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Thermal conductivity of ternary mixtures for concrete pavements

Alex Hak-Chul Shin [a,*], Upender Kodide [b,1]

[a] Department of Civil and Environmental Engineering, Louisiana State University, 3505-C Patrick F. Taylor Hall, Baton Rouge, LA 70803, United States
[b] Department of Civil and Environmental Engineering, Louisiana State University, 3418 Patrick F. Taylor Hall, Baton Rouge, LA 70803, United States

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ABSTRACT

This study used a standard procedure to measure the thermal conductivity of ternary concrete mixtures and investigated several factors influencing thermal conductivity. Three different coarse aggregates (Kentucky limestone, Mexican limestone, and river gravel) were used for the concrete mixtures. The measured thermal conductivity of concrete is significantly affected by the type and percentage of coarse aggregate, and moisture content. This finding was confirmed statistically by an Analysis of Variance (ANOVA) method. To understand the effect of supplementary cementitious materials (SCMs), the thermal conductivity of the control and ternary mixtures were measured and provided for use in Portland cement concrete (PCC) pavement design. The thermal conductivity of ternary mixtures increased by 7–10% due to an increase of 1% in moisture. The study developed a model equation that predicts the thermal conductivity of concrete as a function of moisture content and coarse aggregate percentage.

1. Introduction

The Mechanistic–Empirical Pavement Design Guide (MEPDG) is a new pavement design guide developed to improve the current American Association of State Highway and Transportation Officials (AASHTO) pavement design process by incorporating mechanistic aspects of design parameters. A few limitations of the AASHTO design were resolved in MEPDG by incorporating thermal properties, new axle loads spectra conditions, and enhanced material models. Thermal properties included in the MEPDG are coefficient of thermal expansion (CTE), thermal conductivity, and heat capacity. Every Portland cement concrete (PCC) mixture has unique thermal property values based on its mixture proportions. These thermal properties are basic parameters in understanding the heat flow in a material. An ASTM E1952 test was recommended by MEPDG for testing the thermal conductivity of concrete. However, the thermal conductivity of concrete (2.0–3.0 W/m K) is typically higher than the measuring capacity (0.1–1.0 W/m K or 0.05779–0.5779 Btu/ft h °F) of the testing equipment specified in ASTM E1952 [1–3]. In addition, the ASTM test using differential scanning calorimetry (DSC) is typically for quite small specimens that may not be homogeneous in the case of concrete and/or aggregates [4].

Thermal conductivity is defined as the ratio of the heat flux to the temperature gradient. It is the uniform flow of heat in a specific sample from one side to the other. Concrete is a heterogeneous and porous solid material, and the heat propagation in concrete at normal operating temperatures is primarily by conduction. Aggregate type, percent of cement paste, coarse aggregate, fine aggregate, porosity, supplementary cementitious materials (SCMs), and the moisture and temperature of local environment are some of the factors that affect the thermal conductivity of concrete [5–8]. Thermal conductivity (K) is generally expressed using the following formula:

$$K = (\Delta Q * x)/(\Delta t * A * \Delta T) \quad (1)$$

where K is the thermal conductivity of material, ΔQ is the change in heat energy between two points, x is the distance between two points, Δt is the change in time, A is the area of object in which heat flow is measured, and ΔT is the change in temperature that produced change in heat flow.

As porosity in concrete increases, the probability of moisture accumulation in concrete becomes higher, and the thermal conductivity of concrete increases with moisture. Also, as the porosity of concrete increases particularly pores not filled with water, the density and solid conductivity of concrete decreases resulting in a decrease in thermal conductivity. Bhattacharjee et al. proposed a model determining the porosity of materials by considering the aforementioned parameters [9,10]. Additional SCMs such as fly ash, slag, and silica fume, decrease the thermal conductivity of concrete because the SCMs show a lower density compared to Portland cement. As the density of a concrete specimen decreases, the thermal conductivity of concrete decreases as well. Uysal et al. found that thermal conductivity fluctuation occurs with density fluctuation [7]. Conditionally, Demirboga and Gul found

* Corresponding author. Tel.: +1 225 578 0277; fax: +1 225 578 8652.
E-mail addresses: shin@lsu.edu (A.H.-C. Shin), ukodid1@tigers.lsu.edu(U. Kodide).
[1] Tel.: +1 225 439 9489.

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that the change in the thermal conductivity of concrete is more influenced by fly ash than silica fume [8].

As moisture content varies in concrete, the coefficient of thermal expansion and thermal conductivity also change [11]. According to Becker and Katz moisture moves from the warm (dry) side toward the cold (wet) side when a specimen is tightly sealed and heated. They also reported that thermal conductivity of the cold side is greater than the warm side [12]. Moisture distribution in concrete pavements depends on parameters such as permeability, voids, cracks present in the concrete, climatic conditions, and humidity present in the atmosphere. The thermal conductivity of water is 25 times higher than that of air. Due to the difference of thermal conductivity, concrete in a saturated condition has a high thermal conductivity compared to that in dry condition [13,14]. Steiger and Hurd noted that a 1% increase in unit weight of concrete due to water absorption results in the increase of the thermal conductivity by 5%, due to water absorption [15].

Kim et al. worked with seven parameters that affected thermal conductivity of concrete and explicitly explained the effect of each individual parameter [6]. The seven parameters were age, amount of cement, SCMs, aggregate volume fraction, water–cement ratio, relative humidity, temperature, and fine aggregate fraction. Among those parameters, age, amount of cement, and SCMs exhibited a low change in thermal conductivity. They concluded that aggregate fraction and moisture mainly effect thermal conductivity of concrete.

This study mainly focuses on using the Quickline-30 equipment and a standard test procedure for measuring thermal conductivity of plain and ternary concrete mixtures. The effects of influencing factors, such as coarse aggregate type, percentage of coarse aggregate, moisture, and SCM's, were investigated.

2. Materials and methods

2.1. Testing equipment

The Quickline-30 is a product of Anter Corporation, Pittsburgh, PA, USA (Fig. 1). It consists of multi-functional portable equipment used for measuring surface temperatures, thermal conductivity, heat capacity, and thermal diffusivity. This equipment uses the principle of the transient heat line method that helps in reducing testing time compared to other methods involving steady-state conditions. The surface temperature and thermal conductivity of the specimen are measured using the probe that contains a heating-coil. Quickline-30 equipment uses the standard ASTM D 5930 method for finding thermal conductivity of plastics by means of a transient line-source technique. It also uses the ASTM D 5334 standard test method for a determination of the thermal conductivity of soil and soft rock by a thermal needle probe procedure. The Quickline-30 with a measuring range of 0.08–6 W/m K (0.46–3.47 Btu/ft h °F) and precision measurement of ±10% of the read values was used. The reproducibility is ±3% of the read values, and the measuring time is typically 16–20 min.

Fig. 1. Experimental set-up of the Quickline-30.

2.2. Concrete mixture design of control mixtures and ternary mixtures

To study the effects of different types of aggregate on thermal properties, five different mixtures were designed. Three mixtures had different coarse aggregates: Kentucky limestone (limestone from the Three rivers rock quarry in Kentucky), siliceous river gravel (TXI, Dennis Mills), and Mexican limestone (limestone from Tampico, Mexico). Siliceous sand (TXI, Dennis Mills) was used as a fine aggregate for all of the mixtures. These aggregates are mostly used in the construction of PCC pavements in the Louisiana Department of Transportation and Development (DOTD), and the aggregate properties are presented in Table 1. To study the composition of the coarse aggregates, the microanalysis of the aggregates was performed using the energy-dispersive X-ray spectroscopy (EDAX) connected to a scanning electron microscope (SEM). Table 2 presents the microanalysis results of the aggregates. In case of river gravel, two distinct gravels having different color from the same source were used for the analysis. The number in the table shows the weight percent of the elements.

Two additional mixtures were fabricated using Kentucky limestone to study the effects of coarse aggregate proportion on thermal properties. The mixtures were named using the type and percentage of coarse aggregate in the concrete mixture. For example, K_{65} represents the concrete mixture that consists of 65% Kentucky limestone by volume. The same amount of Type II Portland cement (Holcim) was used in all blends. Daravair 1440 and WRDA 35 were used as admixtures to provide desired air content and workability.

SCMs mixtures were cast to understand the effects of different SCMs individually as well as collectively on thermal conductivity and moisture content. All the SCM mixtures used Kentucky limestone as a coarse aggregate. The mixtures had the same coarse aggregate proportions (60%) and fine aggregate proportions (40%) by volume. They had a water-to-cementitious material ratio (*w*/*cm*) of 0.45 by mass. Cement paste proportions were varied based on the nomenclature of the specimen described. Concrete mixtures made of 100% ordinary Portland cement (OPC) or with a single SCM are named as control mixtures. Concrete mixtures containing two SCMs are known as ternary mixtures. In these mixtures, a different type of Portland cement (Type I) was used since this study had been focused on the replacement of Portland cement with SCMs. An OPC mixture was designated as $TI_{(100)}$, where TI represents Type I cement and the subscript represents the percentage of component in the cement paste. Class C fly ash (C), class F fly ash (F), grade 100 slag ($G^{100}S$), and grade 120 slag ($G^{120}S$) were the SCMs used for casting concrete specimens. Table 3 presents chemical compositions of the SCMs according to X-ray fluorescence (XRF) analyses. ASTM C618 specifies the limitations of chemical requirements for fly ashes [16]. All of the chemical compositions of fly ashes met the standard. The class C fly ash was obtained from Headwaters Inc., Westlake, Louisiana; the class F fly ash was obtained from Headwaters Inc., Tatum, Texas; the grade 100 slag

Table 1
Properties of coarse and fine aggregates.

Aggregate type	Absorption (%)	Specific gravity	Maximum size (in.)
Kentucky limestone	1.0	2.69	1.5
Mexican limestone	3.5	2.62	1.5
River gravel	2.2	2.53	1.5
Siliceous sand	0.5	2.61	–

Table 2
Element composition of coarse aggregates.

Element	Kentucky limestone	Mexican limestone	River gravel a[a]	River gravel b[a]
C K	12.93	19.48	16.41	10.44
O K	35.35	38.21	40.61	37.69
NaK	–	–	0.39	0.32
MgK	3.06	3.36	4.26	–
AlK	1.05	1.48	1.18	1.14
SiK	3.96	4.79	3.70	49.82
K K	–	–	0.60	–
CaK	43.65	32.08	33.44	0.58

[a] Two distinct aggregates having different color from the same river gravel.

Table 3
Chemical compositions of SCMs.

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

was obtained from Holcim Inc., Theodore, Alabama; and the grade 120 slag was obtained from BuzziUnicem, New Orleans, Louisiana. Detailed mixture proportions can be found in Kodide's thesis [17].

Concrete specimens were fabricated and mechanical properties were tested according to the ASTM standards. Thermal properties were measured after 28 days of curing. The aging effect of thermal properties was not examined in this study. Table 4 shows the mechanical properties of control mixtures and ternary mixtures fabricated for testing thermal conductivity and heat capacity. Some mixtures (K_{20} and $TI_{(30)}$–$G^{100}S_{(50)}$–$F_{(20)}$) had zero slump due to their extreme mixture designs and resulted in large voids in some specimens, and those specimens were not used for thermal conductivity tests.

2.3. Experimental procedure measuring thermal conductivity

The top surface of cylindrical specimens ($\Phi 10 \times 20$ cm) is normally undulated compared to the bottom, because the top surface is left open during the curing process of the concrete. The measurement of thermal properties in undulated surfaces with the Quickline-30 probe was difficult, as it required a smooth surface to have complete contact between the probe and testing surface.

Table 4
Mechanical properties of mixtures.

Mixtures	Compressive strength (MPa)	Poisson's ratio	Elastic modulus (GPa)	Slump (cm)	Unit weight (kg/m^3)	Air content (%)
Different aggregate mixtures						
K_{65}	51.1	0.26	44.6	0.6	2313	7.0
K_{20}	19.3	0.19	21.0	0.0	2293	3.5
K_{80}	32.0	0.24	34.6	0.6	2383	3.6
G_{65}	33.8	0.14	35.0	3.8	2242	6.3
M_{65}	40.9	0.26	31.4	3.2	2389	4.0
Control mixtures						
$TI_{(100)}$	40.4	0.23	36,5	5.8	2361	4.5
$TI_{(80)}$–$C_{(20)}$	33.5	0.23	31.2	12.7	2306	6.0
$TI_{(80)}$–$F_{(20)}$	33.4	0.20	33.6	12.7	2306	5.8
$TI_{(50)}$–$G^{100}S_{(50)}$	46.8	0.22	36.0	6.4	2348	4.4
$TI_{(50)}$–$G^{120}S_{(50)}$	48.0	0.19	34.6	6.4	2309	5.1
Ternary mixtures						
$TI_{(50)}$–$G^{100}S_{(30)}$–$C_{(20)}$–$SF_{(5)}$	55.2	0.24	39.3	7.6	2348	4.5
$TI_{(50)}$–$G^{100}S_{(30)}$–$C_{(20)}$	29.5	0.20	30.5	17.3	2354	4.3
$TI_{(40)}$–$G^{100}S_{(30)}$–$C_{(30)}$	37.7	0.21	34.6	8.4	2313	4.7
$TI_{(30)}$–$G^{100}S_{(30)}$–$C_{(40)}$	33.3	0.22	34.3	12.7	2297	5.2
$TI_{(30)}$–$G^{100}S_{(50)}$–$C_{(20)}$	44.3	0.23	34.3	10.9	2345	3.5
$TI_{(20)}$–$G^{100}S_{(50)}$–$C_{(30)}$	38.3	0.20	35.5	7.6	2332	3.9
$TI_{(10)}$–$G^{100}S_{(50)}$–$C_{(40)}$	18.7	0.20	30.3	8.9	2354	2.7
$TI_{(50)}$–$G^{100}S_{(30)}$–$F_{(20)}$	41.9	0.22	35.8	7.1	2364	3.9
$TI_{(40)}$–$G^{100}S_{(30)}$–$F_{(30)}$	38.0	0.23	33.6	13.3	2370	3.9
$TI_{(30)}$–$G^{100}S_{(30)}$–$F_{(40)}$	31.0	0.24	32.9	15.2	2361	5.8
$TI_{(30)}$–$G^{100}S_{(50)}$–$F_{(20)}$	39.6	0.23	33.4	0.0	2383	2.8
$TI_{(20)}$–$G^{100}S_{(50)}$–$F_{(30)}$	33.1	0.22	34.5	1.3	2389	2.6
$TI_{(10)}$–$G^{100}S_{(50)}$–$F_{(40)}$	20.7	0.21	31.0	20	2361	2.8
$TI_{(50)}$–$G^{120}S_{(30)}$–$C_{(20)}$	59.2	0.23	36.5	2.5	2389	3.2

C: Class C fly ash; F: Class F fly ash; G100S: grade 100 slag; G120S: grade 120 slag.

The bottom surface of specimens showed a higher thermal conductivity compared to the top surface. By examining the cut surface of the cylinders, it was noted that aggregates are accumulated at the bottom surface of the specimen, which causes the difference of thermal conductivity between the two surfaces. For better contact between the probe and the concrete surface, the top surface of the concrete specimens was smoothly ground by 1–2 cm. Thermal conductivity of the concrete specimen was measured by placing a surface probe directly on the ground surface, and these tests were repeated at least three times until satisfactory results were obtained. The standard deviation of the readings was 4.1%.

2.3.1. Effects of specimen size on thermal conductivity and calibrating experimental procedure

The shapes and sizes of the specimens were concerns while testing thermal conductivity of concrete in the early stage of this research. Three different shapes of specimens (rectangular, cubical, and cylindrical) with the same mixture proportions were cast. The thermal conductivity of the rectangular and cubical specimens was measured on three sides, i.e., along length, breadth, and bottom surfaces of specimen. The cylindrical specimen was measured on bottom and top surfaces. From the measurements, it was concluded that shape and size have no significant effect on the thermal conductivity of concrete [17].

2.3.2. Moisture measurement in concrete specimen

Moisture content in concrete specimens was varied to understand the relationship between thermal conductivity and moisture, and to predict their effects on concrete pavement performance. Ground cylindrical concrete specimens were placed in a water bath until the specimens reached an equilibrium saturated condition by monitoring weight change. Thermal conductivity of the saturated specimens was measured. The specimens were then placed in a room with 50% relative humidity, maintained at a temperature between 23 and 25 °C. The weight of the specimens decreased gradually due to the evaporation of water. The specimens were weighed and thermal conductivity tests were conducted at intervals of approximately 24 h until the weight of the specimen remained constant. These specimens were moved into an oven to attain an oven-dry condition. Again the concrete specimens were weighed at intervals of approximately 24 h until the specimen's weight remained constant. Oven temperature was maintained between 45 and 50 °C to prevent any change in the concrete properties.

3. Results and discussion

3.1. Effects of aggregate type and percentage on thermal conductivity

Five mixtures were made of three different types of aggregates, i.e. Mexican limestone (M_{65}), Gravel (G_{65}), and Kentucky limestone (K_{20}, K_{65}, and K_{80}). Thermal conductivities of the mixtures were measured in both saturated surface dry (SSD) and air dry conditions and are presented in Fig. 2. Thermal conductivity of gravel was higher than Mexican limestone and Kentucky limestone. Thus, it was confirmed that aggregate type plays an important role in the thermal conductivity of a mix proportion [6]. Kentucky limestone had two other mixes with different aggregate ratios: K_{20} and K_{80}. Two extreme ratios were chosen to verify the phenomenon of percentage of aggregate affecting thermal conductivity. The K_{20} mix had a higher thermal conductivity due to a high fine aggregate proportion. This is attributed to the high proportion of siliceous sand having a higher thermal conductivity than Kentucky limestone. The errors in the readings were minimized by taking an average of all readings.

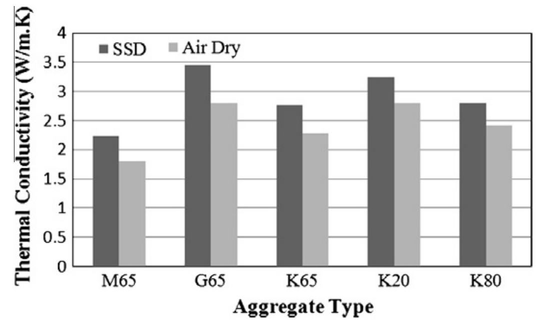

Fig. 2. Thermal conductivity for different aggregate types and proportions.

3.2. Statistical analysis

An Analysis of Variance (ANOVA) was utilized to validate the impact of variables on the thermal properties. One-way ANOVA was employed to investigate the effect of aggregate type, coarse aggregate percentage, and moisture content. Thermal conductivity was measured in air dried and saturated conditions to estimate the significance of moisture on thermal conductivity. The Pr-value indicates the probability of error of the statement. The overall ANOVA results are summarized in Table 5. From column 3 in Table 5, the probability of error was less than 0.05, indicating statistical significance [18]. A statistical analysis was performed for different moisture contents including air dry and saturated conditions. The analysis results verified that the moisture content had a significant effect on the thermal conductivity of concrete. From the analysis, it was also observed that thermal conductivity was significantly affected by the changes in coarse aggregate type and coarse aggregate proportion in the concrete mixtures, respectively.

3.3. Effects of SCMs on thermal conductivity and moisture content in control mixtures

The effects of SCMs on the thermal conductivity of concrete were analyzed by testing specimens with an OPC ($TI_{(100)}$) mixture with Kentucky limestone aggregate. Two other control mixtures containing 20% SCMs (Class C fly ash (C) or Class F fly ash (F) each) were designated as $TI_{(80)}$–$C_{(20)}$ and $TI_{(80)}$–$F_{(20)}$, respectively. Fig. 3 shows the percentage change of thermal conductivity with the change in moisture content. As moisture content increased, thermal conductivity was linearly increased for all the tested specimens. Moisture absorbed by fly ash mixtures was higher compared to that of an OPC mixture, which increased its percentage change in thermal conductivity value by 15%.

Based on the trend lines of percentage change of thermal conductivity of specimens $TI_{(50)}$–$G^{100}S_{(50)}$ and $TI_{(50)}$–$G^{120}S_{(50)}$ in Fig. 4, the moisture absorbed by the Grade 120 slag ($G^{120}S$) was lower than that absorbed by the Grade 100 slag ($G^{100}S$). From all of the four control mixtures, fly ash absorbed the most moisture. The Class F fly ash concrete had a moisture content of about 3.2%, and the percent change of thermal conductivity was 26%. It was observed from the results that, the moisture content in the concrete had to be 2.5–3.5% for a semi saturated condition (i.e. close to 100% relative humidity). For a specimen stabilized in 50% relative humidity, the moisture absorbed was about 1.0–1.5% [17].

3.4. Effect of SCMs on thermal conductivity and moisture content in ternary mixtures

Fig. 5 shows the moisture contents of all the SCM mixtures. The moisture content (%) was calculated using the weight difference of

Table 5
Summary of ANOVA results.

Variables	*F*-value	Pr > *F*	Significance
Moisture content (air dry and saturated condition)	28.80	0.0058	Yes
Aggregate types (K, G, M)	1022.29	<0.0001	Yes
Coarse aggregate proportion (20%, 65%, 80% of K)	786.10	<0.0001	Yes

K: Kentucky limestone, G: gravel, M: Mexican limestone.

each cylinder specimen in saturated and oven-dry conditions. The figures are colored differently to show the groups having a variation of SCM proportion. By comparing control mixtures on the left side of the figures, it was observed that the specimen with fly ash has more moisture absorption, compared to normal concrete and slag-mixed specimens. Among the fly ash concretes, it was noticed that the amount of water absorbed by the mixture containing Class F fly ash is higher than that of Class C fly ash.

Fig. 6 shows the percentage change of thermal conductivity from a dry condition to a saturated condition for control mixtures and ternary mixtures. The thermal conductivity change was proportional to the percentage increase in moisture in concrete specimens. By comparing both figures, ternary mixes having a higher moisture absorption had a higher percentage of thermal conductivity change and vice versa. The change in moisture content was in the range of 1.4–3.4%, and the thermal conductivity change was in the range of 15–36% for these ternary mixtures. Most of the ternary mixtures had a low percentage of moisture content change compared to the $TI_{(100)}$ mixture [17].

The influence of fly ash on control mixtures and ternary mixtures can be further observed. Fly ash absorbed more moisture than OPC as a common phenomenon. As the percentage of fly ash increased in ternary mixtures from 20% to 40%, the moisture absorption of the concrete specimen also increased. A greater fly ash percentage increased moisture absorption and thermal conductivity of the concrete mixtures. Addition of slag decreased moisture absorption of ternary mixtures; mixtures with slag had a decrease in moisture absorption. The slag absorbed low moisture due to its low permeability. These trends explain the significance of the SCMs and their percentages in changing concrete thermal conductivity as well.

Fig. 7 presents the thermal conductivity values of ternary mixtures at SSD condition. Thermal conductivity of ternary mixtures was in the range of 2.12–2.53 W/m K in SSD conditions. The percentage increase of thermal conductivity in control mixtures was 7–10% for a 1% change of moisture content, but the percentage change of thermal conductivity of ternary mixtures was higher compared to control mixtures. An increase in the percentage of thermal conductivity in ternary mixtures was due to moisture change, as well as the high moisture-retaining capacity of fly ash. Demirboga and Gul [8] showed that the addition of SCMs decreases the density of the concrete and consequently decreases thermal conductivity. However, the addition of two or more SCMs can increase the density of concrete, increasing thermal conductivity of ternary mixtures as shown in Table 4.

Steiger and Hurd noted that the thermal conductivity increases 5% for every 1% increase of moisture [15], but the measured increase in thermal conductivity in this research was in the range of 7–10%. SCMs have a higher percentage of thermal conductivity change, and these result in more heat dissipation or high temperatures in middle and lower layers of PCC pavements. According to Janssen [19], moisture distribution through the depth of a pavement profile is often non-linear. The surface of the pavement had 50% humidity: from 5 cm depth, a drastic increase in humidity was observed, reaching 100% humidity at the bottom layers of

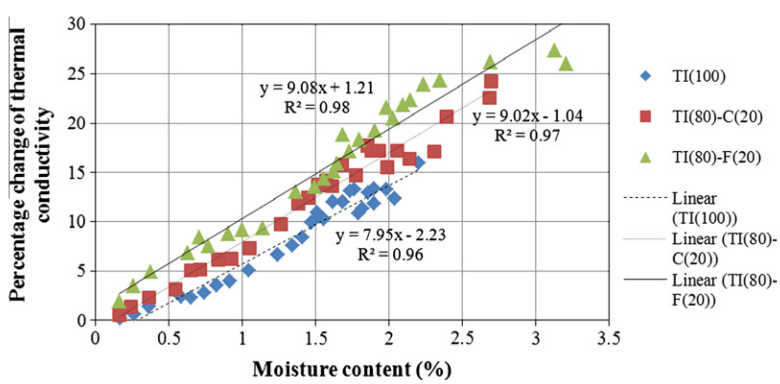

Fig. 3. Thermal conductivity vs. moisture content for control mixture.

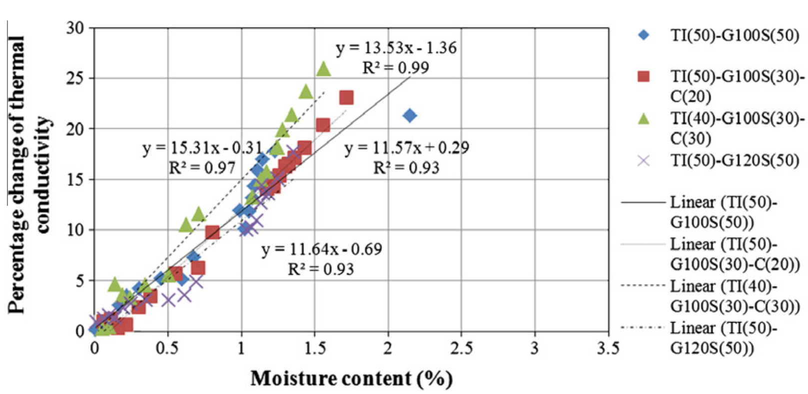

Fig. 4. Thermal conductivity vs. moisture content of ternary mixtures.

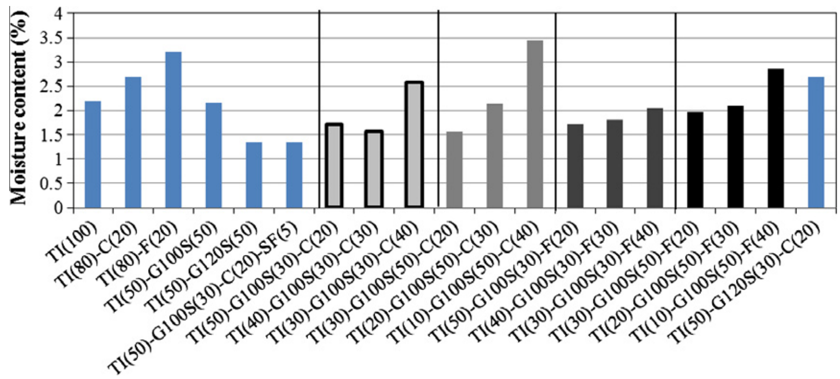

Fig. 5. Moisture content in control and ternary mixes.

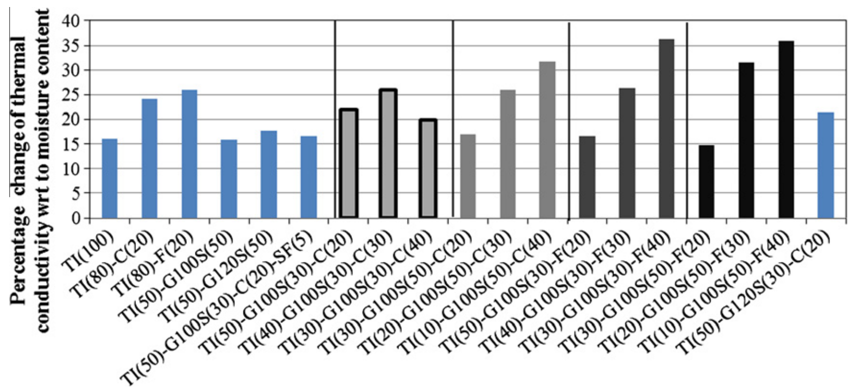

Fig. 6. Percentage change of thermal conductivity with respect to moisture content.

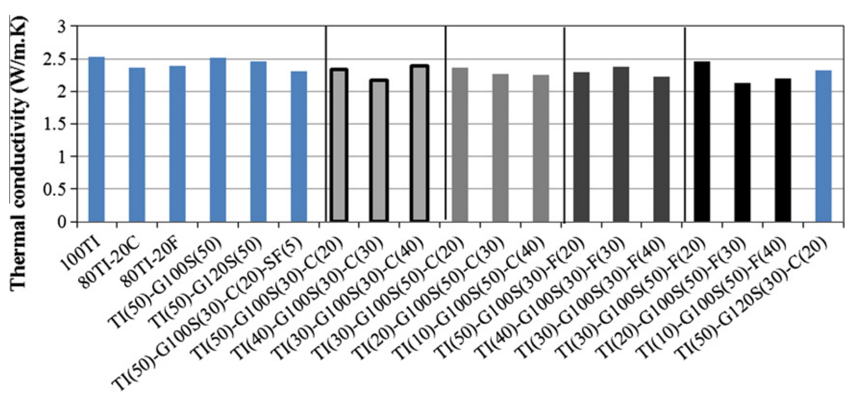

Fig. 7. Thermal conductivity of ternary mixtures at SSD condition.

the pavement. From these observations, it is considered that the thermal conductivity profile is also non-linear through the pavement depth; hence, the temperature in the pavement is also non-linear. These non-linear temperature and moisture profiles can cause curling stresses in pavements. The curling stress developed in some ternary mixtures can be critical for an early age of the PCC pavements. The effects of type and percentage of coarse aggregate, moisture, and SCMs on pavement performance are further studied in another publication [20].

3.5. Prediction model of thermal conductivity

3.5.1. Effect of percentage of coarse aggregate on thermal conductivity

Conductivity ratio is defined as the ratio of the thermal conductivity of two different moisture states of the same specimen. R_1 is the ratio of thermal conductivity at air dry condition to oven-dry condition, and R_2 is the ratio of thermal conductivity of SSD condition to oven-dry condition. Fig. 8 shows two thermal conductivity ratios with respect to the percentage change of coarse aggregate presented in Section 3.1. The equation for R_1 was chosen due to its better correlation factor and is presented in the following equation:

$$R_1 = -0.0012X_1 + 1.17 \tag{2}$$

where $R_1 = \lambda_a/\lambda_d$, λ_d is the thermal conductivity of specimen at oven-dry condition, λ_a is the thermal conductivity of specimen at air dry condition, and X_1 is the percentage of coarse aggregate.

The equation can be re-written as

$$\lambda_a = \lambda_d(-0.0012X_1 + 1.17) \tag{3}$$

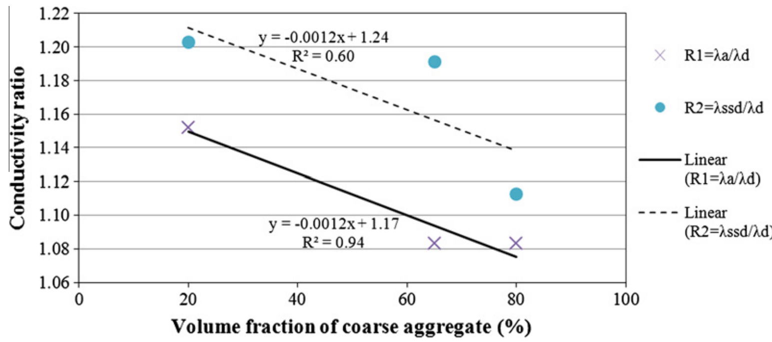

Fig. 8. Conductivity ratio with respect to volume fraction of coarse aggregate.

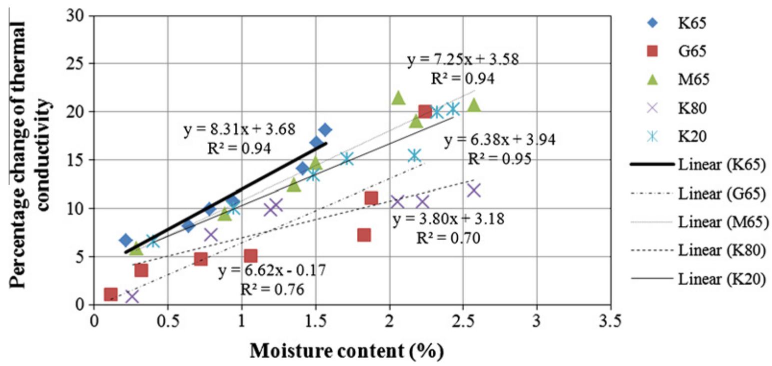

Fig. 9. Thermal conductivity vs. moisture content of different aggregates.

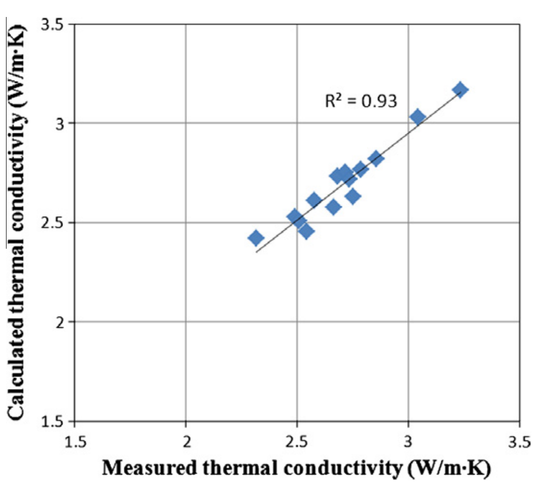

Fig. 10. Calculated vs. measured values of thermal conductivity of Kentucky limestone concrete mixtures.

3.5.2. Effect of moisture content on thermal conductivity

The *X*-axis in Fig. 9 represents the change in moisture content, referring to the oven-dry condition, and the *Y*-axis represents the percentage change in thermal conductivity, with respect to the moisture change in the specimens. The origin of the *X*-axis indicates the moisture in the oven-dry condition, and the origin of the *Y*-axis indicates the thermal conductivity in the oven-dry condition. The trend line for Kentucky limestone (K_{65}) that represents the percentage change in thermal conductivity with respect to percentage change in moisture content is

$$\frac{\Delta\lambda}{\lambda_a} * 100 = 8.31X_2 + 3.68 \quad (4)$$

Table 6
Calculation of dry thermal conductivity of limestone concrete from mixture design.

Components of concrete (1)	Thermal conductivity (2)	Volume fraction of mix design (3)	(4) = (2) * (3)
Limestone	3.1	14.33	44.42
Cement	1.5	3.24	4.86
Water	0.6	1.46	0.88
Sand	3.5	7.98	27.93
Air	0.03	–	–
		27.00	78.09

where $\Delta\lambda = \lambda_X - \lambda_a$, λ_X is the thermal conductivity for X_2 change in moisture content, and X_2 is the change of moisture content.

After simplification, it can be written as following;

$$\lambda_X = \lambda_a(0.0831X_2 + 1.04) \quad (5)$$

By combining Eq. (3) and (5), we get

$$\lambda_X = \lambda_d(-0.0012X_1 + 1.17)(0.0831X_2 + 1.04) \quad (6)$$

The above equation predicts the thermal conductivity of mixtures containing different percentages of Kentucky limestone as coarse aggregate for the percentage change in moisture. Fig. 10 shows the measured thermal conductivity vs. the calculated values using Eq. (6) for the percentage change in moisture content. A strong correlation exists between the values, and it explains the change in thermal conductivity with respect to change in moisture content and aggregate proportion of the concrete. Similarly, the equations may be developed for gravel and Mexican limestone in order to predict thermal conductivity with percentage change in coarse aggregate and moisture.

Experiments in this study show that thermal conductivity varies with different types and percentage of coarse aggregate in a mixture. Moisture change in concrete specimens was calculated for a better understanding of the relationship between water content and thermal conductivity. The model developed in the study used a constant reference value (dry thermal conductivity). This value can be calculated, if the mixture proportions of the concrete are known.

A generalized equation to predict thermal conductivity for a percentage change in coarse aggregate and moisture content may be developed similar to Eq. (6). "λ_d" is the reference value of thermal conductivity for different aggregate type and aggregate compositions; these are predicted from further tests carried out on other specimens.

$$\lambda_X = \lambda_d(AX_1 + B)(CX_2 + D) \tag{7}$$

where λ_d is the dry thermal conductivity value of a concrete specimen for respective composition and coarse aggregate types and *A*, *B*, *C*, and *D* are constants from graphs. The value of "λ_d" was calculated from the mix design of the concrete and the thermal conductivity values of the components [21–23]. Table 6 shows the details of the calculation. The calculated thermal conductivity of the limestone concrete mixture is 78.09/27 = 2.89 W/m K (1.67 Btu/ft h °F) and the value was slightly higher than the measured value. The calculated thermal conductivity is based on a simple calculation, although a better value could perhaps be obtained using Hashin–Shtrikman bounds [24].

4. Conclusions

A standard procedure was used to measure thermal conductivity of ternary concrete specimens and the measured thermal conductivity was studied to understand its influencing factors including (a) aggregate type, (b) change in coarse aggregate proportion, (c) moisture content, and (d) SCM's. Types and percentages of coarse aggregate, and moisture content had statistically significant effects on the thermal conductivity of concrete. The gravel concrete mix (G_{65}) had a higher thermal conductivity than those of Kentucky limestone (K_{65}) and Mexican limestone (M_{65}). The relationship between thermal conductivity and moisture content was linear: as moisture content decreased, the thermal conductivity of concrete decreased. For every 1% moisture content difference, the thermal conductivity changed by 7–10%, depending upon the concrete mixture. The variation of thermal conductivity with moisture is very important in PCC pavement structures due to the non-linear moisture profiles.

As the density of ternary mixtures changed, thermal conductivity values changed proportionally. For percentage changes in moisture content from saturated condition to dry condition, the percentage change of thermal conductivity was higher in ternary mixtures compared to normal concrete mixtures. Concrete with fly ash had more moisture absorption compared to normal concrete and slag mixed specimens. The moisture content of concrete containing Class F fly ash was higher than that containing Class C fly ash. Concrete mixtures used in this study had 2.5–3.5% of gravimetric moisture content at a semi saturated condition (close to 100% relative humidity) and 1.0–1.5% of gravimetric moisture content was present when the specimens were stabilized at 50% relative humidity. A difference in thermal conductivity from a dry condition to saturated condition ranged from 15% to 36%, with respect to the dry condition, depending on the mixture moisture content.

A model was developed for predicting the thermal conductivity of concrete for factors such as the percentage of coarse aggregate and the moisture content. A strong correlation was observed between model predicted thermal conductivity values and measured thermal conductivity values.

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