}F$), within 1.5%. The standard deviation due to two different test devices at ISU and the Iowa DOT ranged from 0.048 to 1.412 $x10^{-6}/^{o}C$ (0.027 to 1.412 $x10^{-6}/^{o}F$), within 15%. The standard deviation due to batch material inconsistency ranged from 0.179 to 0.466 $x10^{-6}/^{o}C$ (0.011 to 0.259 $x10^{-6}/^{o}F$), within 4%. These variations are generally acceptable in concrete testing.

2. Twenty-eight different CTE samples were collected and tested at the Iowa DOT and ISU's Portland Cement Concrete (PCC) Research Laboratory . The average CTE values for concrete made with limestone, dolomite, and quartzite were $10.25x10^{-6}/^{o}C$ (5.69 $x10^{-6}/^{o}F$), $12.03x10^{-6}/^{o}C$ ($6.68x10^{-6}/^{o}F$), and 12.35 $x10^{-6}/^{o}C$ (6.86 $x10^{-6}/^{o}F$), respectively. In the MEPDG, the default CTE value for PCC is $9.9x10^{-6}/^{o}C$ (5.5 $x10^{-6}/^{o}F$), which is close to the value of Iowa concrete made with limestone. Therefore, different values should be used in the MEPDG for concrete made with aggregate other than limestone.

3. Typical mixes of Iowa PCC and asphalt cement concrete (ACC) (both with limestone as coarse aggregate) were selected, and the thermal conductivity values of the concrete mixes were tested at CTL. The thermal conductivity values were reported to be 9.25 Btu•in/hr•ft^{2}•^{o}F for PCC and 14.5 Btu•in/hr•ft^{2}•^{o}F for ACC. Both values were significantly different than the default inputs in the MEPDG, 15 Btu•in/hr•ft^{2}•^{o}F for PCC and 8.04 Btu•in/hr•ft^{2}•^{o}F for ACC.

4. A literature review has shown that the factors that affect the thermal properties of concrete include concrete materials (especially aggregate), mix proportion, moisture condition, and age. Some of these factors have been considered in the concrete CTE prediction equation. However, due to the lack of a complete set of CTE data for Iowa concrete (with CTE values and information on material and mix proportion), the calibration of this prediction equation could not be performed. Properly documenting all material, design, and construction information is important for further study.

5. Due to the limited duration and budget of the project, only a small number of samples were tested and analyzed. A systematic study of the effect of mix design and aggregate type on thermal properties, especially on CTE, thermal conductivity, and specific heat, is essential. Such a study would help update the typical Iowa material input values and provide rational predictions using the MEPDG in concrete pavement design in the future. The Iowa DOT should continue to routinely run the CTE test on project cores to build a database to further refine the Design Guide input.

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APPENDIX A. CTE DATA FROM LTPP DATABASE

Table A1 shows the 21 sets of CTE data that were found in LTPP database "LTPP_TST_PC03."

Table A1. CTE data from LTPP database

SHRP_ID	TEST_DATE	Agg. Type	CTE, $10^{-6}/^{o}C$ ($10^{-6}/^{o}F$)
3006	28-Oct-96	Chert	11.50 (6.39)
3009	10-Mar-05	NA	9.80 (5.44)
3009	27-Jan-03	Limestone	12.80 (7.11)
3009	16-Jun-04	NA	9.60 (5.33)
3009	08-Jun-04	NA	10.60 (5.89)
3028	03-Nov-97	NA	8.80 (4.89)
3033	21-Oct-03	NA	8.30 (4.61)
3055	07-Oct-02	NA	10.20 (5.67)
5042	19-May-04	NA	8.90 (4.94)
5042	06-May-04	NA	8.10 (4.50)
5042	27-Apr-04	NA	8.50 (4.72)
5042	05-May-04	NA	8.40 (4.67)
5042	05-Jan-99	NA	8.70 (4.83)
5046	08-Jul-03	NA	8.80 (4.89)
5046	28-Aug-98	NA	9.20 (5.11)
5046	29-May-03	NA	8.00 (4.44)
5046	22-Dec-03	NA	8.80 (4.89)
9116	03-Sep-98	NA	9.90 (5.50)
9126	25-Nov-97	NA	12.40 (6.89)
9126	15-Oct-02	NA	11.50 (6.39)
9126	24-Sep-02	NA	10.80 (6.00)
	Average		9.70 (5.39)
	STDEV		1.42 (0.79)
	Rel. STDEV, %		14.69
	Number of Data		21

APPENDIX B. THERMAL CONDUCTIVITY PCC SAMPLE MIX DESIGN

Table B1. Thermal conductivity PCC sample mix design

Rev 02/01 | **Iowa Department Of Transportation** | Form E820150E

Office Of Materials

PORTLAND CEMENT CONCRETE

Project No.: ____________ **County :** ____________

Mix No.:	C-3WR-C20	Pounds Cement:	571		
1st Adjusted lbs. Cement:	457	Source:	Lafarge I/II	Sp. Gr.:	3.14
IM 491.17 Fly Ash:	114	Source:	Ottumwa	Sp. Gr.:	2.73
IM 491.14 Slag GGBFS:		Source:		Sp. Gr.:	
2nd Adjusted lbs. Cement:	457				
Total Cementitious	571				

IM T203	Fine Aggregate Source:	Hallet Ames South	Sp. Gr.: 2.66
IM T203	Interm. Aggregate Source:		Sp. Gr.:
IM T203	Coarse Agregate Source:	Ames Mine	Sp. Gr.: 2.57

Basic w/c	0.400	Water (lbs/cy) = Design w/c (wt. cement + wt Fly Ash +Slag) =	228
Max w/c	0.489	Max. Water (lbs/cy) = Design w/c (wt. cement + wt Fly Ash +Slag) =	279

Absolute Volumes

Cement	(lbs/cy) / (Sp. Gr. X 62.4 X 27)	=	0.086
Fly Ash	(lbs/cy) / (Sp. Gr. X 62.4 X 27)	=	0.025
Slag	(lbs/cy) / (Sp. Gr. X 62.4 X 27)	=	
Water	(lbs/cy) / (1.00 X 62.4 X 27)	=	0.136
Air			0.060
	Subtotal	=	0.307
	1.000 - Subtotal	=	0.693
	Total	=	1.000

% FA Agg.:	45	Fine Aggregate (1.000 - Subtotal) X % In Mix	=	0.312
% In. Agg.:		Interm. Aggregate (1.000 - Subtotal) X % In Mix	=	
% CA Agg.:	55	Coarse Aggregate (1.000 - Subtotal) X % In Mix	=	0.381
		Aggregate Total	=	0.693

Aggregate Weights

Fine Aggregate (abs vol.) X Sp. Gr. X 62.4 X 27	=	1398
Intermediate Aggregate (abs vol.) X Sp. Gr. X 62.4 X 27	=	
Coarse Aggregate (abs vol.) X Sp. Gr. X 62.4 X 27	=	1650

Summary

Cement	457	(lbs/cy)
Fly Ash	114	(lbs/cy)
Slag		(lbs/cy)
Water	228	(lbs/cy)
Fine Agg.	1398	(lbs/cy)
Interm. Agg.		(lbs/cy)
Coarse Agg.	1650	(lbs/cy)

Distribution: ___ Materials, ___ DME, ___ Proj. Engr., ___ Contractor

APPENDIX C. PCC THERMAL CONDUCTIVITY TEST REPORT

April 2, 2007

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ASTM C177 Thermal Conductivity Test Results for a Portland Cement Paving Concrete
CTLGroup Project No. 313119

Dear Kejin:

As authorized by ISU Purchase Order No. I7-50977-00, CTLGroup has performed thermal conductivity testing of provided specimens that were indicated to be a portland cement paving concrete. This report documents the test method and results.

TEST SPECIMENS

On February 21, 2007, three test specimens were delivered to CTLGroup. They arrived in the wood moulds that they were cast in, per our instructions (in a series of emails to/from Dr. Jiong Hu of ISU). Dr. Hu indicated that the specimens were cast on the afternoon of February 15, 2007. On February 22nd (when the specimens were 7 days old), we removed the specimens from the wood moulds, visually examined and weighed them, selected two specimens for testing, and placed the selected specimens in a controlled laboratory environment (set at 73°F and 50% relative humidity). On March 15th (when the specimens were 28 days old), the specimens were sealed in plastic bags until the time of testing. The purpose of placing the specimens in the sealed bags was so that internal moisture could re-equilibrate, if needed, prior to the thermal conductivity testing.

Thermal conductivity testing began on March 22nd, as described below. Immediately before this testing, the specimens were weighed and their dimensions were measured. On March 26th, the thermal conductivity testing was completed. Specimens were removed from the test apparatus and weighed. Specimens were then oven dried, by placing them in a 230°F drying oven until their weight change was less than 0.15% in a 24 hour period.

Dimensions and calculated apparent unit weights (weight divided by dimensional volume) of the specimens are presented in Table 1. The calculated apparent moisture contents of the specimens are also presented in Table 1. The apparent moisture contents were determined from the unit weight of the oven dry specimens.

Table 1 – Specimen Dimensions and Unit Weights

ID	Average Dimension, in.			Apparent Unit Weight, pcf (lb/ft^3)				Moisture Content, %			
	Length	Width	Thickness	As Rec'd*	Before Testing	After Testing	Oven Dry	As Rec'd*	Before Testing	After Testing	Oven Dry
B	12.0	12.1	1.45	139.8	136.6	136.5	132.8	5.2	2.8	2.8	0.0
C	12.1	12.1	1.46	139.7	136.3	136.3	132.6	5.4	2.8	2.8	0.0

* Based on when the specimens were removed from the wood moulds.

THERMAL CONDUCTIVITY AND R-VALUE

The thermal conductivity of the specimens was measured at CTLGroup facilities in general accordance with ASTM C177-04, "Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate Apparatus". This method is a primary test method for measuring thermal conductivity of materials, and is the method that is most appropriate for concrete. Testing targeted a mean temperature of 75±5°F.

TEST METHOD

Using a guarded hot plate, two (nearly) identical specimens of the material to be tested are placed on either side of a horizontal flat plate heater assembly consisting of a 5.88-in. square inner (main) heater surrounded by a separately controlled guard heater to form a 12-in. square assembly. The function of the guard heater (the primary guard) is to eliminate lateral heat flow to or from the main heater thereby forcing all heat generated in the main heater to flow one-dimensionally through the two test specimens. The performance of the primary guard is verified by heat flow sensor and a separate temperature sensor. Liquid cooled heat sinks are also placed in contact with the specimens producing a uniform and constant temperature on the outside of each specimen. The apparatus is surrounded by a container filled with vermiculite insulation. The vermiculite insulation serves as a secondary guard. The guarded hot plate apparatus is located in a laboratory maintained at a controlled temperature.

Temperatures were measured with twenty 30-gage Type K thermocouples. Thermocouples consisted of bare wires within a 0.06-in. nominal diameter insulating round dual wire alumina sheathing. All thermocouples had nearly identical electrical resistances and were all from the same production lot to minimize variation and errors in temperature measurement. Measurements were made using a computer-based data acquisition and analysis system.

The rate of heat flow through the specimens is determined by measuring heat input into the heater plate. Data are collected at 10-minute intervals. Thermal conductivity is calculated from data collected over a 3-hour period after equilibrium heat flow and temperatures are reached.

THERMAL CONDUCTIVITY TEST RESULTS

Thermal conductivity test results are presented in Table 2. Test results are averages of data collected over a 3-hour period after steady-state equilibrium was achieved.

Test duration includes the time before steady-state equilibrium is reached. The average temperature gradient is the temperature gradient across each specimen, averaged for the two specimens. Other terms used in Table 2 are defined in ASTM C 1045-01, "Standard Practice for Calculating Thermal Transmission Properties under Steady-State Conditions".

Table 2 – Thermal Conductivity Test Results

Test		Temperature, °F				Heat Flux (q) Btu/hr·ft²	Thermal Conductivity** (k) Btu·in./hr·ft²·°F
Date	Duration,* days	Hot Side (T_h)	Cold Side (T_c)	Average Gradient (ΔT)	Mean (T_m)		
3/26/2007	3.6	76.6	65.2	11.4	70.9	49.6	9.25

* Includes time before steady-state equilibrium was achieved.

Thank you for choosing CTLGroup for your testing needs, we appreciate the opportunity to work with you. We will retain the tested and untested specimens until May 1, 2007, at which time they will be discarded unless we hear otherwise from you. Should you have any questions or need thing else, please contact me.

Sincerely,

CONSTRUCTION TECHNOLOGY LABORATORIES, INC.
An AASHTO Accredited Laboratory – Aggregate, Cement and Concrete

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Principal Engineer
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cc: Jiong Hu, Iowa State University, johnlhu@iastate.edu

APPENDIX D. THERMAL CONDUCTIVITY HMA SAMPLE MIX DESIGN

Table D1. Thermal conductivity HMA sample mix design

Iowa Department of Transportation
Highway Division - Office of Materials
HMA Gyratory Mix Design

County: GREENE | Project: MP-004-1(704)11--76-37 | Mix No.: 1BD3-003
Mix Size (in.): 1/2" | Contractor: MANATS INC | Contract No.: 37-0041-7(
Mix Type: HMA 1M | Design Life ESAL's: 1,000,000 | Date Reported: 4/15/2003
Intended Use: Surface | Project Location: IOWA 4 FROM N. OF N. JCT IOWA 144, N 10.85 MILES

Aggregate	% in Mix	Source ID	Source Location	Beds	G_{sb}	%Abs	FAA
Aggregate,	1/2 CR ASPH EC	A85006	MARTIN MARIETTA AMES	28-39	2.598	2.16	45.0
Source IDs,	1/4 CL CHIP GC	A85006	MARTIN MARIETTA AMES	19-25	2.6	1.78	5.0
Beds & % in	MANF SAND EC	A85006	MARTIN MARIETTA AMES	28-39	2.584	2.76	10.0
Mix:	SAND	A85510	HALLETT MTLS AMES S PIT		2.583	1.52	40.0

Job Mix Formula - Combined Grdation (Sieve Size in.)

	1"	3/4"	1/2"	3/8"	#4	#8	#16	#30	#50	#100	#200
Upper Tolerance	100	100	100	95	72	58		29			6
	100	100	98	88	65	53	39	25	9.4	4.4	4
Lower Tolerance	100	100	91	81	58	48		21			2

Asphalt Binder Source and Grade: BITUMINOUS MTLS PG 64-22

			Gyratory Data		Interpolated	
% Asphalt Binder	4.5	5.5	6.5		5.59	Number of Gyrations
Corrected Gmb @ N-Des.	2.32	2.346	2.38		2.349	N-Initial
Max. Sp.Gr. (G_{mm})	2.488	2.451	2.409		2.447	7
% G_{mm} @ N-Initial	87.3	89.6	92.1		89.8	N-Design
% G_{mm} @ N-Max	94.1	96.6	99.6		96.9	76
% Air Voids	6.8	4.3	1.2		4	N-Max
% VMA	14.5	14.4	14.1		14.4	117
% VFA	53.4	70.4	91.5		72.3	Gsb for Angularity
Film Thickness	7.1	9.2	11.6		9.5	Method A
Filler Bit. Ratio	1.15	0.89	0.71		0.87	2.585
G_{sb}	2.591	2.591	2.591		2.591	Pba/%Abs Ratio
G_{se}	2.665	2.665	2.656		2.662	0.54
P_{be}	3.44	4.46	5.59		4.56	Slope of Compaction
P_{ba}	1.11	1.11	0.97		1.06	Curve
% New Asphalt Binder	100	100	100		100	17.3
Asphalt Binder Sp.Gr. @25c	1.031	1.031	1.031		1.031	Mix Gmm Linearity
% Water Abs	1.95	1.95	1.95		1.95	
S.A. m^2/Kg.	4.82	4.82	4.82		4.82	Pb Range Check
%+4 Type Agg. Or Better	98	98	98		98	
%+4 Type 2 or 3 Agg.	2	2	2		2	Specification Check
Angularity-method A	41	41	41		41	
% Flat & Elongated	0	0	0		0	TSR Check
Sand Equivalent	81	81	81		81	

Disposition: An asphalt content of is recommended to start this project.
Data shown in column is interpolated from test data.

Comments: Target AC 6.1

Copies to: MANATTS INC District 1 Marshalltown RCE Central Lab
District 1 Lab

Signed: ____________________

APPENDIX E. HMA THERMAL CONDUCTIVITY TEST REPORT

October 18, 2007

CTLGROUP
Building Knowledge. Delivering Results.
CONSTRUCTION TECHNOLOGY LABORATORIES
ENGINEERS & CONSTRUCTION TECHNOLOGY CONSULTANTS

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ASTM C177 Thermal Conductivity Test Results for Asphalt Concrete Specimens
CTLGroup Project No. 313119

Dear Kejin:

As authorized by ISU Purchase Order No. I7-50977-00, CTLGroup has performed thermal conductivity testing of provided specimens that were indicated to be asphalt concrete. This report documents the provided specimens, test method, and results.

TEST SPECIMENS

At your request, CTLGroup picked up four test specimens from the Illinois Institute of Technology on September 13, 2007. The specimens had nominal dimensions of 15x8x2 in., and were labeled by others as "ISU 1-1", "ISU 1-2", "ISU 1-3", and "ISU 1-4". You indicated that the specimens were fabricated at Iowa State University.

Upon receipt, the specimens were driven back to CTLGroup facilities, where each specimen was weighed, sealed in a plastic bag, and placed in a temperature-controlled laboratory environment until the time of testing.

Two specimens are required for the thermal conductivity testing. Specimens "ISU 1-1" and "ISU 1-2" were selected for this testing. Dimensions and calculated apparent unit weights (weight divided by dimensional volume) of the specimens are presented in Table 1. The specimens were tested in their as-received condition.

Table 1 – Specimen Dimensions and Unit Weights

ID	Average Dimension, in.			Apparent Unit Weight, pcf (lb/ft^3)	
	Length	Width	Thickness	Before Test	After Test
ISU 1-1	15.1	8.2	1.94	142.7	141.8
ISU 1-2	15.1	8.3	1.96	140.9	140.1

THERMAL CONDUCTIVITY

The thermal conductivity of the specimens was measured at CTLGroup facilities in general accordance with ASTM C177-04, *Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded Hot Plate*

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