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Effects of Thermal Conductivity of Concrete on Jointed Plain Concrete Pavement's Performance and Design Slab Thickness

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This study investigates the influence of thermal conductivity of paving concrete on the performance of Jointed Plain Concrete Pavement (JPCP). The thermal properties of concrete play a crucial role in determining the response of pavements to temperature variations, affecting their durability and structural integrity. Through a comprehensive analysis, this research aims to elucidate the direct relationship between thermal conductivity of paving concrete and JPCP performance. The experimental approach involves varying levels of thermal conductivity in concrete mixtures to observe corresponding changes in pavement behavior. Thermal conductivity alterations are achieved by modifying material composition and incorporating additives. The study evaluates how these changes impact critical factors such as temperature-induced stresses, crack propagation, and overall pavement distress. Results from this investigation contribute valuable insights for optimizing JPCP design and materials selection, with a focus on enhancing pavement performance. By understanding the nuanced effects of thermal conductivity, engineers and practitioners can make informed decisions to improve the resilience and longevity of concrete pavements, especially in regions prone to temperature extremes. The pavement designers should incorporate laboratory tested thermal conductivity data for JPCP design otherwise the use of default data will result in under designed pavement that might fail prematurely. This research has implications for sustainable infrastructure development, offering a foundation for more robust and climate-responsive pavement design practices.

Key Words: Thermal Conductivity, JPCP, Concrete, Transverse Cracking, Faulting

Introduction

Thermal conductivity is an important thermal property of paving concrete, but in the past with the empirical design methods in place it did not provide much influence on the design. With the advent of Mechanistic-Empirical Pavement Design Guide (MEPDG) and Pavement ME Design software (PMED), the importance of mechanical and thermal properties came to the forefront, but the focus of most research revolved around the mechanical properties including compressive strength, elastic modulus, and modulus of rupture (MOR) and thermal properties including coefficient of thermal expansion (CTE) (Sabih 2016), (Vandenbossche 2011), (Ceylan 2013). There are a few works on the analysis of the effect of thermal stress and coefficient of thermal expansion on concrete pavements (Mackiewicz 2014), (Shin 2011) but not much research is available on the effects of thermal conductivity (TC) on the performance of the JPCP system (Mirnezami 2023), (Panchmatia 2014), (Kodide 2010), (Cavalline 2018), (Cavalline and Morrison 2018). The focus of this study is to analyze and quantify the impact of thermal conductivity on the JPCP performance and how it affects the design slab thickness.

MEPDG evaluates the performance of concrete pavement over the designed life by predicting the performance parameters. International Roughness Index (IRI) is one of them which is basically a measure of pavement smoothness, with lower values indicating smoother surfaces and better ride quality for vehicles. Another parameter Joint Faulting refers to the vertical displacement or offset at the joints of a concrete pavement, which can lead to pavement distress and reduced service life and cracking in concrete pavements can lead to structural deterioration and reduced service life, making it a critical concern in pavement engineering. The Thermal Conductivity of paving concrete used in JPCP can have a notable influence on all the performance parameters of JPCP over the designed service life of the pavement.

This study focuses on the impact of thermal conductivity on the performance of JPCP. JPCP is a commonly used concrete pavement, which uses transverse joints to control cracking, and there is no reinforcing steel. For the purpose of this study, simulations were conducted in Pavement ME design (PMED) software and the sensitivity analysis were carried out to analyze the impact of thermal conductivity on the terminal pavement performance parameters and the performance over the design life of JPCP.

Methodology

To analyze the effects of thermal conductivity on JPCP pavements, several design simulations were performed in Pavement ME Design and IRI, Faulting and Cracking indicators were compared. In pavement ME, level 3 analysis was used for each individual mixture, coefficient of thermal expansion (CTE) and compressive strength were selected for level 3 analysis. The baseline model found in Table 1, used for simulations was kept constant for the entire simulation work which included four pavement layers that include the PCC layer, a lime stabilized base course layer, a crushed gravel base course layer, and a subgrade layer. The JPCP design life was also kept constant at 30 years while all other design inputs were set at PMED default values. The test data used for thermal conductivity, coefficient of thermal expansion (CTE) and compressive strength is found in Table 2.

The concrete mixture designs were based on type of coarse aggregates, fine aggregates, and percentage of fly ash. The mixes used in this study used the following denotation for the mix matrix. Coarse aggregates are designated as C1 and C2. Fine aggregates (natural sand) are designated as N1 and N2. Cement type is designated as O, as there is only one type. Fly ash composition is designated as 20% or 30%, which is denoted as F20 and F30. An example of a mix designation is C1N1OF20 based on Coarse aggregate-1, Natural sand-1, OPC, and 20% Fly Ash.

The range of thermal conductivity values for paving mixtures as per PMED is 0.2 to 2.0 Btu/ft.hr.F with a default value of 1.25 Btu/ft.hr.F. In the initial phase, the effects of the typical range of thermal conductivity values were analyzed on the performance of JPCP with PMED simulations and keeping other design variables as constant. After conducting the simulations, analysis of the effects of thermal conductivity on each of the three performance indicators for JPCP was performed. In the next phase, the effects of using default value of thermal conductivity were compared to using the lab tested value of thermal conductivity. In the final phase of the analysis, the impact of thermal conductivity on the design slab thickness was analyzed using PMED simulations.

Table 1: Sensitivity Analysis Inputs and Baseline Model

Input Category	Variable
PCC Thickness	8
AADTT	6000
Climate	Charlotte
Slab Length	15
Dowel Diameter	1.25
Friction Loss	240 Months
PCC Shortwave Absorptivity	0.85
PCC Heat Capacity	0.28
Slab Width	12

Table 2: Leve 3 Simulation Input Data

Mixture ID	28 Day CTE	28 Day Compressive Strength	56 Days Thermal Conductivity
C1N10	5.66	4656	1.057
C1N1OF20	5.433	4303	0.922
C1N1OF30	5.325	3176	0.886
C1N20	5.358	5051	1.150
C1N2OF20	5.195	4425	0.930
C1N2OF30	5.164	3610	0.871

Effects of Thermal Conductivity on JPCP Performance Indicators of Baseline JPCP Model

Impact Of Thermal Conductivity on IRI

The simulation results are shown in Figure 1, and it is evident that as Thermal Conductivity increases from 0.7 to 2 Btu/ft.hr.F, there is a consistent trend of decreasing IRI values, indicating that higher thermal conductivity is associated with smoother pavement surfaces. When Thermal Conductivity is at 0.7 Btu/ft.hr.F the IRI is highest at 162 in/mi, signifying a rougher pavement surface. As Thermal Conductivity gradually increases up to 1.2 Btu/ft.hr.F, there is a sharp decreasing trend in IRI. This suggests that materials with higher thermal conductivity tend to result in smoother pavement surfaces. The decreasing trend continues as TC rises further, with IRI values consistently decreasing. At TC values of 1.5 Btu/ft.hr.F and 2 Btu/ft.hr.F, the IRI is 116.78 in/mi and 113.43 in/mi, respectively, indicating a significantly smoother pavement surface compared to lower TC values. So, the concrete mixture with better TC has the advantage of dissipating heat more efficiently, reducing temperature-induced stresses, and contributing to a smoother pavement surface.

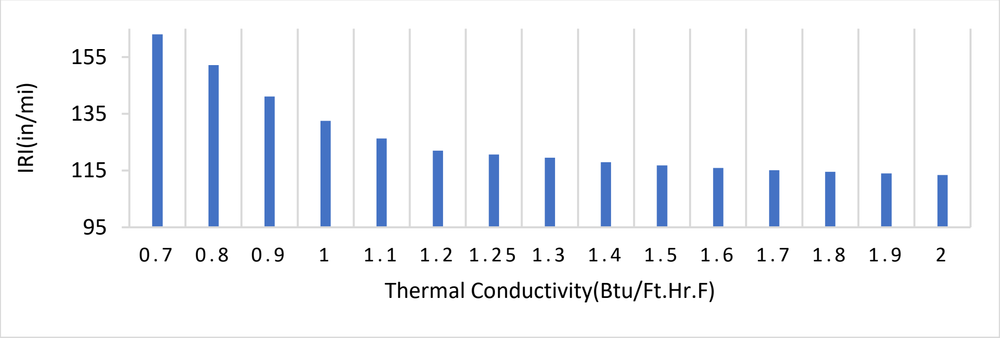

Figure 1: Effects of Thermal Conductivity on IRI

Impact Of Thermal Conductivity on Faulting

The analysis of simulation results is shown in Figure 2. It was found that while TC does have some influence on faulting in JPCP, the effect is relatively minor within the range studied. Engineers and pavement designers should consider a holistic approach, considering various factors, to mitigate faulting issues effectively and ensure long-lasting concrete pavement performance.

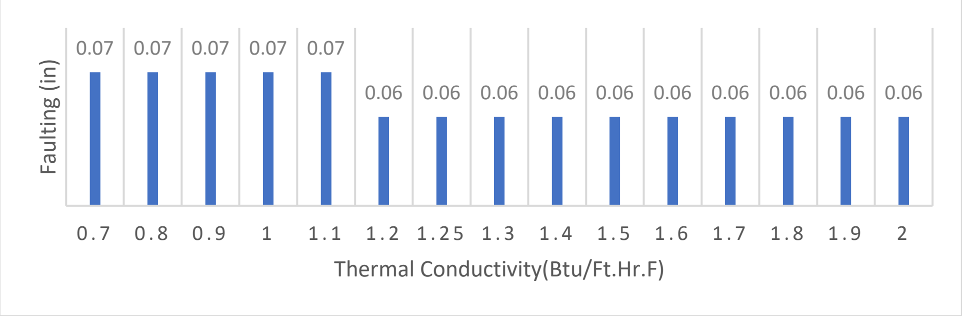

Figure 2: Effects of Thermal Conductivity on Faulting

Impact of Thermal Conductivity on Cracking

As shown in Figure 3, when TC increases from 0.7 to 2, there is a clear trend of decreasing cracking. When TC is at its lowest value of 0.7, cracking is at its highest (57%). This suggests that materials with low TC do not efficiently dissipate heat, leading to greater temperature differentials within the pavement, and thus, a higher likelihood of cracking. As TC gradually increases up to 1.2, a sharply decreasing trend in cracking is visible. This implies that materials with higher TC can dissipate heat more effectively, reducing the temperature-induced stresses within the pavement and resulting in fewer cracks. The trend continues as TC increases further, with cracking levels decreasing as TC rises. When TC reaches 2.0, cracking is at its lowest point, measuring 2.76%. This demonstrates that materials with excellent TC offer superior thermal stability to the JPCP, minimizing the temperaturerelated stresses that lead to cracking. In practice, selecting concrete mixtures or materials with higher TC can be a valuable strategy to reduce the occurrence of cracking in concrete pavements.

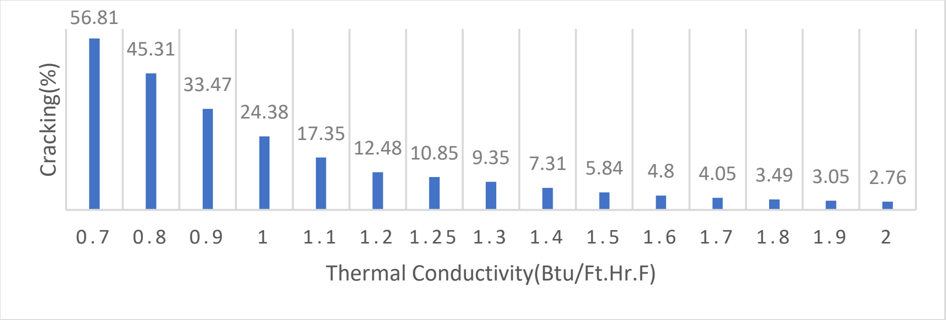

Figure 3: Effects of Thermal Conductivity on Cracking

Summary of Thermal Conductivity Impact on IRI, Faulting, and Cracking Of JPCP

As TC increases from 0.2 to 2, IRI consistently decreases. Higher TC values are associated with smoother pavement surfaces, as more efficient heat dissipation minimizes temperature-induced stresses, resulting in a smoother ride quality. TC has little impact on faulting and across the entire TC range (0.2 to 2), faulting remains relatively constant at 0.05 to 0.07 inch. Increasing TC from 0.2 to 2 substantially reduces cracking. Higher TC materials better handle thermal stresses, resulting in fewer cracks. The relationship is nonlinear, with a significant reduction in cracking as TC exceeds 0.5. In summary, TC significantly affects IRI and cracking, with higher TC values correlating with smoother surfaces and fewer cracks. However, TC has minimal impact on faulting and it's essential to consider all factors holistically for effective pavement design and maintenance.

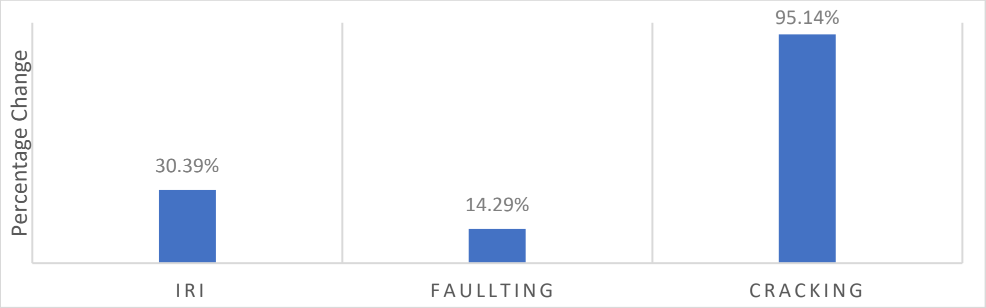

Figure 4: Percentage Change in Baseline Model

Results Of JPCP Performance Indicators (Using TC Lab Data and Default Data)

Impact of Thermal Conductivity on IRI

A comparison of the effects of lab tested TC values and the PMED default values with regards to the pavement roughness (IRI) of JPCP is presented in Figure 4. The effects of TC on the IRI in JPCP varies among different concrete mixtures, as evident from the provided data with varying values of

IRI obtained for different mixtures. In the overall scenario, 5 of the 6 simulated mixtures show a higher IRI for lab tested TC in comparison to the PMED default TC. Only one concrete mixture showed a lower IRI value with lab tested TC as compared to PMED default TC value. It is found that there is a significant difference between the IRI indicators obtained with the lab tested TC and the PMED default TC values and pavement designers needs to take this in to account while designing any new JPCP system.

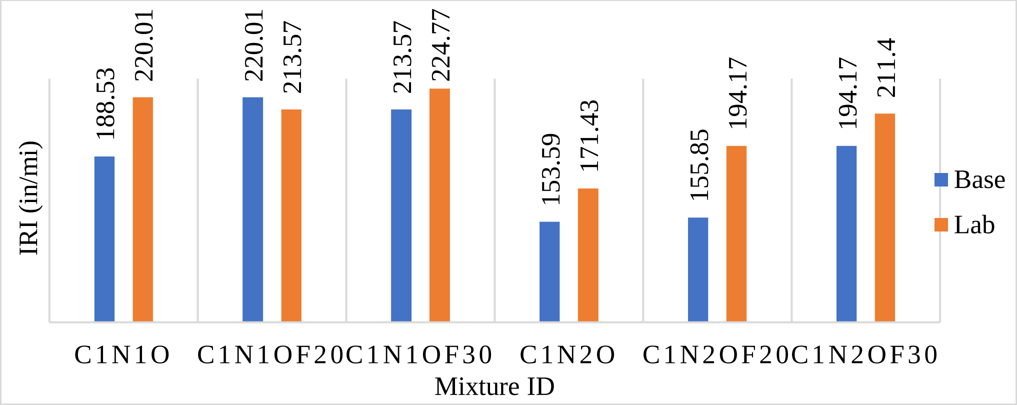

Figure 5: Effects of Lab Tested Thermal Conductivity on IRI

Impact of Thermal Conductivity on Faulting

The effects of TC on faulting in JPCP appear to be minimal across different mixtures, as indicated by the results of the simulations as shown in Figure 5. The simulations conducted with lab tested TC values and the simulations conducted with the PMED default TC values show the same faulting indicator values. In summary, the simulation results indicate that TC has minimal to no effect on faulting levels in JPCP for the studied mixtures.

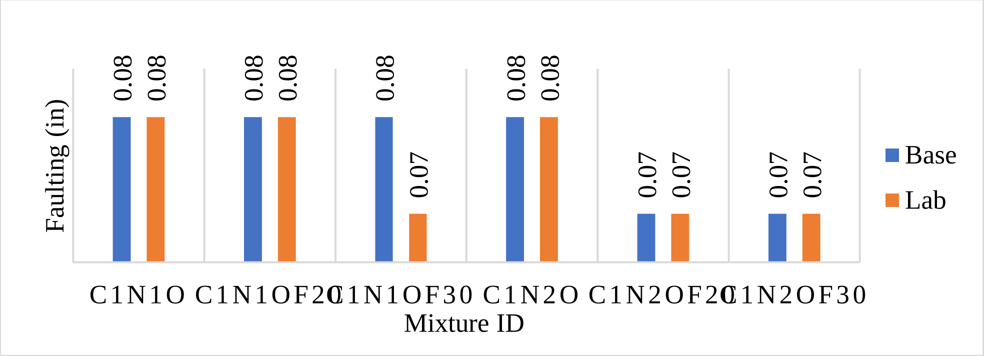

Figure 6: Effects of Lab Tested Thermal Conductivity on Faulting

Impact of Thermal Conductivity on Transverse Cracking

The impact lab tested TC on transverse cracking in JPCP varies across different mixtures, as indicated by the simulation results shown in Figure 6. In summary, the simulation data indicates that TC has varying effects on cracking in JPCP for different mixtures. Lab tested TC values tends to result in higher cracking severity compared to PMED default TC values for all of the simulated mixtures. It is evident that accurate characterization of material properties is vital for predicting and managing pavement cracking effectively.

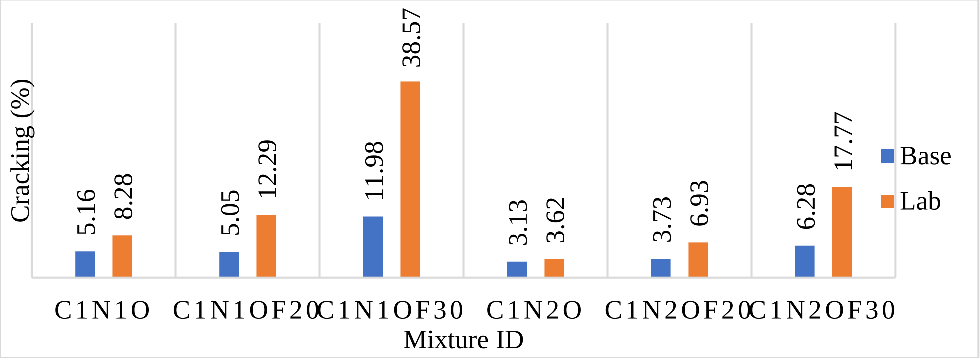

Figure 7: Effects of Lab Tested Thermal Conductivity on Cracking

Summary of Comparison of Lab Tested Thermal Conductivity and Default TC on JPCP Performance

TC variations have a mixed impact on IRI. In some mixtures, such as C1N1O, lab TC data results in higher IRI values than baseline data, indicating potential differences in material properties. However, for other mixes like C1N2OF20 and C1N2OF30, TC variations have minimal impact on IRI. TC has negligible influence on faulting across different mixtures. Both baseline and lab TC data consistently yield similar faulting values, indicating that TC variations do not significantly affect faulting levels. TC differences have a more pronounced impact on cracking. In mixtures like C1N1O and C1N2O, lab TC data leads to higher cracking severity compared to baseline data. In summary, the effects of TC on JPCP performance indicators vary across different mixtures, with lab TC data generally showing higher IRI and cracking values for some mixtures, while faulting remains largely unaffected by TC variations. Accurate characterization of material properties is crucial for reliable pavement performance predictions and design decisions.

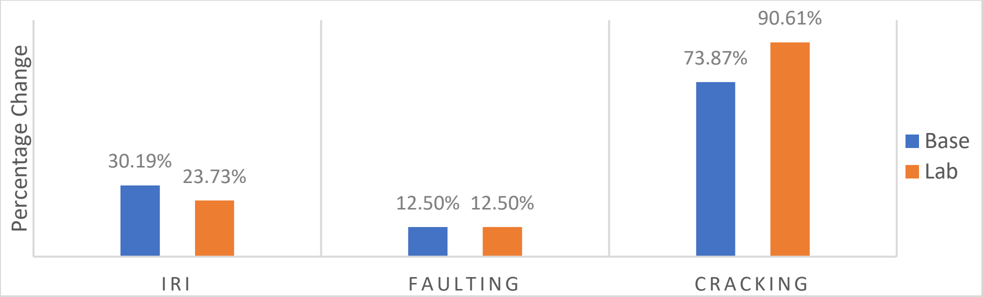

Figure 8: Percentage Change in Default data and Lab data

Effects of Thermal Conductivity Values on Design Slab Thickness

The use of default TC values of the concrete paving mixtures results in in-accurate performance indicator values in comparison to the scenarios where lab tested TC values are used for the simulations. Increasing the PCC slab thickness can help reduce the difference between the two simulated scenarios. Analysis was conducted to quantify the impact of baseline TC vs lab tested TC values on the slab thickness of JPCP system. Additional simulations were conducted in PMED with the increased PCC slab thickness to match the cracking indicator values of the lab tested cases to the baseline cases for all the mixtures. The cracking indicator was selected for this matching analysis because the cracking performance indicator has the most severity among all three performance indicators. The summary of the analysis is given in Table 2. The baseline TC simulations have a PCC slab thickness of 10 inches and after running the simulations for the lab tested TC models for all the paving mixtures, a PCC slab thickness of up to 12 inches shows similar cracking indicator results. It is evident that an increase of up to 2 inch in the PCC slab thickness matches cracking values for both the simulated scenarios for all the paving mixtures.

Table 3: Effects of Thermal Conductivity on Design Slab Thickness

	Default TC Simulations	Slab Thickness for Lab Tested TC Simulations				
Mixture ID	10 inches	10 inches	10.5 inches	11 inches	11.5 inches	12 inches
C1N1O	5.16	-	5.89	-	-	-
C1N1OF20	5.05	-	-	6.91	-	-
C1N1OF30	11.98	-	-	-	-	11.48
C1N2O	3.13	3.62	-	-	-	-
C1N2OF20	3.73	-	5.45	-	-	-
C1N2OF30	6.28	-	-	-	7.65	-

Conclusion

This study finds that the use of default TC values will result in lower transverse cracking predictions and the difference in cracking performance between default TC and laboratory tested TC values is up to 26%. It is evident from the analysis conducted in this study that using the default/baseline values of TC will result in under designed JPCP system which might fail prematurely without completing the design service life and the difference between using the lab tested TC and the PMED default/baseline TC is up to 2 inch of PCC slab thickness which has numerous financial, sustainability, and environmental implications. It is highly recommended that JPCP design should be conducted according to the lab tested concrete properties including TC values. To provide additional confidence and support local calibration of PMED, these findings should also be confirmed through field observations.

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