EFFECT OF LAYDOWN SITE CONDITIONS, ENVIRONMENTAL VARIABLES & LAYER THICKNESS ON DEGREE OF COMPACTION OF ASPHALT

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Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree

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DECLARATION

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ABSTRACT

The degree of compaction is crucial for the enduring durability of asphalt pavements, and achieving optimal compaction involves various factors. This research focuses on the impact of laydown site conditions, environmental variables, and layer thickness on asphalt compaction in tropical climates, particularly in Sri Lanka. The research objectives include developing a mathematical model for heat transfer in asphalt layers and determining an optimal layer thickness for enhanced compaction. Degree of compaction depends on the Time Available for Compaction (TAC). A 3D-FEM transient heat transfer model was developed using Abaqus/CAE 6.14 software to simulate asphalt behavior under different site conditions and to explore the heat transfer mechanisms during both day and night times, considering factors like solar radiation, convection, and conduction. Validation of the model was achieved by comparing field data with model results. Mathematical equations for Time Available for Compaction (TAC) were derived using regression analysis, considering laydown temperature, air temperature, wind velocity, base temperature, and layer thickness. These equations, tailored to different base types and time periods, highlight the significant impact of environmental variables on compaction time. The results provide insights into the interplay of these factors and offer equations for predicting TAC, aiding in optimal compaction planning for asphalt construction in diverse conditions. Also, an optimal thickness for asphalt layer was determined considering different scenarios by varying the input environmental parameters and average time required for compaction process.

Keywords: Asphalt compaction, Time available for compaction (TAC), Environmental variables, Heat transfer FEM model

ACKNOWLEDGEMENT

I would like to gratefully acknowledge the valuable guidance and support of every individual who helped me to make this M.Eng research project a success and appreciate their support through this acknowledgement.

First and foremost, I would like to express my sincere gratitude to my research project supervisor, Prof. W.K. Mampearachchi who gave me continuous lead way from beginning to end. Also, I would like to extend my sincere appreciation to Mr. R.M.J. Bandara, Project Manager, and his staff of the Gampaha District i-Road Project (Package 4), as well as Mr. Pasindu Thilakerathne, Material Engineer, and his staff of the Colombo-Kandy Road Rehabilitation Project, for their invaluable assistance in facilitating the data collection process for my research.

I would also like to thank the Department of Civil Engineering at the University of Moratuwa for providing me with the opportunity to conduct this research.

At the same time, I make this an opportunity to thank all the lecturers who gave me knowledge throughout the Master of Engineering degree & those who helped me with giving different insights.

Also, I thank my family members who were there all the time providing me all the things I need in time.

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
TAC	Time Available for Compaction
FEM	Finite Element Method

CHAPTER 1

INTRODUCTION

1.1. Background

The successful construction and longevity of asphalt pavements rely on various factors, with the degree of compaction standing out as a critical parameter. The most significant factor influencing the enduring durability of asphalt pavement is the degree of compaction of the mix that is achieved by the contractor at the time of construction (Scherocman, 2000). Achieving optimal degree of compaction ensures the asphalt layer's structural integrity, load-bearing capacity, and resistance to environmental stresses.

The primary factors that impact the successful compaction of asphalt include the following (Asphalt Compaction, 2010).

- Rolling methods & techniques
- Mix temperature
- Layer thickness
- Characteristics of the mix
- Laydown site conditions that mean soundness & stiffness of the underlying base
- Rate of cooling

However, according to AUSTROADS (Asphalt Guide, AP-G66/02, 2022) degree of compaction depends on the Time Available for Compaction (TAC). The time available for compaction will depend on the initial temperature at which the asphalt mix is laid and cooling rate (Asphalt Compaction, 2010).

The cooling rate is a function of;

- Layer thickness
- Laydown conditions - Temperature of the underlying base
- Environmental variables such as air temperature, wind velocity & moisture etc.

Thicker layers maintain heat for a longer period, allowing more time for compaction. Additionally, thicker layers offer more space for the alignment of aggregate particles, facilitating compaction. Conversely, high wind speeds and low air temperatures typically accelerate heat loss (Asphalt Compaction, 2010). Air temperature, base temperature, and weather conditions during construction significantly affect the workability of asphalt mixtures. Like that cooling rate varies with these factors. Therefore, investigating how these laydown site conditions, environmental factors and layer thickness interact with the asphalt mixture and their collective influence on degree of compaction of asphalt is essential for devising strategies to optimize compaction under diverse climatic conditions especially in tropical climates.

Here the base temperatures & environmental variables are uncontrollable. Layer thickness is the only controllable factor. Therefore, through this it will be able to determine an optimum value or a range for the thickness of asphalt which can achieve a higher degree of compaction in Sri Lankan condition.

1.2. Problem Statement

The volume ratio of HMA (Hot Mix Asphalt) samples extracted from core cuts of newly laid pavement to those prepared in the laboratory using the Marshall method should not be less than 97%. However, in certain construction sites, achieving the required HMA compaction is challenging due to insufficient time for compaction. To optimize compaction, it is crucial to ensure that the process occurs within the designated time frame when the asphalt mix maintains optimal temperature and workability. According to ICTAD standard specifications, the laydown temperature should not be less than 135°C. According to a study conducted by (Jack S. Corlew, P.F. Dickenson, 1968), it has been established that the minimum temperature for effective compaction is 80°C. When temperatures fall below this threshold, the probability of achieving a substantial increase in density is greatly reduced. In some instances, this can lead to the fracturing of the aggregate mix and as a result, a reduction in density (Mohd Rosli Hainin, Nur Izzi Md. Yusoff. Mohd Khairul Idham Mohd Satar, E. Ray Brown, 2013). Therefore, the asphalt compaction process should be completed within this time range to achieve a higher degree of compaction.

In fact, several researches such as (Ying Gao, Renxiao Wang, Wenbin Yu, 2011) and (Chieh-Min Chang, Yen-Jui Chang, Jian-Shiuh Chen, 2009) have been conducted to evaluate the factors affecting the degree of compaction of asphalt layers. However, in some studies, only a few factors have been considered for analysis. Also, there is no proper mathematical model to estimate the effect of all the above factors on TAC and the degree of compaction of asphalt in a tropical climate considering different site conditions. Time available for compaction and an optimum thickness for bituminous layers to achieve a higher degree of compaction in Sri Lankan conditions have not been determined with the variation of the environmental variables & laydown conditions.

Through a comprehensive understanding of these interrelated factors, engineers and practitioners can refine their methodologies, implement effective quality control measures, and ultimately enhance the durability and performance of asphalt pavements in diverse operational environments.

CHAPTER 2

OBJECTIVES

This research aims to achieve the following objectives.

- To investigate the effect of lay down site conditions, environmental variables & layer thickness on degree of compaction of asphalt in tropical climates.
- To develop a mathematical model for the heat transfer of asphalt layer & TAC.
- To determine an optimum thickness for asphalt layers which can achieve higher degree of compaction in tropical countries such as Sri Lanka.

CHAPTER 3

LITERATURE REVIEW

3.1. Interaction between the pavement and its environment during day time

The cooling behavior of freshly constructed asphalt mixtures is primarily influenced by the local climatic conditions. The heat transfer mechanisms in asphalt pavement are governed by thermodynamic principles, including conduction, radiation, and convection as illustrated by the Figure 1 (Taqia Rahman, Nick Thom, Andrew Dawson, 2019).

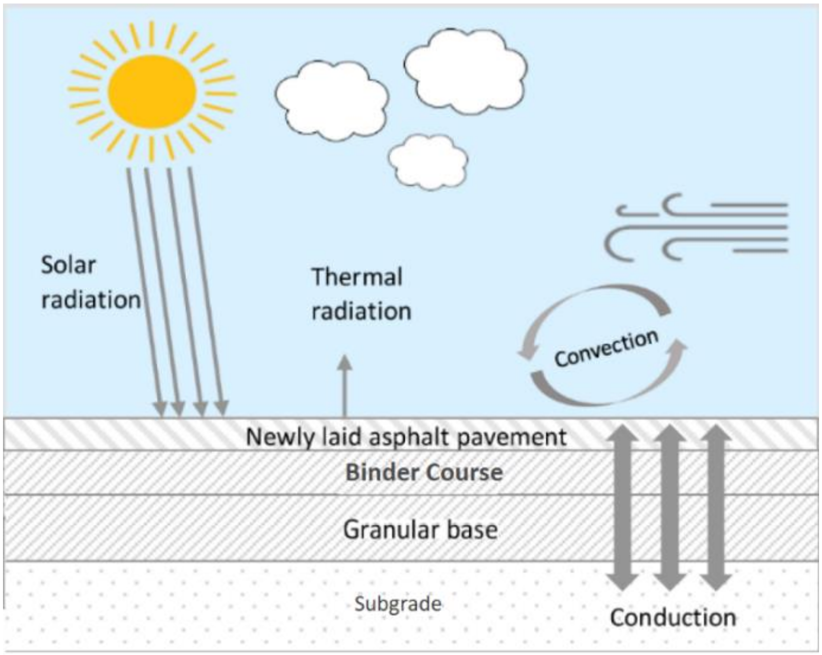


Figure 1: Interactivities between the pavement and its environment during day time

Figure 1 illustrates the interactions between newly constructed asphalt pavement and its surrounding during the daytime. The heat flux at the surface of the asphalt pavement includes several components: the radiation from the sun heating the surface, the heat dissipation to the air through convection and radiation, and the conduction of heat into the underlying pavement layers. When the heat transfer on a sunny day is considered, the thermal radiation encompasses outgoing long-wave radiation, counter radiation in the long-wave spectrum, and short-wave radiation, also known as solar radiation.

3.2. Interaction between the pavement and its environment at night time

As night falls, the interactvities between the pavement and its environment undergoes a slight difference than during the day. Figure 2 clearly shows the interactions between the newly laid asphalt pavement and its surroundings during a night time.

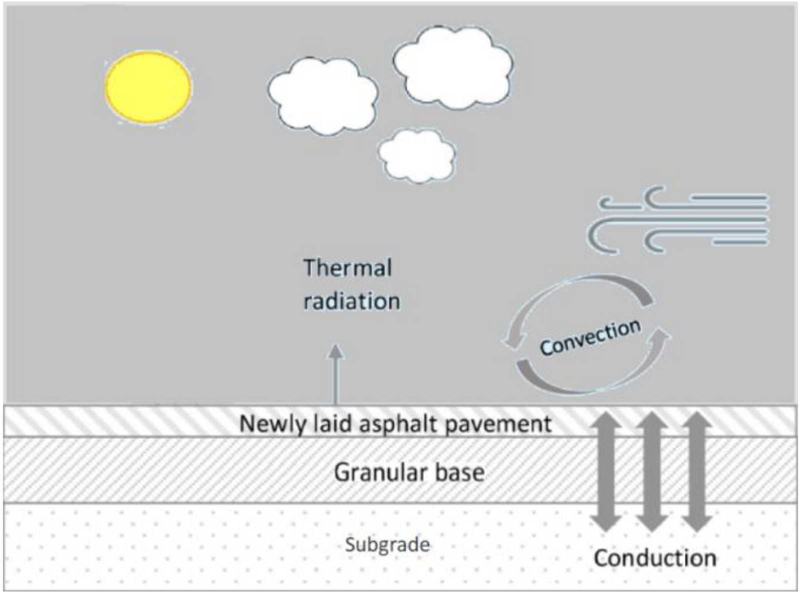


Figure 2: Interactivities between the pavement and its environment at night time

The main difference from the day time is the absence of effect from the solar flux during night time. Only interactions to be considered here are heat diffusion to the air through convection and radiation, and the heat conduction into the underlying layers. Table 1 summarizes the differences in heat transfer methods for a newly constructed hot mix asphalt layer between daytime and nighttime.

Table 1: Comparison of interactions according to the time period of the day

Day Time	Night Time
▪ Thermal Radiation • Outgoing long-wave radiation • Long-wave counter radiation • Short-wave radiation (Solar radiation) ▪ Convection ▪ Conduction	▪ Thermal Radiation • Outgoing long-wave radiation • Long-wave counter radiation ▪ Convection ▪ Conduction

3.3. Equations for interactions between the pavement and its surroundings

Several literatures have specified equations to measure the amount of heat during various interactions between pavement and its surrounding.

Outgoing long-wave radiation

According to (Yuhong Wang, Songye Zhu, Alvin S. T. Wong, 2014), the value for outgoing long-wave radiation is given by the following equation.

$$q_e = \varepsilon_e \sigma T_{sur}^4 \qquad \text{Eq.1}$$

Where;

q_e = Outgoing radiation;

ε_e = Emissivity coefficient of pavement (0.93);

T_{sur} = Pavement surface temperature;

σ = Stefan-Boltzman constant (5.68×10^{-8} W m^{-2} K^{-4})

Long-wave counter radiation

According to (Yuhong Wang, Songye Zhu, Alvin S. T. Wong, 2014), the value for long-wave counter radiation is given by the following equations.

$$q_{\mathrm{a}} = \varepsilon_{\mathrm{a}} \sigma T_{air}^4 \qquad \text{Eq.2}$$

Where;

q_a = Absorbed counter radiation;

ε_a = Pavement surface absorptivity for long-wave radiation (0.95);

T_{air} = Air temperature;

σ = Stefan-Boltzman constant (5.68×10^{-8} W m^{-2} K^{-4})

According to (Yuhong Wang, Songye Zhu, Alvin S. T. Wong, 2014), the values for thermal radiation and solar radiation are given by following equations.

Long wave radiation intensity balance (Thermal radiation)

$$q_{\mathrm{r}} = h_{\mathrm{r}}(T_{\mathrm{sur}} - T_{\mathrm{air}}) \qquad \text{Eq.3}$$

$$h_{\mathrm{r}} = \varepsilon\sigma(T_{\mathrm{sur}} + T_{\mathrm{air}})(T_{sur}^2 + T_{air}^2) \qquad \text{Eq.4}$$

Where;

q_r = Thermal radiation;

h_r = Thermal radiation coefficient

ε_e = Emissivity coefficient of pavement surface;

σ = Stefan-Boltzman constant (5.68×10^{-8} W m^{-2} K^{-4})

Short-wave radiation (Solar radiation)

$$q_s = \alpha_s . q_i \qquad \text{Eq.5}$$

$$q_i = \eta s_c f Cos\Theta \qquad \text{Eq.6}$$

Where;

q_s = Solar radiation absorbed by pavement surface;

α_s = Solar radiation absorption coefficient;

q_i = Thermal incident solar radiation;

η = Loss factor accounting scattering & absorption by atmosphere;

s_c = Solar constant (1353 W/m^2);

f = Factor accounting the eccentricity of earth orbit;

Ɵ = Zenith angle

Convection heat transfer

The primary mechanism for cooling freshly laid asphalt is through convective heat transfer between the asphalt surface and the ambient air. This process is governed by Newton's law of cooling, which can be expressed as follows. (Taqia Rahman, Nick Thom, Andrew Dawson, 2019).

$$q_c = h_c(T_{sur} - T_{air}) \qquad \text{Eq.7}$$

Where;

q_c = Convection heat transfer;

h_c = Convection heat transfer coefficient;

T_{sur} = Pavement surface temperature;

T_{air} = Air temperature;

In this context, the heat transfer coefficient (h_c) can be determined using empirical equations. The empirical equation used in the studies of (Matthew R. Hall, Pejman

Keikhaei Dehdezi, Andrew R. Dawson, James Grenfell, Riccardo Isola, 2012) and (Yuhong Wang, Songye Zhu, Alvin S. T. Wong, 2014) is as follows where; V_w = Wind velocity in m/s.

$$h_c = 5.8 + 4.1v_w \qquad \text{Eq.8}$$

However, in the study of (Cedric Vuye, Gert Guldentops, Nima Rahbar, Alireza Mahdavi Nejad, Wim Van den bergh, 2016), heat transfer coefficient is estimated by following equation where; V_w = Wind velocity in m/s.

$$If\ v_w \leq 5\ m/s \qquad h_c = 5.6 + 4.0v_w \qquad \text{Eq.9}$$

$$If\ v_w > 5\ m/s \qquad h_c = 7.2v_w \qquad \text{Eq.10}$$

Conduction heat transfer

According to (Taqia Rahman, Nick Thom, Andrew Dawson, 2019), the transfer of heat through freshly laid asphalt and its base layers is generally described by Fourier's law of heat conduction.

$$q_{cond} = -k\frac{\partial T}{\partial x} \qquad \text{Eq.11}$$

Where;

q_{cond} = Conduction heat transfer;

k = Thermal conductivity of asphalt mixture;

∂T = Temperature difference;

∂x = Thickness of the pavement in the heat transfer direction

3.4. Boundary conditions of heat transferring

A depth of 300 mm is assumed to have an adiabatic boundary. This assumption is considered reliable based on previous observations, which have shown negligible temperature fluctuations within the simulated time frames, typically not exceeding 24 hours (Cedric Vuye, Gert Guldentops, Nima Rahbar, Alireza Mahdavi Nejad, Wim Van den bergh, 2016).

3.5. Correlation between TAC and other variable factors

In studies by (Ying Gao, Renxiao Wang, Wenbin Yu, 2011), the following mathematical equation has been developed from their experimental work, where t is effective compactible time of pavement (min), x1 = air temperature (°C), x2 = wind velocity (m/s), x3 = mixture paving temperature (°C) and x4 = layer thickness (cm).

$$t = 0.1555x1 - 1.2098x2 + 0.3274x3 + 11.7272x4 - 60.2727 \qquad \text{Eq.12}$$

And the study identified that the correlation between TAC and independent variables such as air temperature, wind velocity, laydown temperature and layer thickness was linear. Furthermore, according to the literature, warmer air temperatures increase TAC by restricting the heat diffusion of the asphalt mixture. Hence, a positive correlation between air temperature and TAC is acknowledged, as outlined in the equations for thermal radiation and convection heat transfer (Eq.2, Eq.3, Eq.4 and Eq.7). Higher wind speeds may lead to faster cooling and potentially reduce the time available for effective compaction according to the equations for convection heat transfer (Eq.8, Eq.9, and Eq.10). It justifies the negative correlation of this parameter. The initial temperature of the asphalt mixture during placement has a positive influence on the TAC. Moreover, higher layer thicknesses impede heat diffusion from the asphalt layer, as indicated by the equation for conduction heat transfer (Eq.11). It justifies the positive correlation of this parameter.

Research done by (Chieh-Min Chang, Yen-Jui Chang, Jian-Shiuh Chen, 2009) has developed the following mathematical equation, where Y_{T80} = time taken to cool to 80°C (min.); X_D = lift thickness (cm); X_A = air temperature (°C); and X_V = percentage of air voids (%).

$$Y_{T80} = 6.76X_D + 6.24X_A + 0.02X_V - 78.71 \qquad R^2 = 0.84 \qquad \text{Eq.13}$$

Here, R^2 value indicates that 84% of the variation in the time needed for the mix temperature to fall to 80°C is accounted for by the pavement thickness and air temperature. This study further assessed the regression relationship between the response and predictor variables using the F-test. With a p-value of 0.00003, the F-test demonstrates a significant correlation between the cooling time and the variables in the model.

In studies done by (Guopin Qian, Zhiyu He, Huanan Yu, Xiangbing Gong, Jie Sun, 2020), a comprehensive regression model has been developed to assess the effective compaction time, incorporating the interplay of various influencing factors. Through rigorous regression analysis, this model accounts for the complex coupling of multiple variables, yielding valuable insights into the compaction process. By integrating diverse factors, the model provides a robust framework for predicting compaction time under real-world conditions.

$$t = 0.8t_p - 0.6h + 0.5797t_a + 0.33t_u - 7.4s_w - 123.59 \qquad \text{Eq.14}$$

where, t is time available for effective compacting of asphalt mixture (min), t_p is paving temperature (°C), h is the asphalt layer thickness (cm), t_a is air temperature (°C), t_u is temperature of the underlying layer (°C) and s_w is the wind speed (m/s).

The findings from this investigation suggest that elevations in both the upper and lower temperatures of the rolling layer correlate positively with increases in both the paving temperature and the thickness of the rolling layer. The temperature field of HMA is predominantly influenced by wind speed and ambient temperature, with a primary impact observed on the upper layer, while changes in these conditions mainly influence the underlying temperature field at the bottom of the layer.

CHAPTER 4

METHODOLOGY

4.1. Data Collection

In understanding the effect of laydown site conditions, environmental variables & layer thickness on degree of compaction of asphalt, systematic data collection plan across diverse conditions is paramount in ensuring the reliability, comprehensiveness, and applicability of research findings. Figure 3 shows the plan for data collection and experimental work of this research.

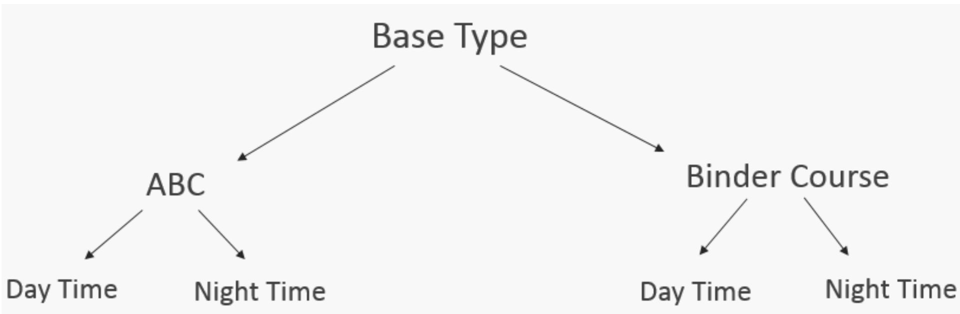


Figure 3: Basic plan for data collection and analysis

In this research, the wearing course was considered as the asphalt layer to be tested. Basically, the analysis work was divided according to the base type of the newly constructed asphalt layer as Aggregate Base Course (ABC) and binder course. Then separate analyzes were performed for day time and night time for each base type. The inclusion of different base types and time periods in the analysis recognizes the potential variability in TAC based on the type of base and the time of day. This allows for a more nuanced understanding of the factors influencing TAC.

When the data collection is considered, field data were collected from the Gampaha District i-Road Project (Package 4) for night time and day time where the base type is ABC. And field data were collected from the Rehabilitation and Improvement of Colombo – Kandy Road Project for night time and day time where the base type is asphalt binder layer. In both these projects, wearing course type III materials were used for the construction. Also, the rolling procedure was the same in both the projects.

The following data were collected and recorded from those projects.

- Asphalt Laying Records
- Summary of core samples of wearing course
- Base Temperatures
- Wind velocity
- Air Temperature
- Laydown Temperature
- Details of asphalt mixes used for wearing course
- Details of base conditions at site

The base temperature before laying the asphalt was measured using an infrared thermometer (Figure 4) & average base temperature was recorded for each asphalt truck.

Figure 4: Measuring of base temperature using an infrared thermometer

Air temperature & wind velocity were measured using a digital anemometer with thermometer (Figure 5). When conducting air temperature measurements, it was necessary to obtain readings from a distance away from the construction site to ensure that the measured air temperature accurately reflected the ambient conditions unaffected by the artificial heat generated by the hot mix asphalt. Those values were also recorded for each asphalt truck.

Figure 5: Measuring of wind velocity & air temperature a digital anemometer with thermometer

For the rate of cooling, the temperature on the surface of the freshly constructed asphalt layer was recorded at every 5 minutes using an infrared thermometer until it reached 80^0C (Figure 6 & 7). Here, surface temperature readings were obtained by taking an average value at specific location for an asphalt truck. This process was repeated for every asphalt truck utilized in the construction process, ensuring comprehensive data collection across the entirety of the operation. The total time taken for the asphalt layer to reach 80^0C was considered as the Time Available for Compaction (TAC) for the respective asphalt truck.

Figure 6: Measuring of asphalt surface temperature in day time

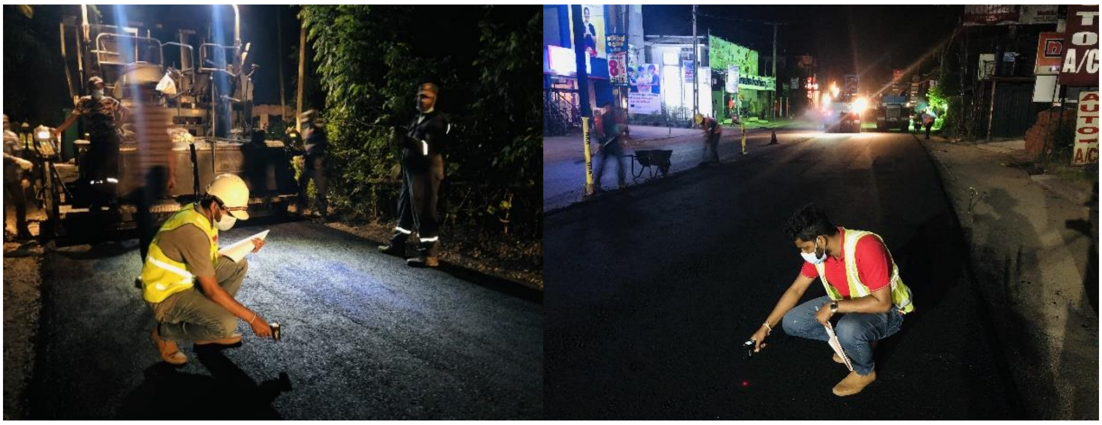


Figure 7: Measuring of asphalt surface temperature in night time

Asphalt laydown temperatures were taken from asphalt laying records. Meanwhile, crucial parameters such as layer thickness and the degree of compaction were extracted from summaries of asphalt core samples and dip measurement sheets.

Details of asphalt mixes used for wearing course were collected from the material laboratory staff of the relevant project. And details of base conditions at site were obtained by discussing with the site staff overseeing the relevant project.

4.2. Pavement Heat Transfer FEM Model

Then under this research, 3D-FEM (Three-Dimensional Finite Element Method) transient heat transfer model was developed using the Abaqus/CAE 6.14 software, for simulating the thermal behavior of an asphalt pavement section. This comprehensive model considered various factors influencing thermal performance, including material properties, environmental conditions, and construction parameters. Through meticulous calibration and validation procedures, the model was refined to ensure its reliability and accuracy in predicting temperature distributions and thermal responses within the pavement structure under diverse operating conditions.

For this research, an asphalt layer was modeled with the length of 10 m and width of 3 m. Here, the pavement structure was idealized as a series of uniform horizontal layers with consistent thickness. Table 2 gives the values used for the density, thermal conductivity and specific heat of different materials which were used for developing the FEM model. These values were obtained from the previous studies of (Yuhong Wang, Songye Zhu, Alvin S. T. Wong, 2014) and (Ying Gao, Renxiao Wang, Wenbin Yu, 2011). When performing the FEM modeling for the data collected in the field, the values obtained from the Marshall test were used as the asphalt density to ensure the accuracy of the model.

Table 2: Thermo-physical properties of the materials used for FEM model

Material	**Density (kg/m³)**	**Thermal Conductivity (W/mK)**	**Specific Heat (J/kgK)**
Asphalt	2450	1.5	955
Existing Asphalt	2500	1.5	955
ABC	2200	1.39	921
Subgrade	2100	1.79	1100

Figure 8 shows a sample of the 3D-FEM model of pavement layers developed using Abaqus/CAE 6.14 software. This model offers a visually immersive portrayal of the complex structural composition and layering within the pavement system, providing a detailed insight into its geometric configuration and material distribution.

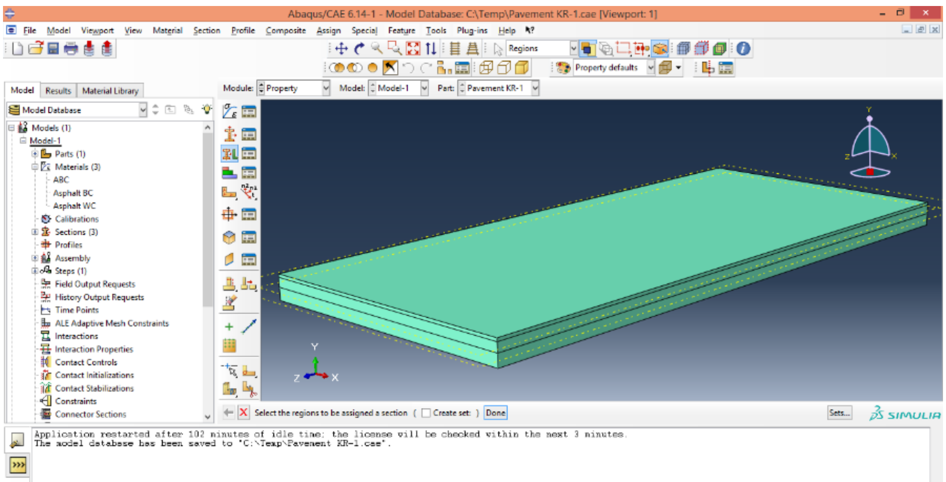


Figure 8: Sample of the 3D-FEM model of pavement layers

when considering the loads applied on the model, solar radiation was regarded as a heat flux acting on top surface of asphalt layer as illustrated by Figure 9. And it was applied only for the models where the day time asphalt laying was done. For night time asphalt laying, the effect from solar radiation was not considered as a load acting on the model.

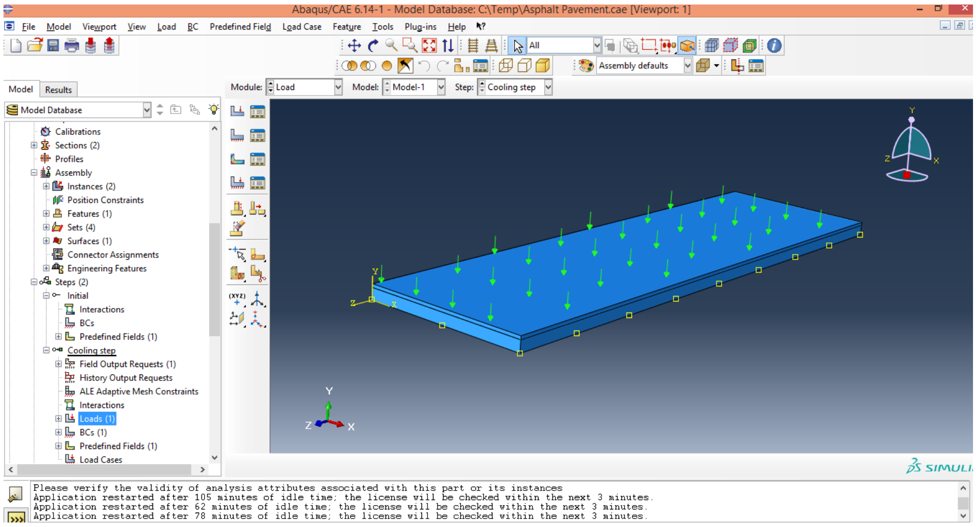


Figure 9: Applying solar radiation as a load acting on the model

As the interactions for the model, convection and radiation were applied on top surface of the asphalt layer as illustrated in Figure 9. This allows the model to simulate the influence of solar radiation, ambient temperature, and other environmental factors on the asphalt's thermal response. Thermal absorptivity and emissivity of asphalt layer were considered as 0.95 and 0.93 respectively for the modeling. (Matthew R. Hall, Pejman Keikhaei Dehdezi, Andrew R. Dawson, James Grenfell, Riccardo Isola, 2012)

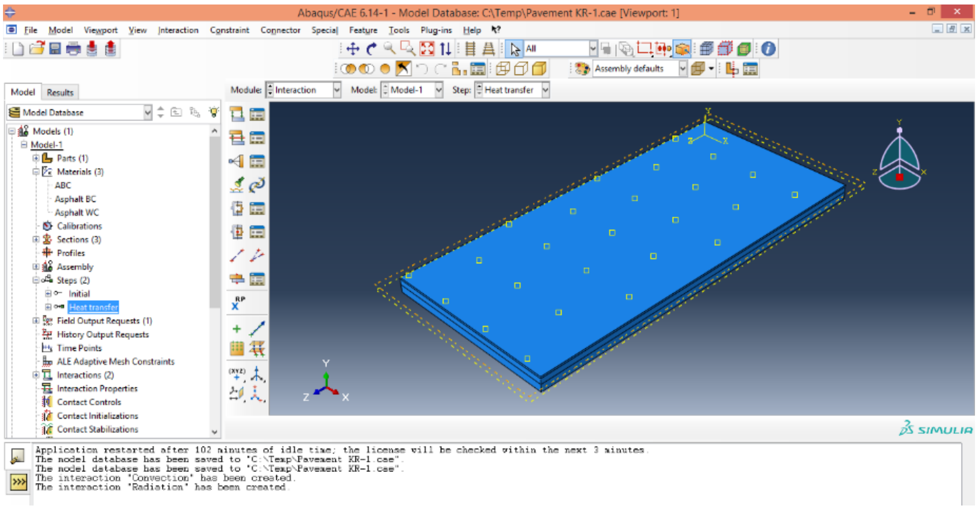


Figure 10: Applying convection and radiation as interactions on top surface of asphalt layer

The meshing process for the model involved the implementation of an 8-Node Linear Heat Transfer Brick element scheme, as illustrated in Figure 11. This meshing approach facilitates the discretization of the pavement layers into smaller, interconnected elements, allowing for a more precise representation of the thermal behavior and heat transfer mechanisms within the system. The 8-Node Linear Heat Transfer Brick elements are systematically distributed throughout the model, encompassing the entire volume of the asphalt layer and other structural components. Each element serves as a computational node where heat transfer equations are solved, enabling the accurate prediction of temperature distributions and thermal responses across the pavement system.

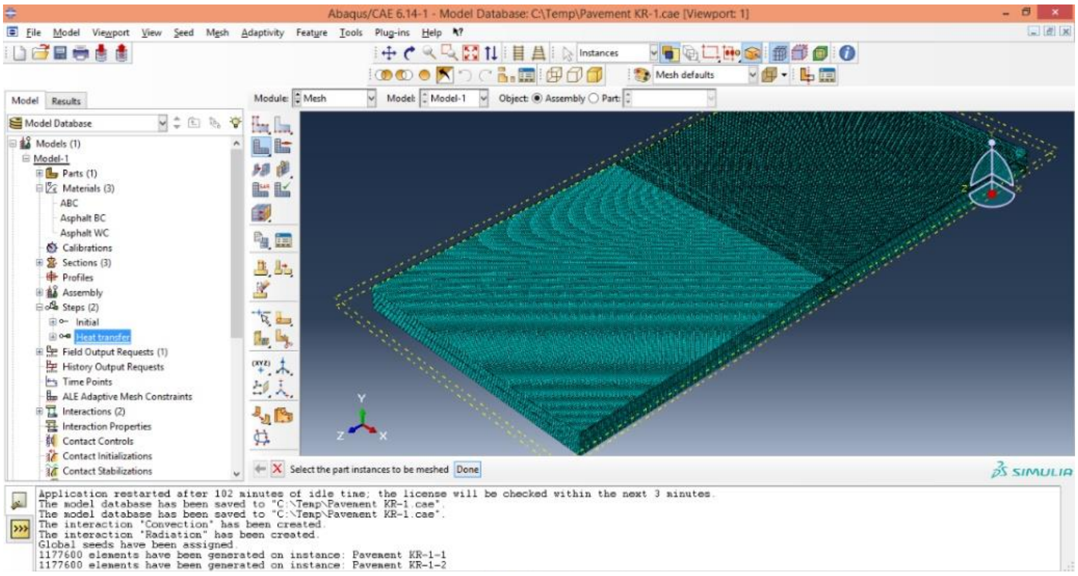


Figure 11: Meshing of FEM model

Laydown temperature and base temperature were set as the predefined temperature at initial step (Figure 12). These predefined temperatures serve as essential starting points for the simulation, providing a foundation for assessing the subsequent evolution of temperature distributions and thermal behavior of the asphalt pavement system over time. Laydown temperature was applied across the entire asphalt layer and this temperature represents the initial thermal state of the freshly laid asphalt material. The base temperature was applied for the top surface of underlying layer. This temperature setting reflects the thermal state of the underlying layer prior to the application of the asphalt pavement.

The horizontal temperature gradient was set as zero. Heat transfer is assumed to occur one-dimensionally in the vertical direction. As a boundary condition, an adiabatic boundary which means a constant temperature was set at a depth of 300 mm from bottom of the new asphalt layer considering the conduction through bottom layers according to the literature. (Cedric Vuye, Gert Guldentops, Nima Rahbar, Alireza Mahdavi Nejad, Wim Van den bergh, 2016)

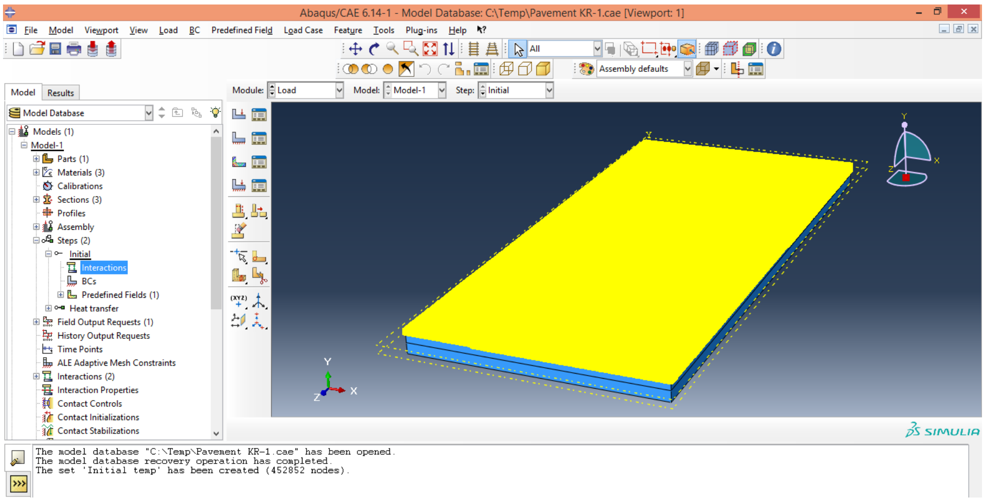


Figure 12: Setting laydown temperature as a predefined temperature at initial step

Then the transient heat transfer model was run and results were obtained, unveiling the dynamic thermal behavior of the asphalt FEM (Finite Element Method) model. Figure 12 & Figure 13 show an example of the output temperatures of the asphalt FEM model.

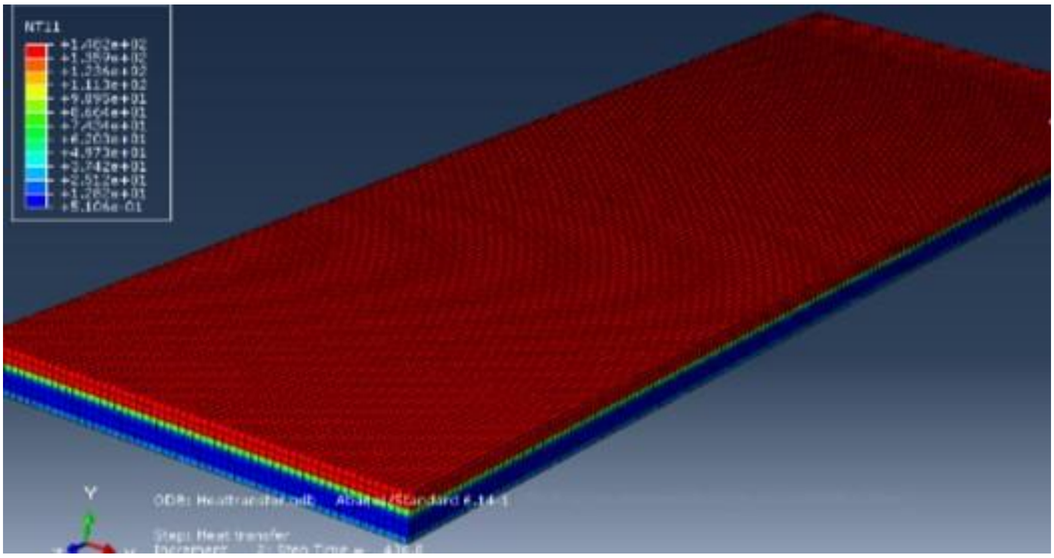


Figure 13: Output temperatures in the FEM model (3D view)

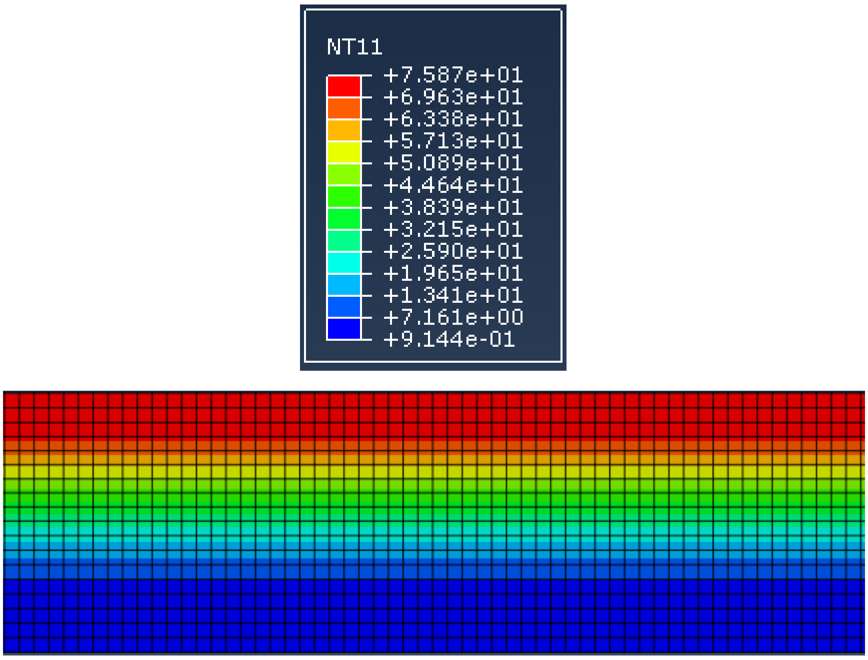
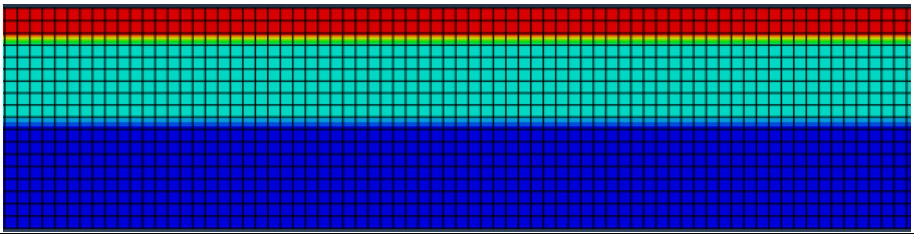
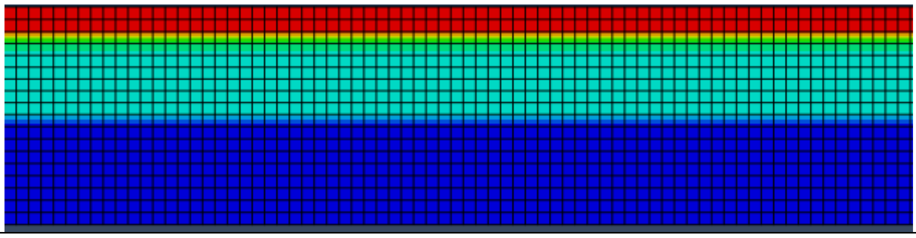
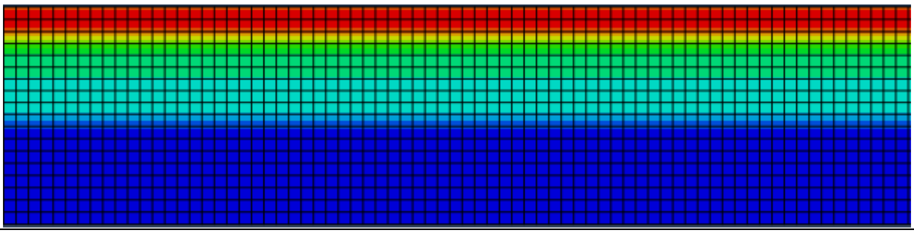
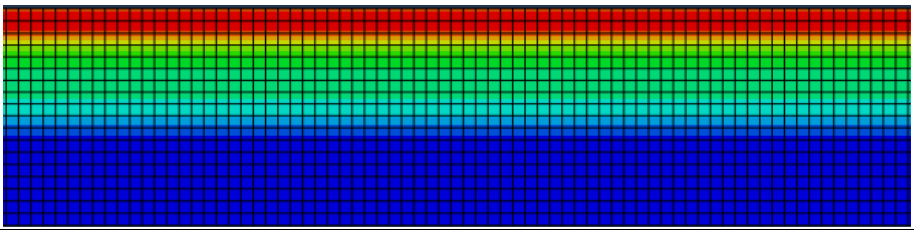
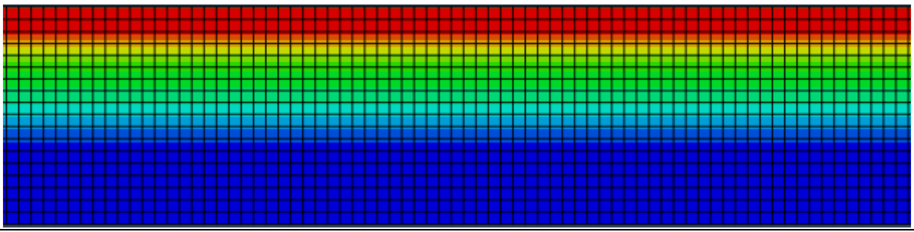
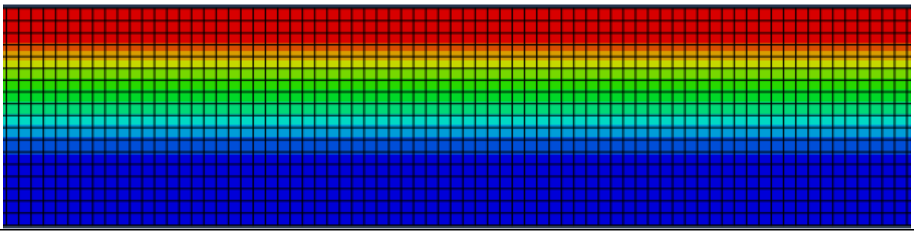
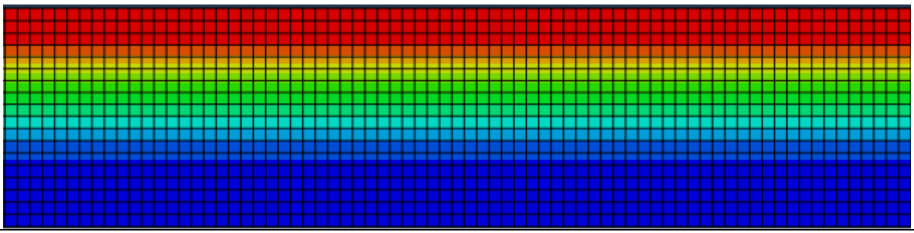
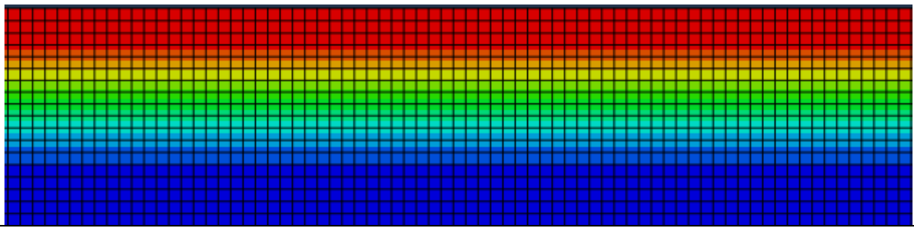


Figure 14: Output temperatures in the FEM model (Cross-section view)

In this way, using the Abaqus FEM model, the temperature distribution of pavements over time can be effectively analyzed. This model allows for the detailed assessment of how temperature varies across the pavement structure throughout different periods. For instance, Table 3 presents an overview of the temperature distribution changes at various time intervals when the wearing course was laying during a day time for a specific pavement section along the Colombo-Kandy road project.

Table 3: Variation of the temperature distribution of pavement over time

Time (s)	Temparature Distribution in Pavement Layer (Cross Section)
0.0	
129.0	
509.8	
901.0	
1652.0	
2871.0	

3342.0	
4500.0	

Furthermore, the temperature variation over time at a single node within the pavement layers can be obtained through the Abaqus FEM model. This detailed analysis allows for the monitoring of temperature changes at specific points within the structure. For example, Figure 15 demonstrates the changes in nodal temperature over time at the surface of the newly laid asphalt layer.

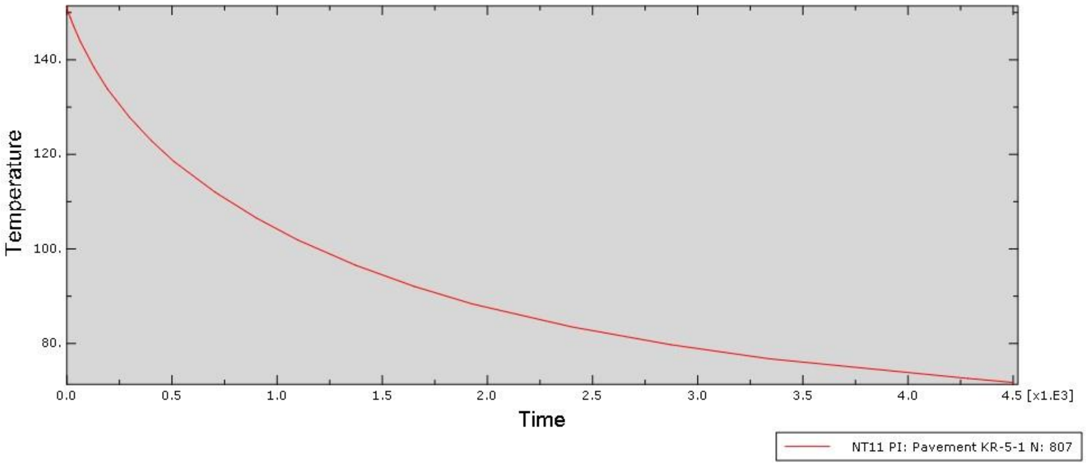


Figure 15: Variation of nodal temperature over time at the top of the newly constructed asphalt layer

Then in this way, the temperature variation of a node at the top of the model over time was obtained as output from the model, representing the thermal response of the asphalt pavement within the FEM model. These simulated temperature variations were then compared with temperature data collected from field measurements, establishing a robust comparison to verify and validate the accuracy of the FEM model. The comparison involved plotting both sets of temperature data on the same graph, allowing for a direct visual assessment of their agreement or discrepancies.

CHAPTER 5

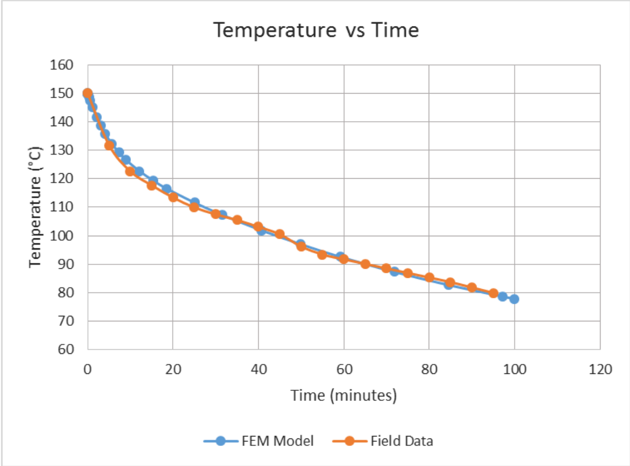
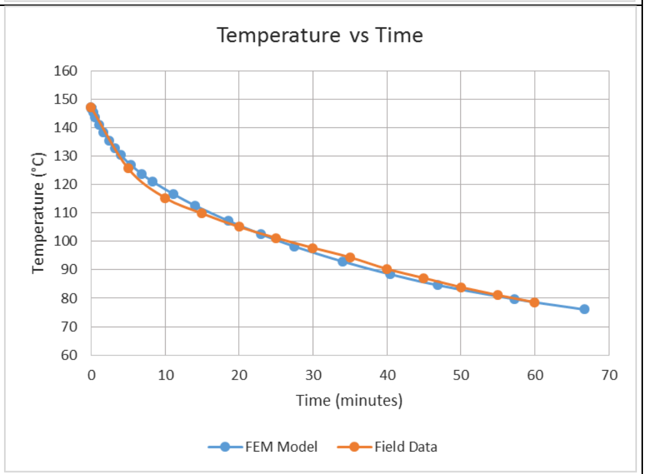
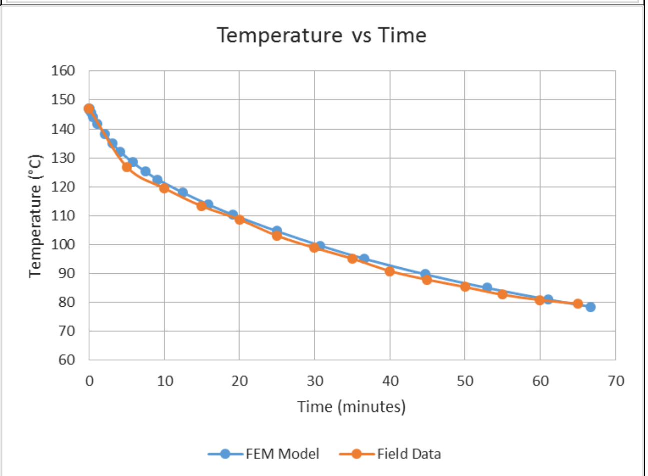
OUTPUTS & VALIDATION OF THE FEM MODEL

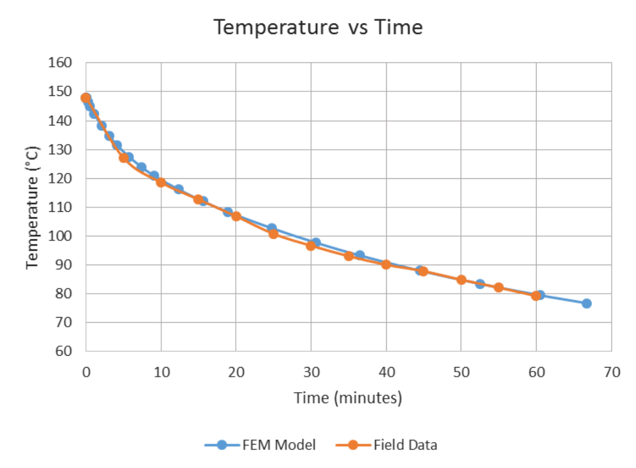
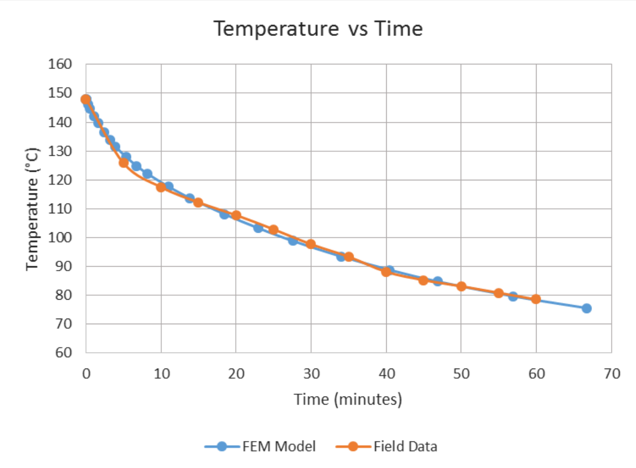
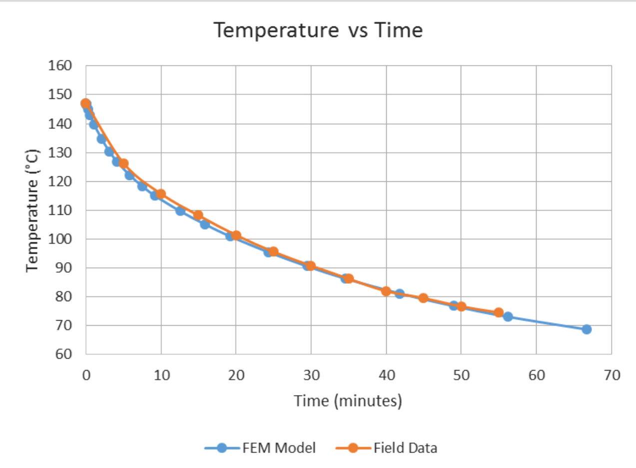
Validation examines the accuracy of the model as well as how well it reproduces the physical characteristics of the real-world situation it is intended to simulate. Here, to validate the FEM model which was developed using Abaqus/CAE 6.14 software, the temperature variation in the model was plotted with the temperature data collected from the field on the same graph. The data sets collected in the field measurements and the comparison between the temperature variation of the model and the temperature data collected from the field are presented in the following tables: Table 3, Table 4, Table 5, and Table 6. Key aspects considered during this comparison included the magnitude and trends of temperature variations over time, as well as any notable deviations or discrepancies between the simulated and field data points. By overlaying the simulated temperature variation from the FEM model with the corresponding field data points, the fidelity of the model in replicating real-world thermal conditions experienced by the asphalt pavement, can be ascertained.

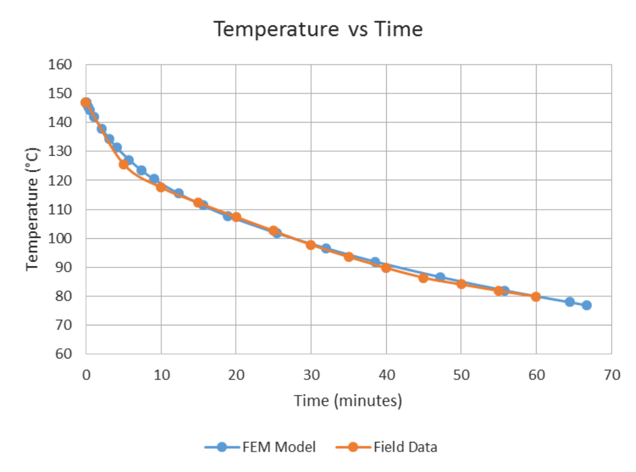
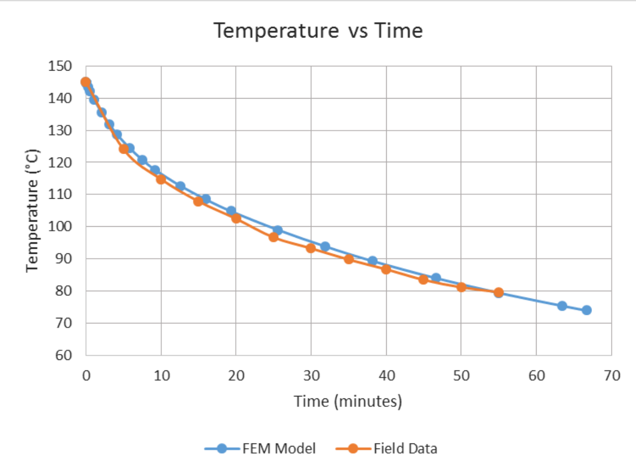
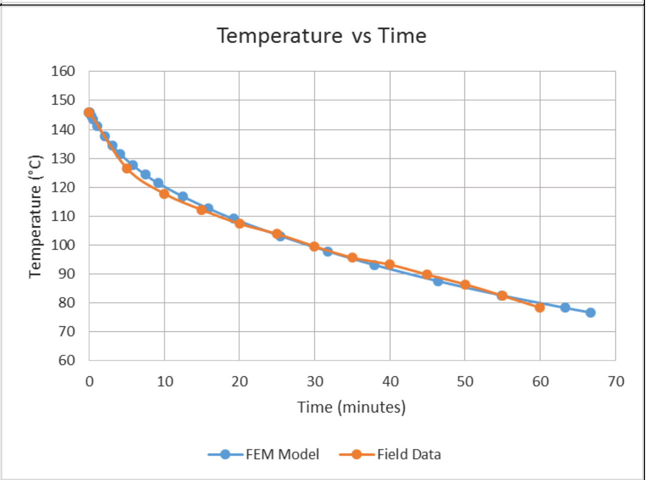
5.1. Outputs & Validation of the FEM Model with Base Type – ABC (Day Time)

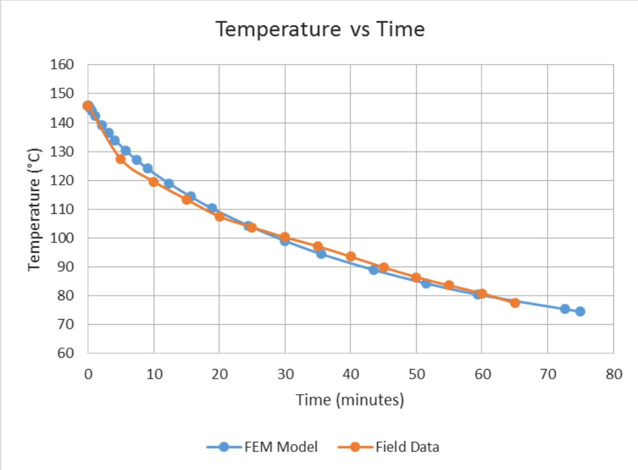
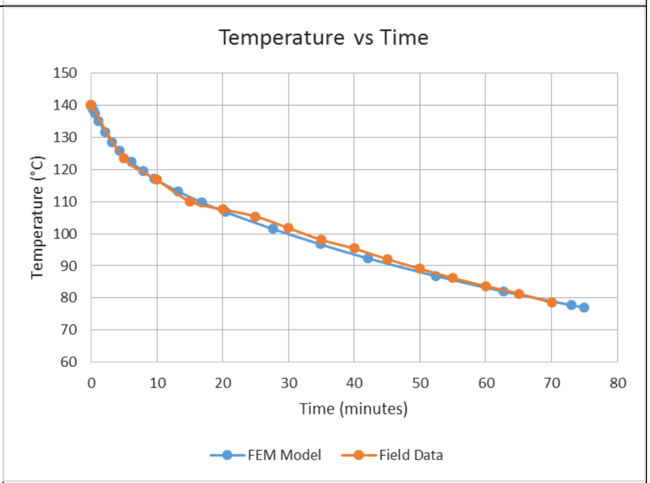
Table 4 shows the data sets collected in the field measurements and comparison between the temperature variations obtained from the FEM model and the temperature data collected from field measurements for each data set where the base type is ABC during day time.

Table 4: Comparison of cooling curves between FEM model & field data for base type - ABC (Day time)

No	Layer Thickness (mm)	Air Temperature (°C)	Wind Velocity (km/h)	Base Temperature (°C)	Cooling Curve
01	100	33.2	1.53	42.93	
02	65	32.8	3.80	40.37	
03	70	32.9	2.30	41.83	

04	75	32.7	2.97	40.23	
05	68	32.4	3.30	40.90	
06	65	30.5	4.13	40.03	

07	85	32.6	2.63	41.47	
08	80	31.8	2.80	40.70	
09	78	32.3	1.70	40.80	

10	62	32.5	2.30	41.07	
11	90	32.9	1.40	42.03	

The time available for compaction (TAC) in both field measurements and the FEM model was extracted from cooling curves specific to each dataset. Table 5 presents a concise comparison of these TAC values, allowing for a straightforward assessment of their alignment or disparity between FEM model and the asphalt layer in the field where the base type is ABC during day time. Percentage difference has been accompanied the comparison to quantitatively evaluate the level of agreement.

Table 5: Comparison of TAC between FEM model and the asphalt layer in the field for base type - ABC (Day time)

No	Field Data: TAC (min)	FEM Model: TAC (min)	Difference %
01	94.7	92.9	-1.90
02	57.2	56.6	-1.05

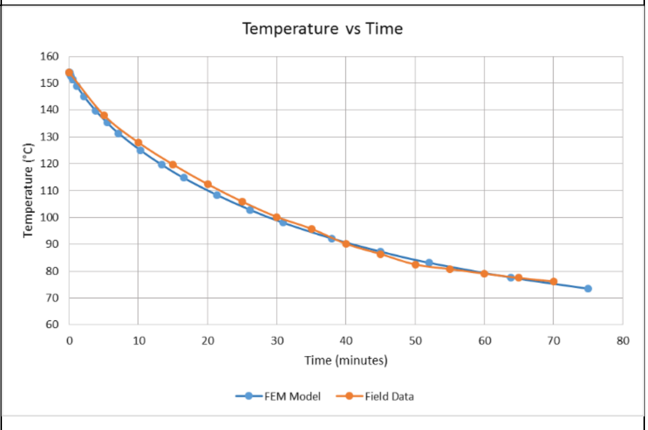
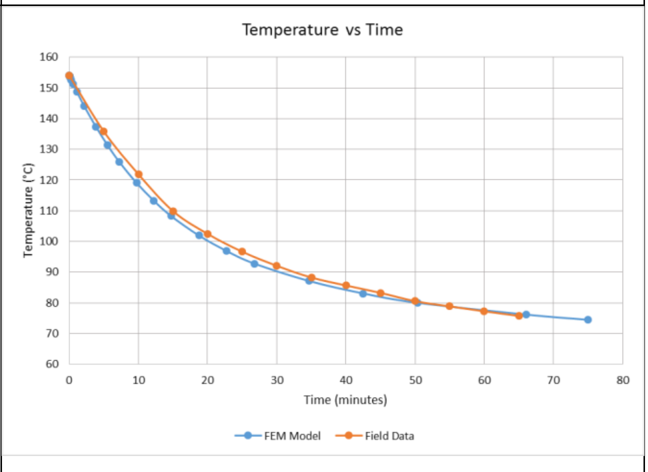
03	63.5	63.4	-0.16
04	58.8	59.6	1.36
05	57.0	56.4	-1.05
06	44.2	43.8	-0.90
07	59.8	60.1	0.50
08	54.0	54.0	0.00
09	59.0	60.1	1.86
10	61.3	60.6	-1.14
11	67.5	67.6	0.15

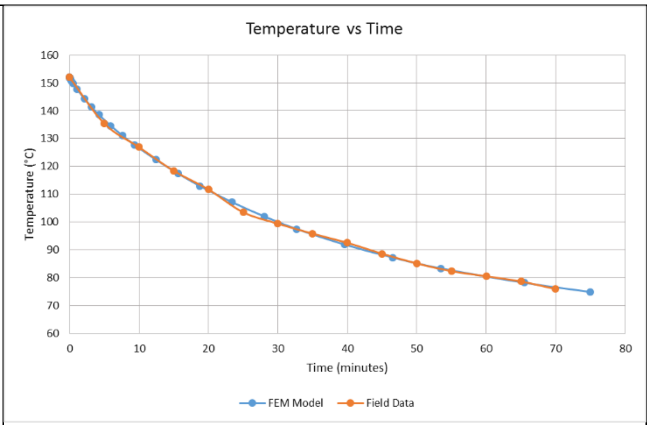
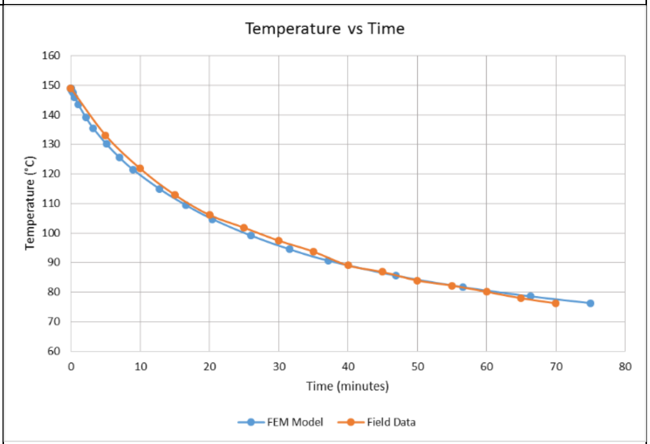
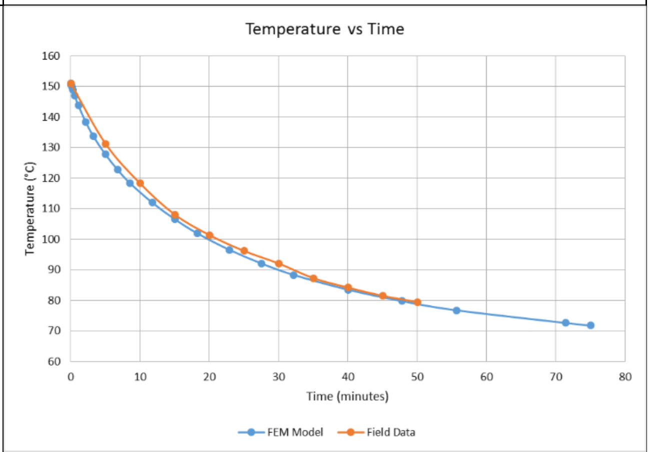
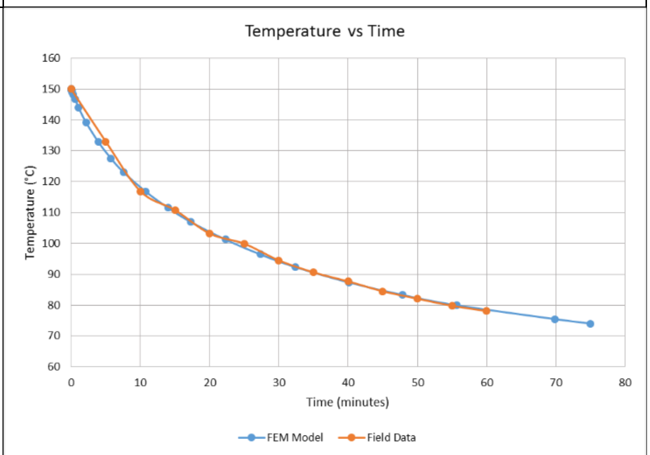
According to the graphs and data in the Table 3, the cooling curves of the FEM model are almost the same as the cooling curves of the asphalt layer in the field where the base type is ABC and for day time. Also, the differences in values of time available for compaction between FEM model and the asphalt layer in the field are comparatively very small. According to the Table 4, the difference is within the range of ±2.0% for all the data sets. Therefore, the heat transfer FEM model developed for the asphalt layer where the base type is ABC and for day time can be considered as validated.

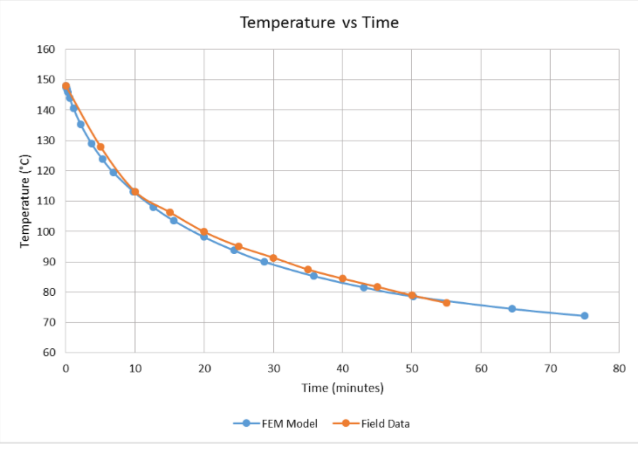
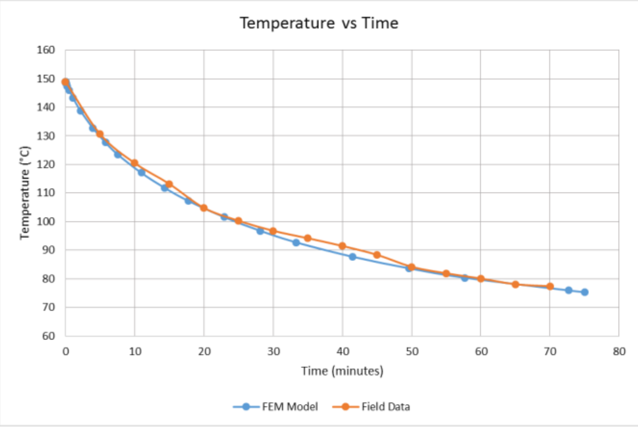
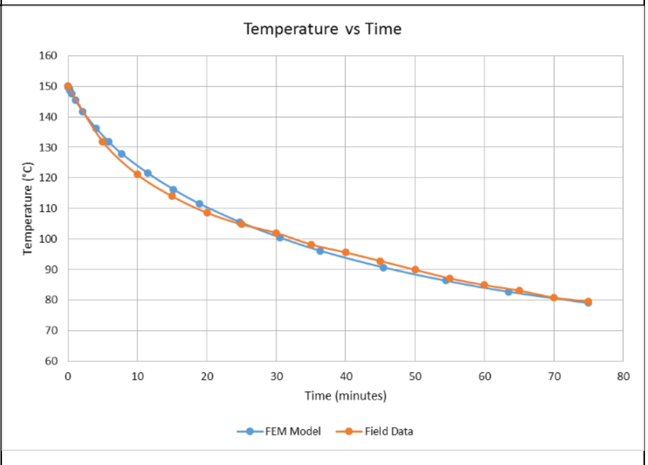
5.2. Outputs & Validation of the FEM Model with Base Type – Asphalt (Day Time)

Table 6 shows the data sets collected in the field measurements and comparison between the temperature variations obtained from the FEM model and the temperature data collected from field measurements for each data set where the base type is asphalt during day time.

Table 6: Comparison of cooling curves between FEM model & field data for base type - Asphalt (Day time)

No	Layer Thickness (mm)	Air Temperature (°C)	Wind Velocity (km/h)	Base Temperature (°C)	Graph (Cooling Curves)
01	51	34.90	1.19	40.53	
02	53.7	34.57	0.92	43.13	

03	52.6	34.60	0.61	46.73	
04	46.6	34.33	0.88	49.67	
05	45	35.07	1.38	44.07	
06	52.5	35.17	1.18	47.93	

<table>
<tr><td>07</td><td>46</td><td>34.83</td><td>1.60</td><td>45.50</td><td>
</td></tr>
<tr><td>08</td><td>53</td><td>35.33</td><td>1.11</td><td>44.30</td><td>
</td></tr>
<tr><td>09</td><td>54.1</td><td>36.43</td><td>0.60</td><td>48.50</td><td>
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The time available for compaction (TAC) in both field measurements and the FEM model was extracted from cooling curves specific to each dataset. Table 7 presents a concise comparison of these TAC values, allowing for a straightforward assessment of their alignment or disparity between FEM model and the asphalt layer in the field where the base type is asphalt during day time. Percentage difference has been accompanied the comparison to quantitatively evaluate the level of agreement.

Table 7: Comparison of TAC between FEM model and the asphalt layer in the field for base type - Asphalt (Day time)

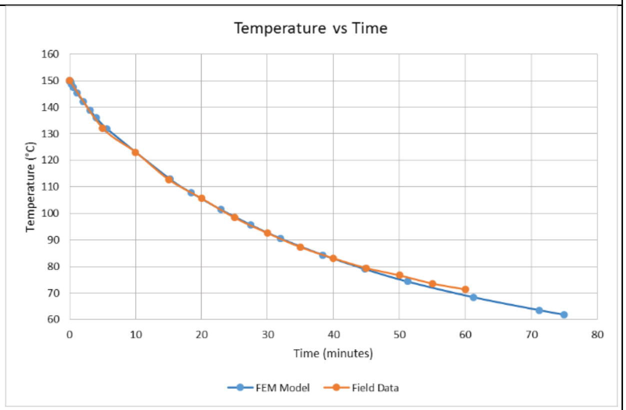
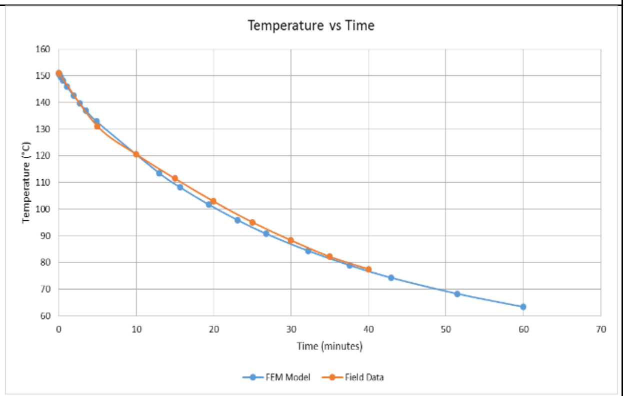
No	Field Data: TAC (min)	FEM Model: TAC (min)	Difference %
01	57.6	58.7	1.91
02	51.7	50.8	-1.74
03	61.3	61.2	-0.16
04	60.4	61.6	1.99
05	48.2	47.4	-1.66
06	54.6	55.6	1.83
07	48.0	47.1	-1.88
08	60.2	59.1	-1.83
09	73.1	71.9	-1.64

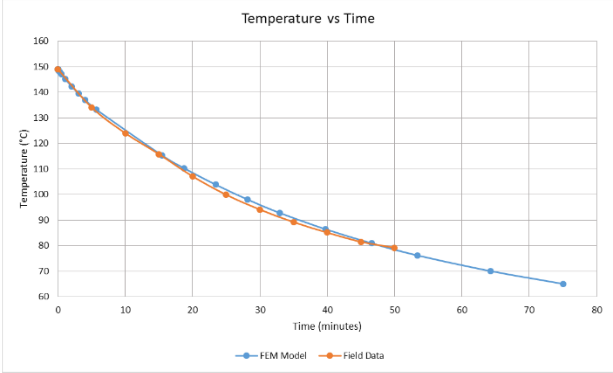
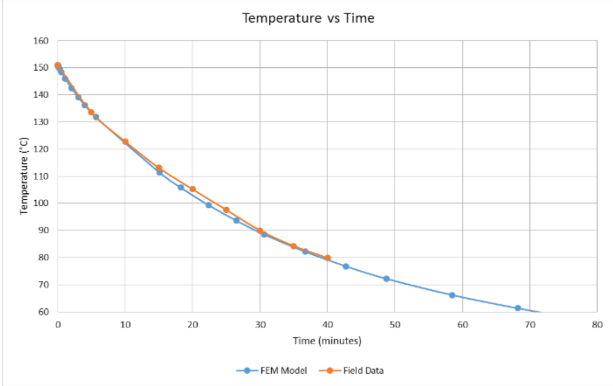
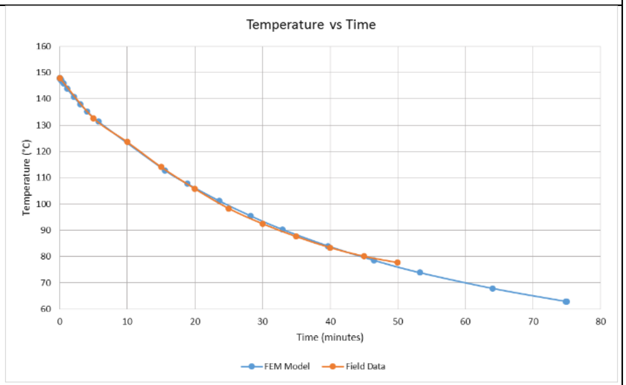
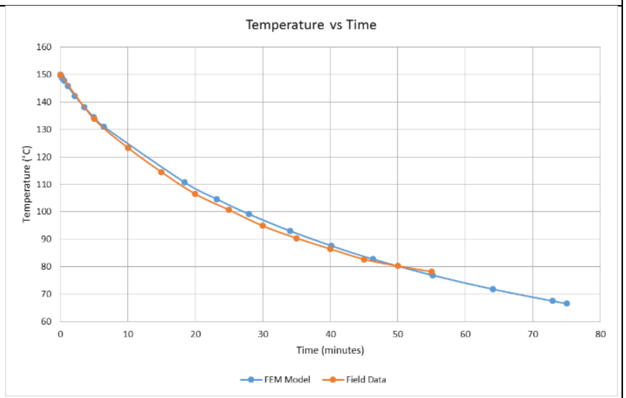
According to the graphs and data in the Table 4, the cooling curves of the FEM model are almost the same as the cooling curves of the asphalt layer in the field where the base type is Asphalt and for day time. Also, the differences in values of time available for compaction between FEM model and the asphalt layer in the field are comparatively very small. According to the Table 6, the difference is within the range of ±2.0% for all the data sets. Therefore, the heat transfer FEM model developed for the asphalt layer where the base type is Asphalt and for day time can be considered as validated.

5.3. Outputs & Validation of the FEM Model with Base Type – ABC (Night Time)

Table 8 shows the data sets collected in the field measurements and comparison between the temperature variations obtained from the FEM model and the temperature data collected from field measurements for each data set where the base type is ABC during night time.

Table 8: Comparison of cooling curves between FEM model & field data for base type - ABC (Night time)

No	Layer Thickness (mm)	Air Temperature (°C)	Wind Velocity (km/h)	Base Temperature (°C)	Cooling Curves
01	53.1	28.2	2.81	27.6	
02	45.4	27.9	2.85	27.6	

03	52.0	29.3	0.8	26.1	
04	45.7	28.2	1.93	27.1	
05	51.4	28.7	1.05	26.3	
06	61.3	28.1	3.69	26.8	

The time available for compaction (TAC) in both field measurements and the FEM model was extracted from cooling curves specific to each dataset. Table 9 presents a concise comparison of these TAC values, allowing for a straightforward assessment of their alignment or disparity between FEM model and the asphalt layer in the field where the base type is ABC during night time. Percentage difference has been accompanied the comparison to quantitatively evaluate the level of agreement.

Table 9: Comparison of TAC between FEM model and the asphalt layer in the field for base type - ABC (Night time)

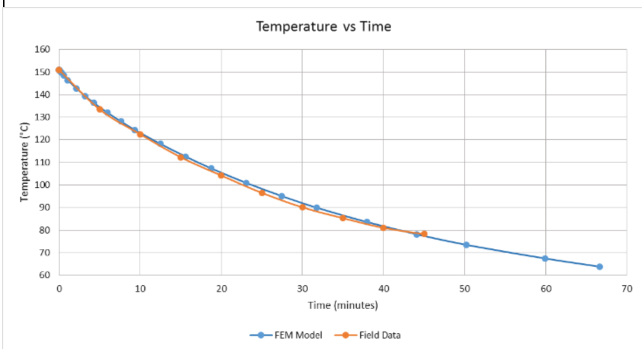
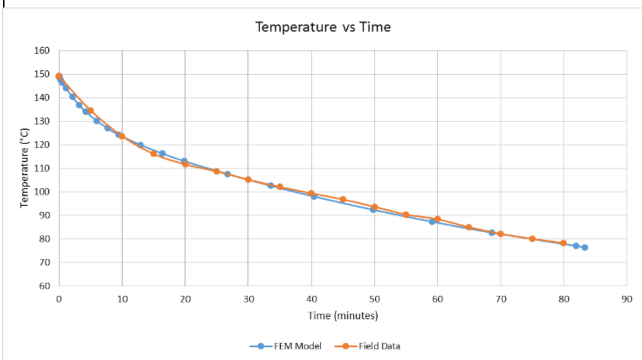
No	Field Data: TAC (min)	FEM Model: TAC (min)	Difference %
01	44.2	43.6	-1.36
02	37.2	36.6	-1.61
03	48.3	47.9	-0.83
04	39.9	39.2	-1.75
05	45.2	44.7	-1.11
06	50.7	50.5	-0.39

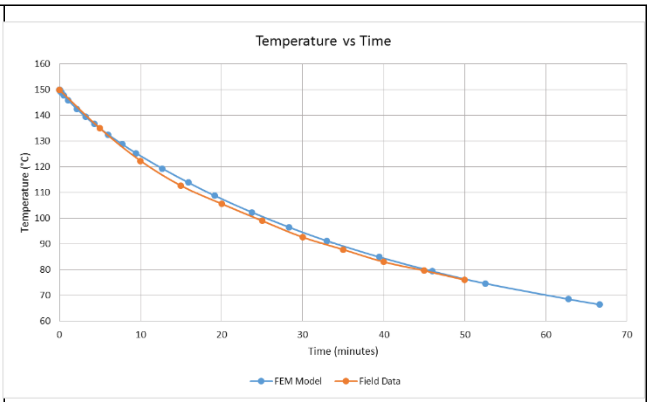
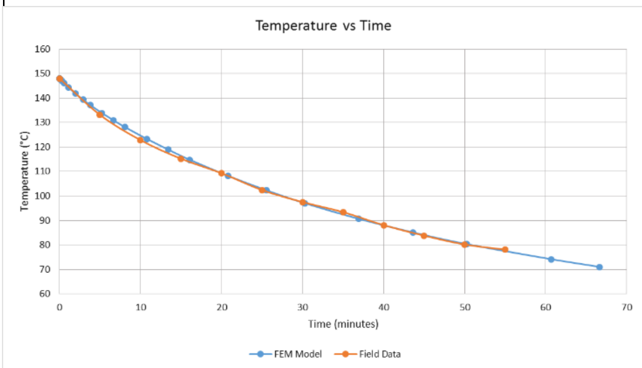
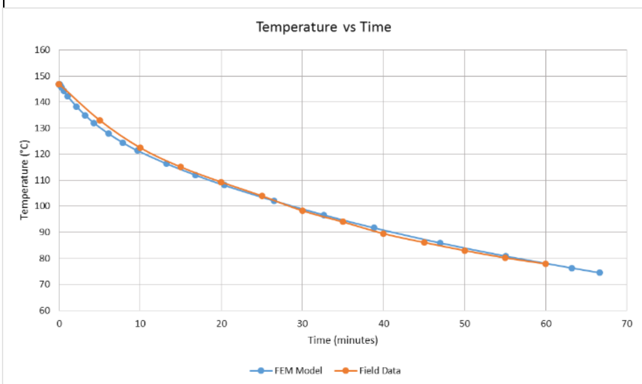
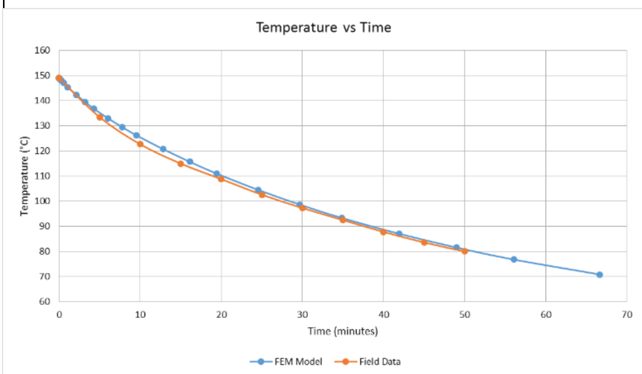
According to the graphs and data in the Table 5, the cooling curves of the FEM model are almost the same as the cooling curves of the asphalt layer in the field where the base type is ABC and for night time. Also, the differences in values of time available for compaction between FEM model and the asphalt layer in the field are comparatively very small. According to the Table 8, the difference is within the range of ±2.0% for all the data sets. Therefore, the heat transfer FEM model developed for the asphalt layer where the base type is ABC and for night time can be considered as validated.

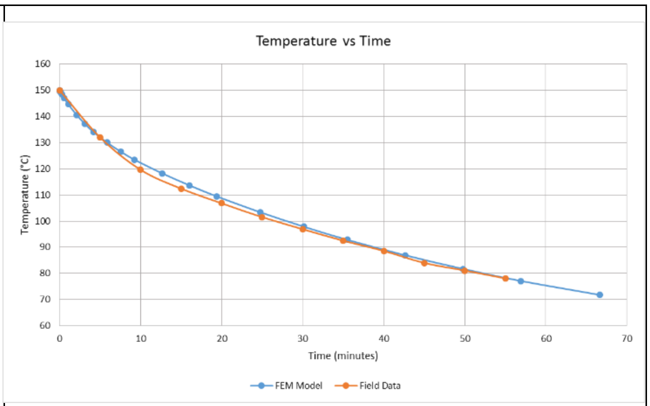
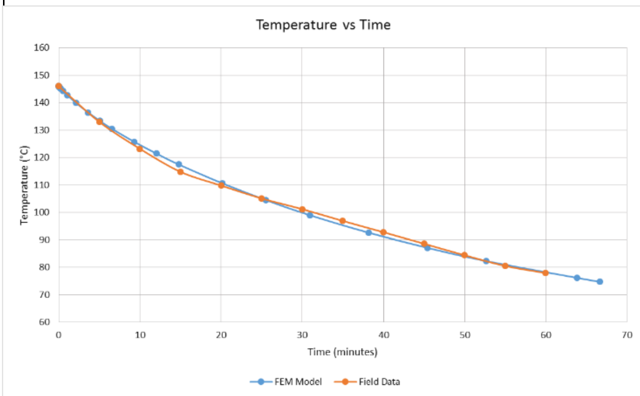
5.4. Outputs & Validation of the FEM Model with Base Type – Asphalt (Night Time)

Table 10 shows the data sets collected in the field measurements and comparison between the temperature variations obtained from the FEM model and the temperature data collected from field measurements for each data set where the base type is asphalt during night time.

Table 10: Comparison of cooling curves between FEM model & field data for base type - Asphalt (Night time)

No	Layer Thickness (mm)	Air Temperature (°C)	Wind Velocity (km/h)	Base Temperature (°C)	Graph (Cooling Curves)
01	51.0	26.05	2.1	25.0	
02	96.0	26.43	3.52	25.8	

03	53.0	26.37	1.08	25.0	
04	54.4	26.27	0.0	26.1	
05	78.5	26.0	4.32	27.3	
06	60.3	25.93	1.14	27.1	

07	69.5	26.13	4.08	28.6	
08	59.1	26.07	0.36	26.5	

The time available for compaction (TAC) in both field measurements and the FEM model was extracted from cooling curves specific to each dataset. Table 11 presents a concise comparison of these TAC values, allowing for a straightforward assessment of their alignment or disparity between FEM model and the asphalt layer in the field where the base type is asphalt during night time. Percentage difference has been accompanied the comparison to quantitatively evaluate the level of agreement.

Table 11: Comparison of TAC between FEM model and the asphalt layer in the field for base type - Asphalt (Night time)

No	**Field Data: TAC (min)**	**FEM Model: TAC (min)**	**Difference %**
01	41.8	42.0	0.48
02	75.0	74.8	-0.27
03	44.6	45.4	1.79

04	50.5	50.8	0.59
05	55.5	56.5	1.80
06	50.2	51.2	1.99
07	51.8	52.5	1.35
08	56.0	56.8	1.43

According to the graphs and data in the Table 6, the cooling curves of the FEM model are almost the same as the cooling curves of the asphalt layer in the field where the base type is Asphalt and for night time. Also, the differences in values of time available for compaction between FEM model and the asphalt layer in the field are comparatively very small. According to the Table 10, the difference is within the range of ±2.0% for all the data sets. Therefore, the heat transfer FEM model developed for the asphalt layer where the base type is Asphalt and for night time can be considered as validated.

CHAPTER 6

RESULTS AND DISCUSSION

After validation of the heat transfer FEM model for each condition, a number of FEM models were developed under different site conditions. That means, the values of the asphalt layer thickness, base temperature, wind velocity, air temperature and laydown temperature were randomly changed for each asphalt FEM model. However, when choosing values for the variables, it was always used values within the minimum and maximum values of each variable obtained from the field data to validate the model.

Then from the output of each asphalt FEM model, Time Available for Compaction (TAC) was obtained. Here, the time taken by the asphalt surface to reach 80^0C was considered as the TAC.

Then regression analysis was performed for the results with TAC as dependent variable and laydown temperature, air temperature, wind velocity, base temperature and asphalt layer thickness as independent variables. Here, according to the literature, it was considered that there is a linear relationship between the independent variable and the dependent variables (Chieh-Min Chang, Yen-Jui Chang, Jian-Shiuh Chen, 2009) (Kevin L. Williams, Ben C. Cox, Isaac L. Howard, L. Allen Cooley, 2015).

Multiple linear regression analysis was used to develop mathematical equations predicting Time Available for Compaction (TAC) by incorporating various factors, including different base types and time periods of the day. This method allowed for the creation of predictive models that could accurately estimate TAC under diverse environmental and material conditions encountered during asphalt pavement construction.

In practice, R^2 values closer to 1 indicate a better fit of the regression model to the data. The standard error of the estimate, is a statistical measure that quantifies the precision of the predictions made by a regression model. It represents the average deviation of the observed values from the predicted values, indicating how closely the data points are scattered around the regression line

6.1. Results of Asphalt Layer with Base Type – ABC (Day Time)

Table 12 shows the results obtained for TAC from the heat transfer FEM models which were created using Abaqus software where the base type is ABC and during day time.

Table 12: Values for TAC obtained from the heat transfer FEM model for base type – ABC (Day time)

TAC (min)	**Laydown Temperature (°C)**	**Air Temperature (°C)**	**Wind Velocity (km/h)**	**Base Temperature (°C)**	**Layer Thickness (mm)**
Y	**X1**	**X2**	**X3**	**X4**	**X5**
94.7	150	33.2	1.53	42.93	100
57.2	147	32.8	3.80	40.37	65
63.5	147	32.9	2.30	41.83	70
58.8	148	32.7	2.97	40.23	75
57.0	148	32.4	3.30	40.90	68
44.2	147	30.5	4.13	40.03	65
59.8	147	32.6	2.63	41.47	85
54.0	145	31.8	2.80	40.70	80
58.0	146	32.3	1.70	40.80	78
61.3	146	32.5	2.30	41.07	62
67.5	140	32.9	1.40	42.03	90
54.2	141	32.30	4.00	34.2	60
48.8	140	33.20	3.50	34.7	40
52.5	142	33.60	1.90	34.8	50
49.0	141	33.70	2.00	34.9	55
54.0	143	33.80	1.50	38.2	45
43.2	144	34.10	3.00	38.8	35
53.8	147	32.70	0.00	36.1	50
50.1	145	33.00	1.00	39.6	40
62.3	148	29.00	2.00	36.5	60
55.0	145	29.50	1.50	39.00	65
45.0	142	30.00	4.00	38	55

Linear regression analysis was performed for the above values in Table 12. The summary output of the linear regression analysis is presented in the Figure 16, including key statistical metrics such as standard errors and goodness-of-fit measures (e.g., R-squared) and coefficients corresponding to predictor variables derived from the regression model where the base type is ABC during day time.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.934475832
R Square	0.873245081
Adjusted R Square	0.833634168
Standard Error	5.172559402
Observations	22

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	2949.186795	589.837359	22.0455685	1.17776E-06
Residual	16	428.0859322	26.75537076		
Total	21	3377.272727			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-76.91233903	63.54036137	-1.210448562	0.243685471	-211.6118878	57.78720976	-211.6118878	57.78720976
X1	0.412431224	0.501317435	0.822694753	0.422773911	-0.650314264	1.475176712	-0.650314264	1.475176712
X2	0.843912613	0.860612905	0.980594884	0.341388365	-0.980505246	2.668330471	-0.980505246	2.668330471
X3	-2.210978383	1.148665319	-1.924823833	0.072219797	-4.64604008	0.224083315	-4.64604008	0.224083315
X4	0.333169826	0.742458425	0.448738696	0.659638091	-1.240771724	1.907111376	-1.240771724	1.907111376
X5	0.572538175	0.102449839	5.588473152	4.07753E-05	0.355354218	0.789722132	0.355354218	0.789722132

Figure 16: Summary output of the linear regression analysis for base type – ABC (Day time).

According to the linear regression analysis, a mathematical equation for TAC where the base type is ABC during day time, was developed as detailed in Eq.15.

$$TAC = 0.412x1 + 0.844x2 - 2.211x3 + 0.333x4 + 0.573x5 - 76.912 \quad \text{Eq.15}$$

Where;

x1 = Laydown Temperature (°C)

x2 = Air Temperature (°C)

x3 = Wind Velocity (km/h)

x4 = Base Temperature (°C)

x5 = Layer Thickness (mm)

Here, R^2 value indicates that 87% of the variance in TAC can be explained by the independent variables; laydown temperature, air temperature, wind velocity, base temperature and layer thickness. A standard error of 5.17 implies that, typically, the actual values of the dependent variable are anticipated to differ from the predicted values by around 5.17 units, on average.

6.2. Results of Asphalt Layer with Base Type – Asphalt (Day Time)

Table 13 shows the results obtained for TAC from the heat transfer FEM models which were created using Abaqus software where the base type is Asphalt and during day time.

Table 13: Values for TAC obtained from the heat transfer FEM model for base type – Asphalt (Day time)

TAC (min)	**Laydown Temperature (°C)**	**Air Temperature (°C)**	**Wind Velocity (km/h)**	**Base Temperature (°C)**	**Layer Thickness (mm)**
Y	**X1**	**X2**	**X3**	**X4**	**X5**
57.4	154.0	34.90	4.27	40.53	51
55.5	154.0	34.57	3.30	43.13	53.7
61.3	152.0	34.60	2.20	46.73	52.6
57.6	149.0	34.33	3.17	49.67	46.6
49.8	151.0	35.07	4.97	44.07	45.0
54.2	150.0	35.17	4.23	47.93	52.5
48.6	148.0	34.83	5.77	45.50	46.0
60.7	149.0	35.33	4.00	44.30	53.0
73.1	150.0	36.43	2.17	48.50	54.1
52.6	146.0	32.50	2.30	38.00	60.0
51.3	140.0	30.00	1.40	42.00	55.0
44.8	139.0	33.00	4.00	39.00	45.0
45.2	138.0	33.20	3.50	40.00	50.0
42.6	137.0	34.00	3.00	44.00	40.0
47.9	139.0	30.00	2.00	41.00	55.0
45.1	136.0	33.00	1.50	39.00	45.0
39.7	139.0	34.10	3.00	42.00	35.0
47.5	139.0	31.00	0.00	37.00	50.0
46.5	140.0	33.00	1.00	40.00	45.0
49.8	140.0	32.00	2.00	43.00	55.0
53.8	145.0	34.00	1.50	42.00	65.0
46.3	140.0	30.00	4.00	40.00	55.0

Linear regression analysis was performed for the above values in Table 13. The summary output of the linear regression analysis is presented in the Figure 17, including key statistical metrics such as standard errors and goodness-of-fit measures (e.g., R-squared) and coefficients corresponding to predictor variables derived from the regression model where the base type is asphalt during day time.

SUMMARY OUTPUT	
Regression Statistics	
Multiple R	0.902832085
R Square	0.815105773
Adjusted R Square	0.757326327
Standard Error	3.70540125
Observations	22

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	968.4586616	193.6917323	14.10719261	2.20639E-05
Residual	16	219.6799748	13.72999843		
Total	21	1188.138636			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-105.4516385	21.32765003	-4.944362756	0.000146434	-150.6642368	-60.23904014	-150.6642368	-60.23904014
X1	0.549324528	0.24429883	2.248576169	0.038981784	0.031434143	1.067214913	0.031434143	1.067214913
X2	0.969260833	0.745702333	1.299795897	0.212086118	-0.611557494	2.55007916	-0.611557494	2.55007916
X3	-1.687505647	0.705657501	-2.391394755	0.029418573	-3.183432723	-0.191578571	-3.183432723	-0.191578571
X4	0.691068049	0.310794264	2.22355471	0.040930109	0.032213642	1.349922456	0.032213642	1.349922456
X5	0.408896216	0.162734419	2.512659695	0.023078491	0.063914658	0.753877774	0.063914658	0.753877774

Figure 17: Summary output of the linear regression analysis for base type – Asphalt (Day time).

According to the linear regression analysis, a mathematical equation for TAC where the base type is asphalt during day time, was developed as detailed in Eq.16.

$$TAC = 0.549x1 + 0.969x2 - 1.688x3 + 0.691x4 + 0.409x5 - 105.452 \quad \text{Eq.16}$$

Where;

x1 = Laydown Temperature (°C)

x2 = Air Temperature (°C)

x3 = Wind Velocity (km/h)

x4 = Base Temperature (°C)

x5 = Layer Thickness (mm)

Here, R^2 value indicates that 82% of the variance in TAC can be explained by the independent variables; laydown temperature, air temperature, wind velocity, base temperature and layer thickness. A standard error of 3.70 suggests that, on average, the actual values of the dependent variable are projected to vary from the predicted values by approximately 3.7 units.

6.3. Results of Asphalt Layer with Base Type – ABC (Night Time)

Table 14 shows the results obtained for TAC from the heat transfer FEM models which were created using Abaqus software where the base type is ABC and during night time.

Table 14: Values for TAC obtained from the heat transfer FEM model for base type – ABC (Night time)

TAC (min)	**Laydown Temperature (°C)**	**Air Temperature (°C)**	**Wind Velocity (km/h)**	**Base Temperature (°C)**	**Layer Thickness (mm)**
Y	**X1**	**X2**	**X3**	**X4**	**X5**
44.2	150.0	28.20	2.81	27.57	53.10
47.8	151.0	29.60	0.50	27.97	51.00
37.3	151.0	27.90	2.85	27.57	45.40
48.3	149.0	29.30	0.18	26.13	52.00
39.9	151.0	28.20	1.93	27.13	45.70
38.0	150.0	28.90	3.40	27.63	48.00
45.2	148.0	28.70	1.05	26.33	51.40
36.0	149.0	28.00	3.69	26.90	45.00
50.5	150.0	28.10	0.00	26.77	61.30
50.1	146.0	32.50	2.30	38.00	60.00
49.2	140.0	30.00	1.40	42.00	55.00
42.6	139.0	33.00	4.00	39.00	45.00
43.1	138.0	33.20	3.50	40.00	50.00
45.7	137.0	34.00	3.00	44.00	40.00
45.5	139.0	30.00	2.00	41.00	55.00
43.4	136.0	33.00	1.50	39.00	45.00
38.3	139.0	34.10	3.00	42.00	35.00
40.3	139.0	31.00	0.00	37.00	50.00
44.3	140.0	33.00	1.00	40.00	45.00
48.5	140.0	32.00	2.00	43.00	55.00
51.2	145.0	34.00	1.50	42.00	65.00
40.3	140.0	30.00	4.00	40.00	55.00

Linear regression analysis was performed for the above values in Table 14. The summary output of the linear regression analysis is presented in the Figure 18, including key statistical metrics such as standard errors and goodness-of-fit measures (e.g., R-squared) and coefficients corresponding to predictor variables derived from the regression model where the base type is ABC during night time.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.863809493
R Square	0.746166841
Adjusted R Square	0.666843978
Standard Error	2.650436012
Observations	22

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	5	330.4016595	66.0803319	9.406705946	0.000248406
Residual	16	112.3969769	7.024811053		
Total	21	442.7986364			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	-33.13955283	44.76702844	-0.740266977	0.469862309	-128.0414136	61.76230799	-128.0414136	61.76230799
X1	0.220356811	0.281312122	0.783317866	0.444881435	-0.375998247	0.816711869	-0.375998247	0.816711869
X2	0.79676688	0.507954593	1.568578946	0.136308793	-0.280048753	1.873582513	-0.280048753	1.873582513
X3	-1.448678548	0.517704095	-2.798275233	0.012887134	-2.546162202	-0.351194893	-2.546162202	-0.351194893
X4	0.152815029	0.27906707	0.54759248	0.591529355	-0.438780731	0.744410789	-0.438780731	0.744410789
X5	0.370054062	0.110677681	3.343529217	0.004123161	0.135427858	0.604680265	0.135427858	0.604680265

Figure 18: Summary output of the linear regression analysis for base type – ABC (Night time).

According to the linear regression analysis, a mathematical equation for TAC where the base type is ABC during night time, was developed as detailed in Eq.17.

$$TAC = 0.220x1 + 0.797x2 - 1.449x3 + 0.153x4 + 0.370x5 - 33.140 \quad \text{Eq.17}$$

Where;

x1 = Laydown Temperature (°C)

x2 = Air Temperature (°C)

x3 = Wind Velocity (km/h)

x4 = Base Temperature (°C)

x5 = Layer Thickness (mm)

Here, R^2 value indicates that 75% of the variance in TAC can be explained by the independent variables; laydown temperature, air temperature, wind velocity, base temperature and layer thickness. A standard error of 2.65 suggests that, typically, the actual values of the dependent variable are anticipated to differ from the predicted values by around 2.65 units, on average.

6.4. Results of Asphalt Layer with Base Type – Asphalt (Night Time)

Table 15 shows the results obtained for TAC from the heat transfer FEM models which were created using Abaqus software where the base type is asphalt and during night time.

Table 15: Values for TAC obtained from the heat transfer FEM model for base type – Asphalt (Night time)

TAC (min)	Laydown Temperature (°C)	Air Temperature (°C)	Wind Velocity (km/h)	Base Temperature (°C)	Layer Thickness (mm)
Y	**X1**	**X2**	**X3**	**X4**	**X5**
42.0	151.0	26.05	2.10	25.00	51.0
74.8	149.0	26.43	3.52	25.80	96.0
45.4	150.0	26.37	1.08	25.00	53.0
50.8	148.0	26.27	0.00	26.10	54.4
56.6	147.0	26.00	4.32	27.30	78.5
51.3	149.0	25.93	1.14	27.10	60.3
52.5	150.0	26.13	4.08	28.60	69.5
56.8	146.0	26.07	0.36	26.50	59.1
50.4	150.0	25.00	2.30	21.50	60.0
46.5	142.0	27.50	1.40	27.60	55.0
43.5	143.0	26.50	4.00	26.10	45.0
42.1	139.0	25.50	3.50	26.80	46.0
40.7	135.0	24.20	3.00	28.00	40.0
46.5	141.0	26.80	2.00	26.40	45.0
56.3	160.0	27.50	3.00	26.00	55.0
39.8	132.0	23.00	3.00	26.00	35.0
55.5	160.0	26.00	0.00	25.00	50.0
49.7	142.0	29.00	1.00	28.70	45.0
48.5	143.0	27.10	2.00	27.90	55.0
41.3	144.0	26.20	4.00	27.00	45.0

Linear regression analysis was performed for the above values in Table 15. The summary output of the linear regression analysis is presented in the Figure 19, including key statistical metrics such as standard errors and goodness-of-fit measures (e.g., R-squared) and coefficients corresponding to predictor variables derived from the regression model where the base type is asphalt during night time.

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.904231826
R Square	0.817635194
Adjusted R Square	0.752504907
Standard Error	4.055051633
Observations	20

ANOVA

	df	SS	MS	F	Significance F
Regression	5	1032.141788	206.4283575	12.55383974	9.20405E-05
Residual	14	230.2082124	16.44344375		
Total	19	1262.35			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	-5.7601047	33.53592699	-0.171759221	0.86608483	-77.68751448	66.16730508	-77.68751448	66.16730508
X1	0.141059117	0.190309597	0.741208639	0.470817967	-0.267114373	0.549232608	-0.267114373	0.549232608
X2	0.254906686	0.98108749	0.259820545	0.798784161	-1.849316703	2.359130075	-1.849316703	2.359130075
X3	-1.113929617	0.753360742	-1.478613836	0.161388303	-2.729727707	0.501868474	-2.729727707	0.501868474
X4	0.127089964	0.754432038	0.168457804	0.868632635	-1.491005828	1.745185757	-1.491005828	1.745185757
X5	0.496056841	0.079513199	6.238672913	2.16781E-05	0.32551799	0.666595692	0.32551799	0.666595692

Figure 19: Summary output of the linear regression analysis for base type – Asphalt (Night time).

According to the linear regression analysis, a mathematical equation for TAC where the base type is asphalt during night time, was developed as detailed in Eq.18.

$$TAC = 0.141x1 + 0.255x2 - 1.114x3 + 0.127x4 + 0.496x5 - 5.760 \qquad \text{Eq.18}$$

Where;

x1 = Laydown Temperature (°C)

x2 = Air Temperature (°C)

x3 = Wind Velocity (km/h)

x4 = Base Temperature (°C)

x5 = Layer Thickness (mm)

Here, R^2 value indicates that 82% of the variance in TAC can be explained by the independent variables; laydown temperature, air temperature, wind velocity, base temperature and layer thickness. A standard error of 4.05 implies that, typically, the actual values of the dependent variable are projected to vary from the predicted values by around 4.05 units, on average.

The coefficients in the above equations represent the strength and direction of the relationship between each independent variable and TAC. A positive coefficient suggests a beneficial impact on TAC, while a negative coefficient implies an adverse effect. The magnitude of each coefficient signifies the degree of influence each variable has on TAC relative to the measured unit of each variable.

When the equations for TAC which are detailed in Equation 15, 16, 17 and 18 are analyzed, the coefficient of asphalt laydown temperature is positive in all the scenarios. This suggests that an increase in the value of asphalt laydown temperature will lead to an increase in the TAC. In other words, it can be said that the asphalt laydown temperature has a positive impact on TAC. Higher asphalt laydown temperatures can slow down the cooling process, providing an extended period for compaction. This ensures that the asphalt remains workable, allowing construction crews to achieve the desired level of compaction.

According to the equations developed, the coefficient of air temperature is also positive in all the scenarios. This suggests that an increase in the air temperature will lead to an increase in the TAC. That means compaction is more effective or feasible at higher ambient temperatures. Simply, it can be said that the air temperature has a positive impact on TAC. Higher air temperatures generally result in a slower cooling rate for the asphalt mixture due to the lesser temperature difference between asphalt mix and surrounding. This allows construction crews more time to compact the asphalt. In contrast, lower air temperatures accelerate the cooling process, reducing the available time for compaction.

When the wind velocity is considered, the coefficient of wind velocity is negative in all cases. Therefore, it can be said that the wind velocity has a negative impact on TAC. This suggests that an increase in wind velocity will lead to a decrease in TAC. That means higher wind speeds might hinder or reduce the effectiveness of the compaction process. Higher wind speeds accelerate the cooling process by promoting heat dissipation from the asphalt surface by convection. It reduces the time available for compaction before the asphalt becomes too stiff for effective compaction. Construction crews may need to adjust compaction equipment parameters, such as vibration frequency and roller speed, to compensate for changes in asphalt workability due to wind-induced cooling.

When the base temperature is taken into account, the coefficient of base temperature is positive in all cases. This implies that an increase in base temperature will lead to an increase in TAC. It can be concluded that the base temperature has a positive impact on TAC. That means a warmer base facilitates better compaction. As the base temperature rises, it reduces the heat dissipation from the newly constructed asphalt layer to the subsurface and contributes to maintain the temperature of the asphalt layer for a longer duration, extending the time available for compaction.

When the asphalt layer thickness is taken into account, the coefficient of asphalt layer thickness is positive in all cases. This implies that an increase in asphalt layer thickness will lead to an increase in TAC. In other words, thicker layers may have more time for effective compaction. With increasing of asphalt layer thickness, heat retention within the mix is prolonged, thereby enhancing the workability and compatibility of the asphalt layer. It is possible to mention that the asphalt layer thickness has a positive impact on TAC.

However, comparison of the degree of impact of these variables on TAC cannot be done directly based on the magnitudes of their coefficients in the equations. This is because the magnitude of the coefficients is highly dependent on the units used to measure each variable. For example, the coefficient of wind velocity will have different magnitudes when it is measured in kilometers per hour (km/h) compared to when it is measured in meters per second (m/s). Similarly, the coefficient of layer thickness will vary depending on whether it is measured in millimeters (mm), centimeters (cm), or meters (m).

Therefore, to facilitate an accurate assessment and meaningful comparison of the degree of impact of variables such as air temperature, laydown temperature, wind velocity, base temperature, and layer thickness on TAC, a sensitivity analysis should be conducted. This analysis will allow us to understand the relative influence of each variable, independent of the units of measurement, providing a clearer picture of their true impact.

When we compare these equations with Eq.12, the directions of the coefficients of all variables are the same in all the equations. The magnitude of the coefficient of wind velocity is slightly larger than that of air temperature and the laydown temperature in equations developed here as well as in Eq.12. The coefficient of the layer thickness in Eq.12 is significantly larger than the equations developed here. The main reason for this is that the unit of layer thickness considered in Eq.12 is cm and, in this study, it was mm. The base temperature was not taken into account as an independent variable in Eq.12. However, according to the literature, this study considered that base temperature an independent variable for TAC.

These equations can be used to predict or estimate TAC based on specific combinations of base types and time periods. This information can be valuable for decision-making in scenarios, where controlling or optimizing time available for compaction is important. Employing these mathematical models enhances the likelihood of achieving the desired compaction level by estimating the time required to reach a temperature at which compaction is no longer possible. Therefore, if the average values for environmental variables, laydown site conditions and details of asphalt layer thickness are available, the time available to complete the asphalt compaction process using rollers can be known in advance and the asphalt construction activities can be planned according to this time considering the construction time period of the day.

Furthermore, if these mathematical equations are available, it can be used to choose a value for asphalt layer thickness which can be compacted effectively within the time required for rolling process considering the environmental variables of the construction area and time of the construction. For example, if the average values for the environmental variables such as air temperature, wind velocity and base temperature in the area of construction are known, we can calculate a minimum value for the asphalt thickness considering average time required for roller procedure as the TAC in the equation. With this information, construction managers or designers can work backward to determine the minimum asphalt thickness required to ensure that compaction can be completed within the TAC. If the average time required for the roller procedure is sufficient, construction professionals may have more flexibility in selecting a thinner asphalt layer, potentially reducing material costs and construction time without compromising quality.

Also, through utilizing this method, construction professionals can efficiently check whether the design thickness of the asphalt layer meets the minimum requirements for effective compaction. If the design thickness is less than the calculated minimum thickness, adjustments can be made to the design to ensure it meets the necessary requirements for durable construction. Otherwise, construction can proceed confidently knowing that it meets or exceeds compaction standards.

Ultimately, these mathematical equations facilitate a more efficient and durable construction process by ensuring that asphalt layers are designed to meet compaction requirements under typical environmental conditions and operational constraints. This proactive approach helps to optimize construction practices, reduce potential rework, and enhance the longevity and performance of asphalt pavements.

However, since the model validation and derivation of equations were done within the minimum and maximum values of the variables collected from the field, currently these equations can only be used for the variables within that range. In the future, the validation of the model should be extended to a wider range by collecting data from cold regions in Sri Lanka as well.

6.5. Determination of an optimal asphalt thickness

To determine the optimal asphalt thickness, different scenarios were analyzed by varying the input environmental parameters and average time required for compaction process. For this analysis, the annual average values of meteorological parameters were taken for the Western province, Sri Lanka. Because the 3D FEM model represented a 10m long asphalt section, the average time required for the compaction process for a 10m long section was considered here. (Annual Weather Averages Near Western Province, 2024)

6.5.1. For an Asphalt Layer with Base Type – ABC (Day Time)

For the daytime scenario with a base type of ABC, the analysis indicated the following conditions:

Average time required for compaction process = 25 min

Laydown Temperature = 135 ^{0}C

Average Air Temperature during day time = 30 ^{0}C

Average Wind Velocity during day time = 9 km/h

Average Base Temperature during day time = 41 ^{0}C

$TAC = 0.412x1 + 0.844x2 - 2.211x3 + 0.333x4 + 0.573x5 – 76.912$

25 = 0.412*135 + 0.844*30 – 2.211*9 + 0.333*41 + 0.573*x5 – 76.912

x5 = 47.50 mm

6.5.2. For an Asphalt Layer with Base Type – Asphalt (Day Time)

For the daytime scenario with a base type of asphalt, the analysis indicated the following conditions:

Average time required for compaction process = 25 min

Laydown Temperature = 135 ^{0}C

Average Air Temperature during day time = 30 ^{0}C

Average Wind Velocity during day time = 9 km/h

Average Base Temperature during day time = 44 ^{0}C

$TAC = 0.549x1 + 0.969x2 - 1.688x3 + 0.691x4 + 0.409x5 – 105.452$

$25 = 0.549 * 135 + 0.969 * 30 - 1.688 * 9 + 0.691 * 44 + 0.409x5 – 105.452$

x5 = 29.47 mm

6.5.3. For an Asphalt Layer with Base Type – ABC (Night Time)

For the nighttime scenario with a base type of ABC, the analysis indicated the following conditions:

Average time required for compaction process = 25 min

Laydown Temperature = 135 ^{0}C

Average Air Temperature during night time = 27 ^{0}C

Average Wind Velocity during night time = 11 km/h

Average Base Temperature during night time = 28 ^{0}C

$$TAC = 0.220x1 + 0.797x2 - 1.449x3 + 0.153x4 + 0.370x5 - 33.140$$

$$25 = 0.220 * 135 + 0.797 * 27 - 1.449 * 11 + 0.153 * 28 + 0.370x5 - 33.140$$

x5 = 50.20 mm

6.5.4. For an Asphalt Layer with Base Type – Asphalt (Night Time)

For the nighttime scenario with a base type of asphalt, the analysis indicated the following conditions:

Average time required for compaction process = 25 min

Laydown Temperature = 135 ^{0}C

Average Air Temperature during night time = 27 ^{0}C

Average Wind Velocity during night time = 11 km/h

Average Base Temperature during night time = 27 ^{0}C

$$TAC = 0.141x1 + 0.255x2 - 1.114x3 + 0.127x4 + 0.496x5 - 5.760$$

25 = 0.141*135 + 0.255*27 – 1.114*11 + 0.127*41 + 0.496*x5 – 5.760

x5 = 27.55 mm

The results indicate that the optimal thickness for asphalt layers varies significantly based on the base type and environmental conditions (day vs. night). According to the above calculations, an optimal asphalt thickness can be recommended for roads in Western Province, Sri Lanka as follows considering only the heat transferring process with degree of compaction.

Optimal asphalt thickness for base type – ABC (Binder Course) = 50 mm

Optimal asphalt thickness for base type – Asphalt (Wearing Course) = 30 mm

CHAPTER 7

CONCLUSION

It is critical to understand the significant impact of laydown site conditions, environmental variables, and layer thickness on the degree of compaction achieved in asphalt, emphasizing the importance of considering these factors for optimizing construction practices and ensuring pavement quality and durability.

Table 16: Summary of equations for TAC

Base Type	**Time Period**	**Equation for TAC**
ABC	Day Time	$TAC = 0.412x1 + 0.844x2 - 2.211x3 + 0.333x4 + 0.573x5 - 76.912$
	Night Time	$TAC = 0.220x1 + 0.797x2 - 1.449x3 + 0.153x4 + 0.370x5 - 33.140$
Asphalt	Day Time	$TAC = 0.549x1 + 0.969x2 - 1.688x3 + 0.691x4 + 0.409x5 - 105.452$
	Night Time	$TAC = 0.141x1 + 0.255x2 - 1.114x3 + 0.127x4 + 0.496x5 - 5.760$

The equations developed through the experimental and mathematical work of this research to find the effect of air temperature, laydown temperature, wind velocity, base temperature and layer thickness on TAC, can be summarized as in Table 16. According to the analysis and discussion of the above equations, it can be concluded that the asphalt laydown temperature has a positive impact on TAC, the air temperature has a positive impact on TAC and the wind velocity has a negative impact on TAC. When the base temperature is taken into account, the base temperature has a positive impact on TAC. When the asphalt layer thickness is considered, it has a positive impact on TAC.

Understanding these significance levels helps prioritize factors during the compaction process and informs decision-making for optimizing conditions during both day and night times.

These equations can be used to predict or estimate TAC based on specific combinations of base types and time periods. This information can be valuable for decision-making in scenarios, where controlling or optimizing time available for compaction is important.

Also the FEM model developed and validated in this study can be widely applied to predict the thermal behavior of hot mix asphalt layers in Sri Lankan conditions. Its accuracy and reliability, demonstrated through validation process, make it a valuable tool for various applications requiring precise thermal analysis of asphalt pavements.

The findings indicate that for daytime conditions, the optimal thickness for asphalt layers with different base types varies, with thicker layers recommended for ABC (Binder Course) compared to Asphalt (Wearing Course). Conversely, nighttime conditions exhibit different optimal thickness requirements, emphasizing the importance of considering diurnal variations.

Ultimately, the recommended optimal asphalt thicknesses for the Western Province, Sri Lanka, considering heat transfer and compaction efficiency, are 50 mm for ABC (Binder Course) and 30 mm for Asphalt (Wearing Course). These recommendations provide valuable insights for road construction and maintenance practices in the region, contributing to improved infrastructure durability and performance.

REFERENCES

Adnan Qadir, Murat Guler. (2012). Finite element modeling of thermal stress restrained specimen test. *5th Eurasphalt & Eurobitume Congress*, 210-216.

Annual Weather Averages Near Western Province. (2024, May). Retrieved from time and date: https://www.timeanddate.com/weather/@1223421/climate

ASCE Library. (2024). Retrieved from ASCE Library: https://ascelibrary.org/

(2010). *Asphalt Compaction.* Australian Asphalt Pavement Association.

Asphalt Guide, AP-G66/02. (2022). In *AUSROADS.*

Cedric Vuye, Gert Guldentops, Nima Rahbar, Alireza Mahdavi Nejad, Wim Van den bergh. (2016). Analysis of a heat exchanging asphalt layer using a finite element approach. *6th Eurasphalt & Eurobitume Congress*, 361-370.

Chieh-Min Chang, Yen-Jui Chang, Jian-Shiuh Chen. (2009). Effect of Mixture Characteristics on Cooling Rate of Asphalt Pavements. *Journal of Transportation Engineering, 135*(5), 297-304.

David H. Timm, Vaughan R. Voller, Eul-bum Lee, John Harvey. (2001). Calcool: A multi-layer Asphalt Pavement Cooling Tool for Temperature Prediction During Construction. *The International Journal of Pavement Engineering, 2*, 169-185.

Departamento de Engenharia Civil. (2024). Retrieved from https://civil.uminho.pt/

Du Yinfei, Wang Shenhyue, Zhang Jian. (2015). Cooling asphalt pavement by a highly oriented heat conduction structure. *Energy and Buildings, 102*, 187-196.

Guopin Qian, Zhiyu He, Huanan Yu, Xiangbing Gong, Jie Sun. (2020). Research on the affecting factors and characteristic of asphalt mixture temperature field during compaction. *Construction and Building Materials, 257*, 119509-119523.

Jack S. Corlew, P.F. Dickenson. (1968). Methods for calculating temperature profiles of hot mix asphalt concrete as related to the construction of Asphalt pavements. . *Proceedia Association Asphalt Paving Technology*, 11-40.

Kevin L. Williams, Ben C. Cox, Isaac L. Howard, L. Allen Cooley. (2015). Models of Asphalt Concrete Field Compatibility with Focus on Lift Thickness. *Transport Research Record: Journal of the Transportation Research Board*, 135-147.

Linbing Wang, Bing Zhang, Dong Wang, Zhongqi Yue. (2006). Fundamental mechanics of asphalt compaction through FEM and DEM modeling. *Analysis of Asphalt Pavement Materials and Systems*, 45-63.

Matthew R. Hall, Pejman Keikhaei Dehdezi, Andrew R. Dawson, James Grenfell, Riccardo Isola. (2012). Influence of the Thermophysical Properties of

Pavement Materials on the Evolution of Temperature Depth Profiles in Different Climatic Regions. *Journal of Materials in Civil Engineering, 24*(1), 32-47.

Mohd Rosli Hainin, Nur Izzi Md. Yusoff. Mohd Khairul Idham Mohd Satar, E. Ray Brown. (2013). The effect of lift thickness on permeability and the time available for compaction of hot mix asphalt pavement under tropical climate condition. *Construction and Building Materials, 48*, 315-324.

Saradhi Koneru, Eyad Masad, K.R. Rajagopal. (2008). A thermomechanical framework for modeling the compaction of asphalt mixes. *Mechanics of Materials, 40*, 846-864.

Scherocman, J. A. (2000, December 28). *Compacting Hot Mix Asphalt Pavements: Part I*. Retrieved from www.roadsbridges.com: https://www.roadsbridges.com/asphalt/article/10581847/compacting-hot-mix-asphalt-pavements-part-i

Taqia Rahman, Nick Thom, Andrew Dawson. (2019). Strategies for Reduced Cooling Time of Asphalt for Airfield Pavement Overlay. *Airfield and Highway Pavements*, 251-265.

THE HONGKONG PLOYTECHNIC UNIVERSITY. (2024). Retrieved from THE HONGKONG PLOYTECHNIC UNIVERSITY: https://research.polyu.edu.hk/

University of Nottingham. (2024). Retrieved from University of Nottingham: https://nottingham-repository.worktribe.com/

Wardati Hashim, Mohd Rosli Hainin, Norfarah Nadia Ismail, Nur Izzi Md. Yusoff, Mohd Ezree Abdullah, Norhidayah Abdul Hassan. (2016). Evaluating the Cooling Rate of Hot Mix Asphaltin Tropical Climate. *Jurnal Teknologi, 78*(4), 97-104.

Wei Hu, Xiaoyang Jia, Xingyi Zhu, Hongren Gong, Genping Xue, Baoshan Huang. (2019). Investigating key factors of intelligent compaction for asphalt paving: A comparative case study. *Construction and Building Materials*, *229*, 116876-116885.

Ying Gao, Renxiao Wang, Wenbin Yu. (2011). Effective Compatible Time of Asphalt Pavement. *Advanced Materials Research*, *255-260*, 3156-3160.

Yuhong Wang, Songye Zhu, Alvin S. T. Wong. (2014). Cooling Time Estimation of Newly Placed Hot-Mix Asphalt Pavement in Different Weather Conditions. *Journal of Construction Engineering and Management*, 140-150.

AUSTROADS (2002) Asphalt Guide, AP−G66/02

AUSTROADS (2002) Framework for specifying Asphalt, AP−T18/02

AUSTROADS AGPT04B/07 : Guide to Pavement Technology - Part 4B: Asphalt