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DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

PAVEMENT TEMPERATURE MONITORING OF FLEXIBLE PAVEMENTS IN BANGLADESH

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree

of

Bachelor of Science in Civil Engineering

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Approval

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Declaration

It is hereby declared that this thesis/project report, in whole or in part, has not been submitted elsewhere for the award of any Degree or Diploma.

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Dedication

To our loving family members and revered teachers

for

the support, patience, and, most of all, faith they have shown in us.

Acknowledgement

This achievement would never have come true without the help, support, and love of many wonderful people to whom we are always indebted.

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Abstract

Monitoring pavement temperatures is critical to assessing the thermal behavior of flexible pavements and determining their performance in various conditions. This research focuses on flexible pavement temperature monitoring in Bangladesh, primarily comparing existing pavement temperature models to actual data obtained at various depths. The applicability of these models to the specific climate and environment of Bangladesh can be tested by analyzing their accuracy. The study's findings will provide insight into existing pavement temperature models' efficacy and applicability to Bangladesh's flexible pavements. The study emphasizes inequalities and identifies improvement opportunities in existing models by comparing predictions with actual data. These findings can help to guide the development of more accurate and dependable temperature models tailored particularly for Bangladesh's unique climate and conditions. Improved pavement temperature models will improve flexible pavement design and maintenance techniques, resulting in more durable and sustainable infrastructure.

Keywords: pavement; temperature; prediction; heat; climate; asphalt; thermal; models

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Chapter 1: Introduction

1.1 Background Study

In order for modern societies to thrive, investing in infrastructure is essential. This means making decisions based on a solid design methodology and having a complete understanding of maintenance requirements throughout the lifespan of a system, intending to minimize construction and maintenance costs. Proper pavement design is crucial in guaranteeing the safety and accessibility of road networks in emerging nations. Insufficient or poorly planned pavements may result in a range of safety risks, including uneven surfaces, cracks, and potholes. These issues present potential hazards to both drivers and individuals on foot, thereby elevating the probability of impacts and physical harm. Developing countries can enhance road safety and improve accessibility to various regions within the country by implementing appropriate pavement design.

The influence of pavement design on vehicle operating expenses is a critical factor to consider. Poor pavement conditions, like bumps or insufficient drainage, can cause increased fuel consumption and maintenance costs for vehicles. Resource limitations are a common challenge encountered by developing nations, and suboptimal pavement designs can further compound economic hardships for both businesses and individuals. However, if governments implement appropriate pavement design, they can reduce expenses and create a transportation system that is both sustainable and cost-effective.

The development of transportation infrastructure in Bangladesh relies on the critical aspect of pavement design. A careful assessment of pavement design is required in light of the numerous issues the nation faces in order to maintain reliable and safe pavements. Engineers must develop pavement structures that can endure diverse soil conditions, high traffic volumes, and heavy rainfall due to these factors.

Flexible pavement structures are commonly used in Bangladesh owing to their capacity to adapt to the diverse soil conditions that exist in the region. The pavements are engineered to distribute the applied load uniformly throughout the various layers, imparting resilience, and robustness. The design of flexible pavements generally encompasses several strata, comprising a subgrade, sub-base, base, and surface layer.

In Bangladesh, asphalt concrete is a prevalent material for the surface layer. Asphalt exhibits exceptional robustness, sleekness, and anti-slip properties, rendering it appropriate for the prevailing roadway circumstances in this country. Using asphalt concrete as a surface layer on roads offers a smooth and pleasant riding experience for motorists while also exhibiting high resistance to the formation of ruts and cracks.

A crucial aspect of pavement design in Bangladesh pertains to adequate drainage management. The nation encounters substantial monsoonal precipitation, and insufficient drainage infrastructure may result in water accumulation and pavement degradation. In order to mitigate this concern, pavement designs integrate cross slopes that facilitate proficient water drainage towards the periphery of the roadway. Furthermore, appropriately engineered drainage infrastructure, such as gutters and culverts, facilitates efficient water control and averts water pooling on the roadway.

Ensuring road safety is an essential consideration in the design of pavements in Bangladesh. Endeavors are being undertaken to integrate safety characteristics that reduce mishaps and safeguard individuals utilizing the roadways. Implementing well-defined pedestrian crossings, appropriate signage, and reflective road markings improves visibility and guides individuals utilizing the roadway. Furthermore, safety barriers and guardrails are implemented in regions characterized by steep embankments or sharp curves with the aim of averting vehicular deviation from the roadway.

Thus, the development of a secure, effective, and environmentally friendly transportation system in Bangladesh is contingent upon the proper design of pavements. Engineers consider the difficulties presented by intense precipitation, substantial traffic flow, and fluctuating soil circumstances in order to devise adaptable pavement configurations that can endure these elements. The longevity and reliability of the roadways in Bangladesh can be enhanced by implementing appropriate drainage systems, incorporating safety features, and utilizing durable materials such as asphalt concrete. The prioritization of appropriate pavement design is imperative for facilitating safe and efficient transportation of individuals, commodities, and amenities across the nation as it advances.

Temperature is a crucial environmental factor that significantly impacts the mechanical properties of asphalt mixtures. The thermal condition of the hot mix asphalt concrete layers is among the numerous factors that influence its structural capacity. Furthermore, temperature has the potential to significantly contribute to various forms of distress. Consequently, temperature is a crucial variable that impacts a pavement's functionality and durability. Following the implementation of Superpave pavement temperature estimation procedures in 1993, numerous scholars have raised apprehensions regarding the precision of the temperature algorithms and the consequences of utilizing the approximated values. Contemporary logistics systems have led us to a point reminiscent of the early stages of scientific advancement. Similarly, precise forecasting of the temperature of asphalt pavement at varying depths, utilizing air temperatures and other uncomplicated weather station metrics, can aid engineers in conducting retroactive calculations of asphalt concrete modulus and approximating pavement deflections. The thermal profile of flexible pavements is significantly influenced by the ambient factors to which it is subjected.

The temperature of the pavement surface and the temperatures inside are influenced by climatic factors and the thermal characteristics of the pavement layers, and the temperature of the pavement surface also influences the temperature of the near-surface air. This is a microclimate system that includes the pavement and the surrounding environment. Precisely estimating pavement temperature holds significant value in various engineering domains such as pavement analysis and design, counteracting the urban heat island (UHI) phenomenon, and administering deicing and anti-icing measures during winter maintenance.

The temperature of pavement is a crucial element that impacts the performance of roadway pavement alongside vehicular loading. The stresses and strains experienced by flexible pavements under vehicular loading are heavily influenced by the temperature profile within the asphalt layer, owing to the viscoelastic properties of the asphalt material. Conversely, the fluctuation in temperature over a 24-hour period, known as diurnal temperature variation, has the potential to cause thermal stress and consequent curling of concrete slabs in the rigid pavement. In order to accurately interpret the results of in-situ tests conducted on the pavement to evaluate its structural capacity and remaining life, such as the falling weight deflectometer (FWD), it is necessary to obtain pavement temperature data. Consequently, it is imperative to accurately characterize temperature distributions within flexible and rigid pavement structures to facilitate pavement analysis and design.

The pavement temperature is a crucial factor in the thermal conditions of the nearby surface environment, particularly concerning UHI phenomenon. Urbanization has resulted in a significant replacement of ground surface in urban areas with various structures such as streets, sidewalks, parking lots, and buildings. The temperature of pavement surfaces is typically higher than that of vegetated or naturally soiled ground due to their lower albedo and higher heat storage capacity.

Compared to the surrounding regions, a warmer environment in urban areas characterizes the phenomenon known as UHI. This is attributed to the rise in pavement surface temperature, which heats the near-surface air temperature. Accurate modeling of pavement temperature fields, particularly pavement surface temperature, is essential for assessing the impact of pavement surface temperature on the UHI effect.

Several research studies have been carried out to formulate models for predicting pavement temperature, catering to diverse application objectives. The models exhibit significant variations in their underlying assumptions, solution techniques, analysis parameters, and application domains.

1.2 Purpose

The aim of this research is to perform a thorough examination of the monitoring of pavement temperature in flexible pavements in Bangladesh. This study aims to authenticate the pavement temperature prediction models previously formulated elsewhere for Bangladesh's environmental and climatic circumstances. Through an evaluation of the precision and dependability of the present model, this study will make a valuable contribution toward enhancing the approaches employed for pavement design and upkeep within the nation.

1.3 Objectives

1. **Validate the existing pavement temperature prediction models:**

   The principal aim of this study is to assess the precision and efficacy of the current pavement temperature forecasting models for flexible pavements. Through a comparative analysis between the anticipated temperatures generated by the model and the accurate temperature readings acquired via monitoring, the investigation will precisely evaluate the model's aptitude to gauge pavement temperatures within the regional setting.

2. **Evaluate the suitability of the model for pavement design and maintenance:**

   The practical implications of the pavement temperature prediction model's validation will be significant for Bangladesh's pavement design and maintenance practices. By assessing the precision of the model, professionals in the field of engineering and public policy can arrive at informed decisions regarding the design of pavement thickness, the choice of materials, and the timing of maintenance operations. This investigation aims to furnish significant perspectives on the model's suitability, thereby augmenting the nation's efficacy and potency of pavement design and upkeep approaches.

3. **Recommend improvements and future research directions:**

   The study's results will suggest improving the current pavement temperature prediction model or creating novel models customized to Bangladesh's unique conditions. Furthermore, the present study aims to pinpoint potential avenues for further inquiry and examination, such as the ramifications of climate change on pavement temperature and the creation of region-specific prognostic models across the nation.

This study's primary aim is to contribute to the progress of pavement engineering practices in Bangladesh. This will be achieved by accomplishing the set objectives, which will facilitate the development of pavement temperature prediction models that are more accurate and reliable. Consequently, this will result in enhanced pavement design, augmented road longevity, and improved transportation infrastructure on a national scale.

1.4 Scope of the Study

This study aims to authenticate the extant flexible pavement temperature forecasting model in Bangladesh, where no prior research has been conducted to contrast the model's outcomes with accurate pavement temperature data. The study's objective is to gather temperature measurements of the pavement at varying depths while considering diverse meteorological variables. The study aims to evaluate the precision and dependability of the model by comparing the projected temperatures with the actual temperature measurements. The scope of the study encompasses the analysis of the influence of pavement thickness, material properties, and surface characteristics on temperature fluctuations. The paper will offer suggestions for enhancing the model and outline potential avenues for future research. This research aims to augment the precision of pavement temperature forecasts, resulting in better pavement design, maintenance tactics, and transportation infrastructure in Bangladesh.

1.5 Thesis Outline

The thesis is split into six distinct chapters, with each chapter being comprehensively discussed. The following sections provide a concise introduction to each of the chapters:

Chapter 1: Introduction- The chapter presents a comprehensive study outline, encompassing the contextual background, problem statement, research purpose, and objectives.

Chapter 2: Literature Review- This chapter talks about the relevant literature pieces that helped develop the best research plan.

Chapter 3: Methodology and Data- This chapter encompasses an in-depth discussion of the scope and limitations of the study, as well as the data collection procedures employed. Additionally, the chapter delves into the iterative nature of the research process and the methodology employed to analyze the gathered data.

Chapter 4: Analysis & Results- The chapter conducts a review of the analysis of the collected data and provides an interpretation of the conclusions that have been obtained.

Chapter 5: Discussion & Conclusion- The present chapter provides a concise overview of the study's primary outcomes and examines the potential ramifications for policy.

Chapter 2: Literature Review

2.1 Introduction

The study's literature review chapter focuses on monitoring pavement temperature in flexible pavements in Bangladesh. The principal aim of this study is to authenticate the current pavement temperature forecasting models in light of the country's distinctive climatic and environmental circumstances. This chapter aims to comprehend the present state of knowledge comprehensively, recognize research gaps, and collect valuable insights for the validation process through a thorough literature review. The study comprehensively reviews the existing literature on pavement temperature monitoring and prediction models. The study investigates diverse techniques and methodologies for assessing and projecting pavement temperatures across diverse geographical locations and weather conditions. The chapter centers on examining research in contexts like that of Bangladesh, assessing the merits and drawbacks of current models and methodologies. This chapter aims to establish a basis for validating Bangladesh's current pavement temperature prediction model through synthesizing literature findings. The study identifies gaps in the existing research and points out the need for additional research in this domain. The literature review findings will provide valuable guidance for the subsequent stages of the research, thereby expediting the validation process and augmenting the advancement of enhanced pavement temperature forecasting models for flexible pavements in Bangladesh.

2.2 Types of Pavements

There are mainly two types of pavements. The two types are differentiated based on their design considerations: flexible and rigid. The difference between flexible and rigid pavements is based on the distribution mode of loads to the underlying subgrade.

2.2.1 Flexible Pavements

Flexible pavement is typically comprised of multiple layers, including a surface course made of bituminous material and base and subbase courses. The bituminous material used in the surface course is often asphalt, which exhibits a high viscosity and can undergo significant plastic deformation. Most asphalt surfaces are constructed on a foundation of gravel, although certain full-depth asphalt surfaces are erected directly on the underlying subgrade. Asphalt is classified into three categories, namely hot mix asphalt (HMA), warm mix asphalt, and cold mix asphalt, based on the temperature of its application. The term "flexible pavement" is attributed to the fact that the pavement surface exhibits the cumulative deflection of all underlying layers in response to the traffic load applied to it.

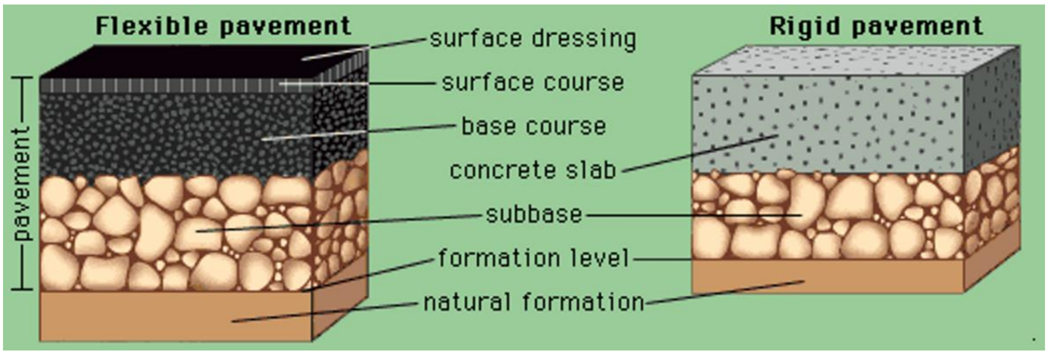


Figure 1: Layers of flexible pavement

2.3 Factors Affecting Pavement Temperature

Most pavements are subject to the influence of their ambient surroundings, which can significantly affect their internal pavement temperatures. Short wavelengths typically characterize the fundamental factors of diffused and direct solar radiation. Upon the arrival of shortwave radiation at the surface of the asphalt pavement, the various layers of the pavement begin to absorb a significant quantity of energy, which is subsequently transmitted as heat flux throughout the pavement structure. Meanwhile, the pavement's surface reflects the residual heat into the atmosphere. It is imperative to acknowledge that fluctuations in climate do not solely impact asphalt pavements but also actively contribute to said variations. There are two reasons for this. Initially, it is noteworthy that a substantial quantity of Greenhouse Gas (GHG) is discharged during diverse stages of a pavement's life cycles.

Moreover, urban areas are extensively covered by asphalt roads. Furthermore, it has been observed that road pavements have the capacity to retain and emit a more significant amount of thermal energy compared to soil, thereby exacerbating the phenomenon of urban heat islands (UHI). Hence, any measure aimed at curbing such emissions has the potential to aid in the mitigation of greenhouse gas emissions on roads with high traffic volumes. Cloud cover, precipitation, and pavement surface temperature impact the degree of reflected and absorbed energy. The pavement surface emits long-wave radiation consistent with that of a black body. The effective long-wave radiation is the net value resulting from the subtraction of pavement-emitted long-wave radiation from the input long-wave radiation. Therefore, it is susceptible to various factors such as cloud cover, pavement surface temperature, air temperature, and relative humidity. Direct and diffuse scattered solar radiation are classified as shortwave radiation and can be considered incoming shortwave radiation. Solar radiation refers to the sum of incoming solar radiation and effective long-wave radiation. Consequently, the predominant modes of heat transfer are convection by air, terrestrial radiation driven by dynamic processes, and solar radiation.

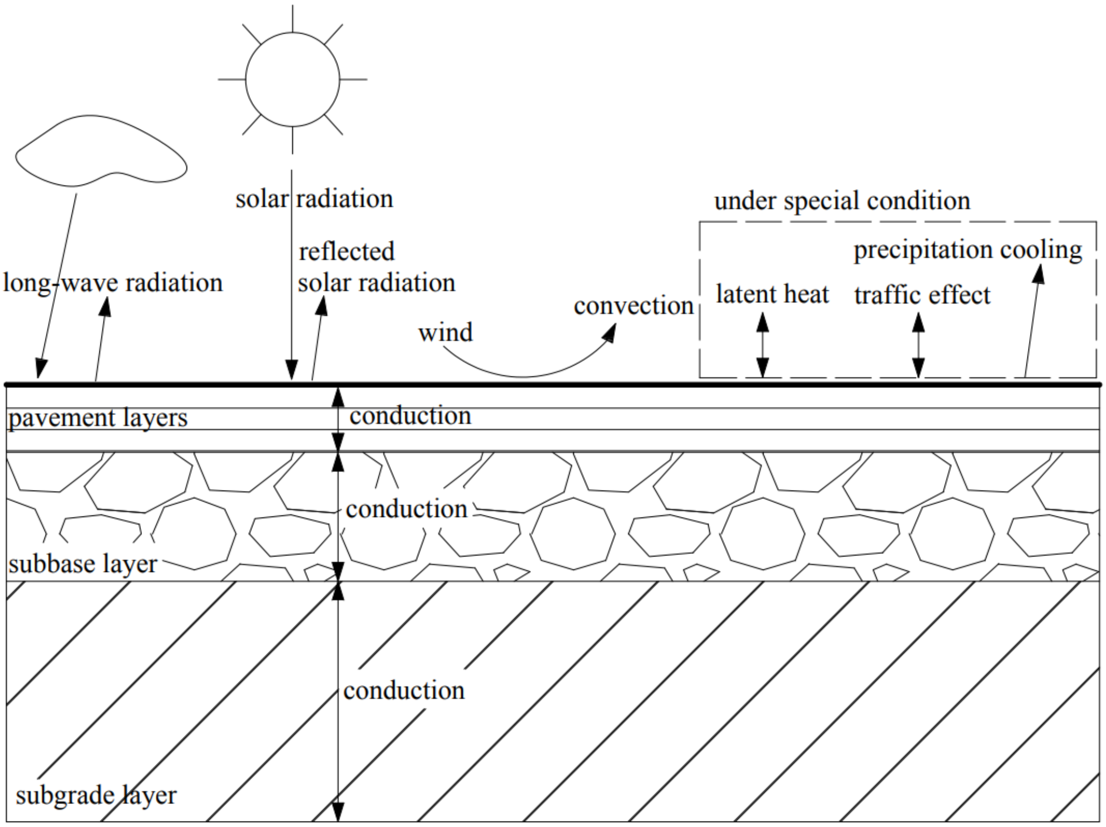


Figure 2: Factors impacting pavement temperature

2.3.1 Effect of Moisture

The mechanical, chemical, and biological decaying processes are all impacted by moisture. The moisture from the interaction of water particles adsorbed onto the asphalt pavement surface with the asphalt pavement surface is deposited there. As a result of repeated traffic loads and freeze-thaw cycles, however, it may also be caused by moisture trapped within the asphalt layer, which results in pore pressure development.

2.3.2 Effect of Solar Radiation

The impact of solar radiation on bituminous materials results in a temperature variation that can shift the volume of pavement structures within the pores. This phenomenon is attributed to the expansion of water when subjected to increased heat from solar radiation. Solar radiation leads to the indirect and diffuse accumulation of heat on the pavement through solar absorption. In addition, solar radiation plays a crucial role in photochemical reactions as it serves as the primary energy source for the stimulation and subsequent cleavage of bonds within the molecules involved in the reaction. Hence, solar radiation of great intensity and suitable wavelengths may incite photochemical reactions that could result in deleterious effects on pavement materials.

2.3.3 Wind Effect

The speed of the wind also influences pavement temperature. The thermal gradient between the pavement surface temperature and the surrounding air temperature can transfer convective heat from the pavement to the atmosphere. The quantification of dissipated energy is contingent upon the velocity of wind and the disparity between the temperature of the air and the temperature of the pavement surface. Moreover, the pavement surface experiences heat exchange, leading to fluctuations in its temperature. Consequently, there is a discernible contrast between the temperature of the pavement surface and that of the pavement structure, as the energy is dissipated to the latter. Wind speed is an additional factor that exerts an influence on pavement temperature. In actuality, the velocity and orientation of wind exhibit persistent fluctuations. The wind velocity along a particular road segment can exhibit variability owing to differences in its design, topography, and presence of any obstructions.

Consequently, incorporating wind speed's impact into temperature forecasting models may present intricacies. Thus, the pavement temperature is impacted by variations in wind speed, and the impact of increasing wind velocity on asphalt pavement materials varies. Therefore, as a result, the movement of wind and water forces the mobile particles of air toward the pavement's surface, leading to localized abrasion and degradation of the material. Furthermore, wind speed impacts both the kinetic energy of particles and the level of inertial impaction of droplets on the surface of materials. The processes of desiccation and hydration impact the alteration in the volume of the structure.

2.4 Temperature Prediction Models

Developing approaches to predicting asphalt pavement temperature and enhancing prediction techniques has been a continuous focus for the past 50 years. Recently, new research has been carried out which uses more complicated computational techniques. Thus, the results of this research have been widely accepted and applied in the engineering field. In addition, several scholars have endeavored to construct mathematical frameworks for forecasting the temperature within an asphalt pavement infrastructure. The researchers employed three principal methodologies: numerical and finite elements, theoretical and analytical, and statistical and probability techniques. The partial differential equation (PDE) simplifies constructing numerical and analytical profiles for heat conduction at specified boundary conditions. The following subsection discusses how statistical analysis was used to build the empirical models.

2.4.1 Analytical Models

The origins of research on analytical solutions for pavement temperature can be traced back to the 1950s. During this time, Barber developed a solution for pavement temperature utilizing weather data. The computation was based on the periodic temperature solution in a semi-infinite mass in contact with air that experienced sinusoidal temperature fluctuations. Subsequently, Solaimanian and Kennedy formulated an equation to compute the maximum temperature of the pavement surface, predicated on the supposition that the surface temperature could attain a state of equilibrium. Despite the challenge posed by the difficulty of achieving equilibrium temperature within a daily cycle, this study exerted a significant impact on subsequent research endeavors. Subsequently, further analytical models were formulated through the resolution of the partial differential equation governing heat conduction, utilizing analytical techniques.

In contrast, the others only apply to single-layer or semi-infinite pavement. In addition to the conventional solution approaches, alternative techniques have been documented for predicting pavement temperature that does not involve the resolution of the heat transfer partial differential equation. With the assumption that pavement surface temperature variations occur daily in sinusoidal waves, Qin created a theoretical model to forecast pavement surface temperature.

2.4.2 Numerical Models

In numerical modeling, the computational domain is partitioned into discrete elements, and subsequently, the partial differential equation governing heat conduction is solved numerically over the nodes or volumes. In contrast to analytical models, numerical models may entail significantly more intricate boundary conditions. The numerical methods that are frequently employed in various fields of study are the finite difference method (FDM), finite element method (FEM), and finite volume method (FVM). The Finite Difference Method (FDM) is a commonly employed computational technique to estimate pavement temperature. The finite difference method (FDM) approximates each derivative in the partial differential equation (PDE) through a difference commonly obtained via Taylor series expansions. The prescribed interconnected points within the computational domain satisfy the governing partial differential equation (PDE). The utilization of FDM (Finite Difference Method) in estimating pavement temperature has a lengthy and established past. Dempsey and Thompson devised a numerical model utilizing the forward-finite-difference method to assess pavement temperature. Subsequently, the model above was incorporated into the mechanistic-empirical pavement design guideline (MEPDG) as an element of the Enhanced Integrated Climatic Model (EICM) initiative, aimed at accounting for the impact of climate on pavement design. The Finite Element Method (FEM) is a widely established numerical technique for addressing diverse engineering challenges. The Finite Element Method (FEM) involves the initial conversion of the Partial Differential Equation (PDE) from its vital to weak form. Subsequently, a finite set of limited-size elements is employed to discretize and resolve the resultant weak form problem, utilizing the principle of variation of parameters.

Table 1: Numerical methods of pavement temperature prediction models

Name	Location	Affecting Factors
Straub and Przbycien, (1968)	USA	• The temperature of the pavement • Radiation from the sun • The temperature of the air
Dempsey and Thompson (1970)	USA	• Long-wave and short-wave light • Thermal characteristics • The temperature of the air • Physical size • Material categorization • Thermal capacity Thermal conduction Moisture content
Rumney and Jimenez (1970)	USA	• The temperature of the pavement • The temperature of the air • Radiation from the sun
Williamson (1972)	South Africa	• Thermal characteristics • Radiation from the sun • The temperature of the air
Anderson and Christison (1972)	Canada	• Radiation from the sun • The temperature of the air • Wind velocity • Physical characteristics
Kondo and Miur (1976)	Japan	• The temperature of the air • The temperature of the pavement
Lytton et al. (1990)	USA	• Pavement construction Materials qualities
Minhoto et al (2006)	Portugal	• Radiation from the sun The temperature of the air • Wind velocity on a daily basis
Lufs de Picado-Santos (2008)	Portugal	• Max monthly air temperature • Min monthly air temperature • Temperatures of the asphalt layer every hour
Mammeri et al. (2015)	France	• The temperature of the pavement • The temperature of the air • Depth • Humidity • Radiation from the sun

2.4.3 Statistical Methods

The existing empirical models can be broadly classified into three distinct categories: non-linear regression, linear regression, and neural network. Linear regression is a straightforward approach to constructing empirical models whereby the minimum or maximum temperature at a given depth can be predicted. Linear regression models commonly comprise multiple parameters and are employed in real-world scenarios for forecasting surface temperature. One limitation of this approach is the intricate and non-linear nature of the daily pavement temperature across its depth. Consequently, using linear regression to forecast pavement temperature is not recommended due to its reliance on time as an independent variable. Empirical models that are advanced in nature typically incorporate sine terms due to the temporal variability of predicted pavement temperature. The statistical analysis technique is typically formulated using actual field data about asphalt pavement specifications and climate databases. The analysis considers various geographical and meteorological variables, including wind velocity, ambient temperature, geographical coordinates, and solar irradiance. Table 2 provides a compilation of studies that have employed statistical techniques to forecast pavement temperature. The regression technique establishes a numerical association between the temperature data and the asphalt pavement. In addition, mathematical formulas are utilized to offer solutions for practical problems and establish correlations between different variables to make projections regarding the temperatures of asphalt pavements in a specific region.

2.4.4 Regional Variations in Pavement Temperature Model

The applicability of a temperature prediction model to regions beyond a specific region may be limited due to regional variations. Hence, the temperature prediction model is notably impacted by the geographical region. Hence, it is imperative to address the variability among regions in the pavement temperature forecasting model and comprehend the origins of these disparities. Various environmental factors, including the daily variation in heat flux at the pavement surface and thermal conduction within the underlying soil layers, influence the thermal properties of the pavement structure. The phenomenon of thermal conduction occurs between the pavement structure and the Earth due to temperature disparity, thereby causing the temperature of pavement structures to be influenced by the temperature of the Earth. At a specific phase, the temperature of the Earth at a given site can be considered constant, and its influence on the pavement temperature can be deemed relatively uniform. Variations in the temperature of the Earth across diverse regions engender dissimilar impacts on the pavement temperature, thereby resulting in regional differences. Pavement temperature can be conceptualized as a dual-component interconnected structure.

Table 2: Statistical methods of pavement temperature prediction models

Name	Location	Influencing Factors
SHRP (Khan et al., 2019)	USA	$1331\alpha\tau a^{\frac{1}{\cos Z}}.\cos Z + \varepsilon\sigma T_a{}^4 - hc(Ts - Ta) - 164k - \varepsilon\sigma Ts^4 = 0$ where α is absorptivity of pavement surface, τa is heat conduct coefficient for air, Z is 20 degrees latitude, ε is pavement surface emissivity, σ is the Stefan-Boltzman constant (5.7×10^{-8} W/m^2), hc is surface coefficient of heat transfer (W/m^2 °C), k is heat conduction coefficient (W/m^2 °C), Ta is air temperature (K), and Ts is surface temperature (K).
(Al-Abdul Wahhab & Balghunaim, 1994)	Saudi Arabia	$T(d) = 3.714 + 1.006T(a) - 0.146d$ where $T(d)$ is pavement temperature at depth d (°C), $T(a)$ is air temperature (°C), and d is depth below pavement surface (cm).
(Park et al., 2001)	USA	$T_d = T_s + (-0.3451d - 0.0432d_2 + 0.00196d_3) \times \sin(0.325\tau + 5.0967)$ where T_d is the temperature of pavement (°C), T_s is the surface temperature (°C), d is depth (mm), τ is the coefficient associated with time.
(Diefenderfer et al., 2006)	USA	$T_{\text{pmax}} = 3.2935 + 0.6356T_{\text{max}} + 0.1061Y - 27.7975P_d$ $T_{\text{pmin}} = 1.6472 + 0.6504T_{\text{min}} + 0.0861Y + 7.2385d_b$ where T_{pmax} is predicted maximum temperature (°C), T_{max} is the maximum daily temperature (°C), T_{pmin} is predicted minimum temperature (°C), T_{min} is the minimum daily temperature (°C), Y is one day of the year (1 to 365), and d_b is depth below the surface (m).
(Sherif & Hassan, 2004)	Oman	$T_{\text{surf}} = -1.437 + 1.121\ T_{\text{air}}$ $T_{\text{20mm}} = 3.160 + 1.319\ T_{\text{airx}}$ where T_{surf} is minimum temperature of pavement (°C), T_{air} is minimum temperature of air (°C), T_{20mm} is pavement temperature at 20 mm in °C, and T_{airx} is maximum air temperature in °C.
(J. Chen et al., 2017)	China	$T_p = P_1 + (P_2\ T_{a5} + P_3\ (Q_5)^2) + H(P_4\ T_a + P_5\ Q) + (P_6\ H + P_7\ H^2 + P_8\ H^3) + P_9T_m$ where T_p is pavement temperature at H cm, T_a is air temperature, Q is solar radiation, kW/m^2, T_{a5} is average air temperature for the previous 5 h, Q_5 is average solar radiation for the previous 5 h, kW/m^2, H is the depth of prediction point in cm, P1–P8 are the undetermined regression coefficients for the prediction model, T_m is the monthly historical average air temperature for the past 20 years.
(Tabatabaie et al., 2008)	Iran	$T = 0.94Sur + 0.94\text{Sin}(2\pi t/24) - 2.99\log(d) - 0.02\ comp + 0.02Air + 0.32BP + 0.17BT - 0.34$ where T is asphalt temperature (°C) airir is air temperature (°C), S is surface temperature (°C), t is time of day in a 24-h system, d is depth (cm), *comp* is level of compaction (number of blows), BP is bitumen content, BT is bitumen type (1 for 40/50 and 2 for 60/7), and BP is bitumen content.
(Zheng et al., 2011)	China	$T_{\text{pave-rising}} = 1.170\ T_{\text{air-rising}} - 0.50h + 3.55$ $T_{\text{pave-falling}} = 1.085\ T_{\text{air-falling}} - 0.07h + 4.3$ $T_{\text{pave}} = 1.118Tair - 0.23h + 4.1$ where $T_{\text{pave-rising}}$ is temperature of asphalt pavement at depth h during the period of rising air temperature (°C). $T_{\text{air-rising}}$ is a period of rising air temperature, and h is a depth of pavement (cm). $T_{\text{pave-falling}}$ asphalt pavement temperature at depth h during period of falling air temperature (°C). $T_{\text{pave-falling}}$ is a falling of air temperature (°C), and h is a depth of pavement (cm). $Tair$ is air temperature, and h is the depth of pavement (cm).

(Wahhab et al., 2001)	Iraq	$T_{Pave} = 3.175 + 0.04866Z + 0.946Tair$ where T_{pave} is pavement temperature (°C), Z is depth below pavement surface (cm), and T_{air} is air temperature (°C).
(Gedafa et al., 2014)	Serbia	$y_{max} = 0.963288x_{max} - 0.151137xd + 4.452996$ $y_{min} = 1.004801x_{min} - 0.1992731xd + 0.051532$ where y_{max} is maximum pavement temperature (°C), x_{max} is maximum air temperature, x_{min} is air temperature (°C), y_{min} is minimum pavement temperatures (°C), and xd is depth (cm).
(H. A. Salem et al., 2014)	Libya	$T_{pav,d}^{max} = 7.059 + 0.7764246T_{sur}^{max}d + 0.054628Day - 0.000141Day^2 + 0.000006Cum_{SR} - 0.053402Lat$ $T_{pav,d}^{min} = 9.8364 + 0.0.668591T_{sur}^{min} + 0.259098d + 0.099289Day + 0.000261Day^{2-}0.000025Cum_{SR} - 0.053402Lat$ where $\mathrm{T}_{\mathrm{pay.d}}^{\mathrm{max}}$ is maximum daily pavement temperature (°C), $\mathrm{T}_{\mathrm{sur}}^{\mathrm{max}}$ is maximum daily surface temperature (°C), d is distance from surface (cm), is day of the year, Day^2 Day^2 is the square of the day of the year, $\mathrm{Cum}_{\mathrm{SR}}\mathrm{Cum}_{\mathrm{SR}}$ is cumulative solar radiation ($\mathrm{W/m}^2$), and Lat is latitude of the section (degrees). $\mathrm{T}_{\mathrm{pay.d}}^{\mathrm{min}}$ is minimum daily pavement temperature at distance d from the surface (°C) and $\mathrm{T}_{\mathrm{sur}}^{\mathrm{min}}$ is minimum daily surface temperature (°C).
(Ariawan et al., 2015a)	Indonesia	$T.00 = 10.813 + 0.919\,RH$ $T.20 = 6.898 + 0.687T.Air + 0.640\ T.00$ $T.70 = 1.965 + 0.755T.Air + 0.331\ T.00$ where RH is humidity, $T.Air$ is air temperature (°C), T.00 is surface temperature(°C), T.20 is temperature at a depth of 20 mm (°C), and T.70 is temperature at a depth of 70 mm (°C).

(Adwan et al., 2021)

Chapter 3: Methodology

3.1 Introduction

The methodology chapter of this study outlines the systematic approach undertaken to achieve the research objectives. This section provides a comprehensive description of the methodology used, beginning with the making of the apparatus, succeeded by the acquisition of data, numerical analysis, and ultimately the validation of the models.

The initial phase of the methodology involved the development of a tailored equipment system aimed at precisely monitoring pavement temperatures. This task involved picking and organizing temperature sensors, data loggers, and other essential apparatus. The apparatus was constructed to prioritize reliability, robustness, and the ability to capture temperature variations at varying depths within the pavement layers.

Following that, a thorough process for collecting data was put into place. Temperature readings were obtained at varying depths of the pavement. The data collection procedures were conducted concurrently with meteorological data collection to capture pertinent climatic variables, including air temperature. The employed methodology facilitated a thorough examination of the correlation between weather patterns and the temperatures of road surfaces.

The gathered data underwent a thorough analysis process to detect discernible patterns, trends, and correlations. The study utilized statistical techniques, specifically accuracy and correlation analysis, to assess the impact of climatic variables on pavement temperatures. The data analysis process encompassed a comparative examination between the accurate pavement temperature measurements and the projected temperatures derived from the pre-existing pavement temperature prediction model.

Ultimately, the validated models were evaluated about their precision and dependability in forecasting pavement temperatures within the confines of Bangladesh. The model's performance was evaluated using a comparison between the predicted temperatures and the actual measurements, which allowed for identifying any discrepancies or limitations.

The methodology chapter provides a comprehensive description of the sequential procedures used for this study, covering the development of equipment, data collection, analysis of findings, and the validation of the model. This approach guarantees that the research outcomes are grounded on dependable and robust methodologies, thereby adding to the general credibility and validity of the study's results.

3.2 Description of the Apparatus

A fully functional and portable apparatus was constructed to facilitate the collection of temperature data for pavement temperature monitoring. The device was developed to integrate multiple components and sensors to acquire six temperature measurements concurrently. The device also had a storage feature that allowed it to save the temperature readings to an SD (Secure Digital) card for later usage and analysis.

Careful selection and integration of the required components were required for the device's construction. These parts included a data gathering system, a microcontroller or data logger, an SD card module, and high-precision temperature sensors. The temperature sensors were installed at predetermined points within the pavement layers to reliably record temperature differences. The data collecting system connected the temperature sensors to the microcontroller or data logger. It made it easier for sensors to provide temperature data to a microcontroller or data logger for processing and storage. The microcontroller or data logger served as the central processing unit of the equipment, overseeing the data acquisition procedure, and enabling the retention of the acquired temperature data.

To offer a dependable and transportable storage solution, the SD card module was essential. The collected temperature data was kept on the SD card as digital files, making it simple to transfer and access for upcoming analysis and validation.

The finished device was made to be portable, making it simple to deploy and gather data at multiple monitoring stations. It was easy to carry, credit to its small size and lightweight, and its durable build provided dependability in various climatic circumstances.

The following parts were used to build the apparatus that would automatically take temperature readings at varying depths of the pavement and store it in a SD card:

Table 3: Name of the parts used

Sl	Name	No of the part used
1	Arduino Mega 2560 CH3	1
2	Max 6675	6
3	K-type Thermocouple	6
4	DS3231 RTC Module	1
5	Arduino Micro SD Module	1
6	Breadboard + Power Supply	1
7	9V Battey + Battery cap	2
8	Thermal Paste	-

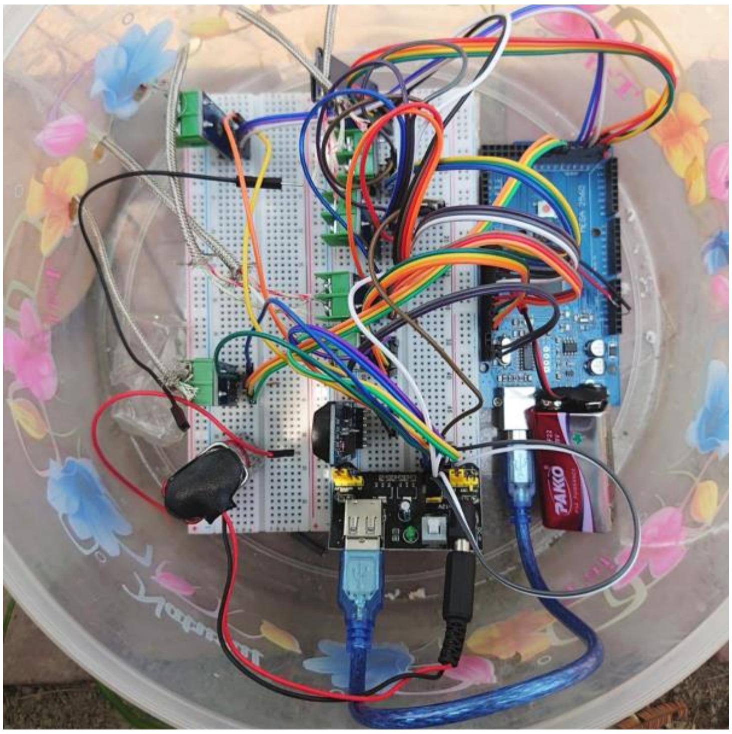


Figure 3: Apparatus for collecting the data

3.2.1

3.2.2 Arduino Mega 2560 CH3

The microcontroller board known as the Arduino Mega 2560 is founded on the ATmega2560. The device boasts a total of 54 digital input/output pins, with 15 of these being capable of functioning as pulse-width modulation outputs. Additionally, the device features 16 analog inputs, 4 UARTs for hardware serial ports, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The device encompasses all the necessary components to facilitate the functioning of the microcontroller. Its operation can be initiated by connecting it to a computer through a USB cable or powering it with an AC-to-DC adapter or battery.

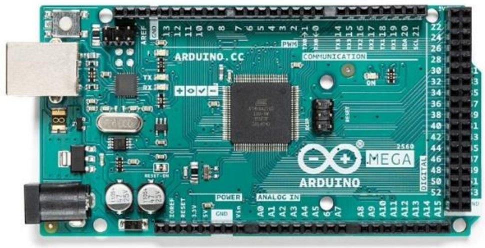


Figure 4: Arduino Mega 2560 CH3

3.2.3 Max 6675

The MAX6675 converts the signal generated by a type-K thermocouple and performs cold-junction compensation. The outputted data is in a read-only format compatible with SPI and has a resolution of 12 bits. The temperature as mentioned above, the converter can determine temperatures with a precision of 0.25°C accurately. It can measure temperatures as high as +1024°C and has a thermocouple accuracy of 8 Least Significant Bits (LSBs) for temperatures from 0°C to +700°C. The MAX6675 is obtainable in a compact 8-pin SO package.

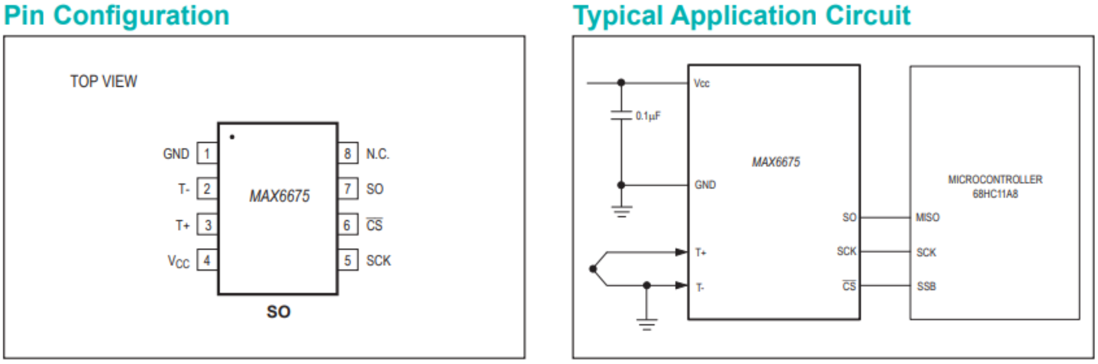


Figure 5: Typical configuration of the Max 6675 sensor

3.2.4

3.2.5

3.2.6 K-type Thermocouple

The Type K thermocouple is known for its ability to operate within a broad temperature range. The system comprises a positively charged leg that is non-magnetic and a negatively charged leg that is magnetic. The K Type Thermocouple employs conventional base metal, enabling it to operate at elevated temperatures and offer a broad range of operating temperatures. Nickel, a magnetic metal, is one of the constituent materials utilized in the K Type Thermocouple. K Type Thermocouples exhibit an unusual behavior whereby their output experiences a deviation upon attaining the Curie Point of magnetic materials, which typically occurs at approximately 185 °C. The K Type thermocouple exhibits excellent performance in oxidizing environments, with a maximum operating temperature of 1260°C (2300°F). Its tolerance class is ± 1.5 K within the temperature range of -40 to 375°C.

Figure 6: K-type thermocouple

3.2.7 DS3231 RTC Module

The DS3231 RTC is a highly accurate real-time clock module that includes a 32Kbit EEPROM and a 10-bit temperature sensor with a resolution of 0.25C. The DS3231 RTC module is an exact and cost-effective I²C real-time clock (RTC). It has a temperature-compensated crystal oscillator (TCXO) and crystal, contributing to its exceptional accuracy. The apparatus features a battery interface and sustains precise chronometry in the event of a disruption to the primary power supply. The incorporation of the crystal resonator results in an improvement in the device's long-term precision and a decrease in the number of individual components required in the manufacturing process. The ds3231 microcontroller board designed for use with Arduino is obtainable in both commercial and industrial temperature ranges, and it is presented in a 16-pin, 300-mil SO package.

Figure 7: DS3231 RTC Module

3.2.8 Arduino Micro SD Module

The Micro SD Card Reader Module has been developed to accommodate dual I/O voltages. The Module presents a straightforward approach for facilitating the exchange of information to and from a conventional SD card. The pin configuration is fully compatible without the need for any additional modifications. As depicted in the diagram below, this device is not limited to Arduino microcontrollers and can be utilized with alternative microcontrollersIt is designed to operate with a 5V or 3.3V power supply, rendering it compatible with the Arduino UNO/Mega. The SD module exhibits diverse applications, including but not limited to data logging, audio processing, video processing, and graphics rendering. The device features six distinct pins, namely GND, VCC, MISO, MOSI, SCK, and CS. GND is responsible for grounding, while VCC serves as the power supply. This circuit is also responsible for supplying power to the Micro SD card.

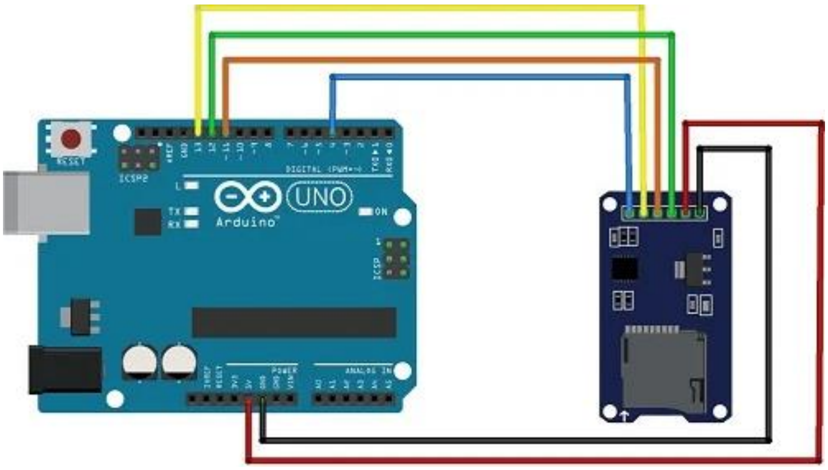


Figure 8: Arduino Micro SD Module

3.2.9 Breadboard

A breadboard, also known as a solderless breadboard or protoboard, serves as a foundational platform for constructing semi-permanent prototypes of electronic circuits. In contrast to perfboards or stripboards, breadboards do not necessitate soldering techniques or the destruction of tracks, rendering them reusable. Breadboards can prototype a diverse range of electronic systems, spanning from modest analog and digital circuits to entire central processing units (CPUs).

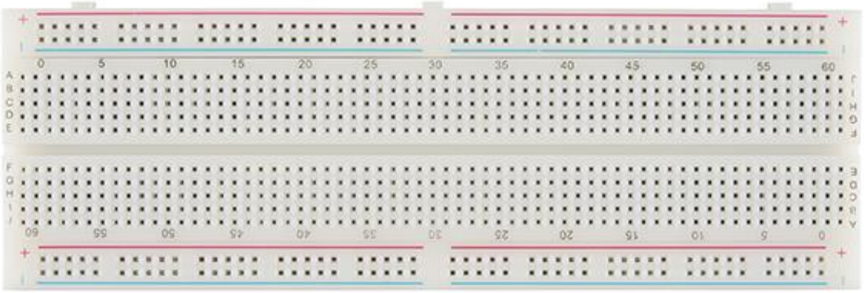


Figure 9: Breadboard

3.2.10 Power Supply

The MB102 Breadboard Power Supply Module is a device that offers two power rails, one at 5V and the other at 3.3V. Additionally, it features a versatile female USB socket. The Breadboard Power Supply Module, designed to provide power to a standard 400 or 800 tie points breadboards, is equipped with reverse polarity protection. It can accept input voltage ranging from 6.5V to 12V and generate output voltages of 3.3V and +5V. The module can produce a 5V output via the USB connector and receive input through the said connector. This product is essential for individuals conducting experiments and prototyping electronic circuits on a breadboard.

Figure 10: Breadboard power supply

3.2.11 9V Battery & Battery Cap

The Universal 9V battery size and its connecting points render it a versatile component in various do-it-yourself (DIY) projects and household applications. Its ease of replacement and installation is comparable to that of AA and AAA batteries.

The battery cap serves the purpose of establishing a connection between a 9V battery and its intended application. The snap power cable with a DC 9V clip male line battery adapter is commonly used to power Arduino boards and other development boards. The connector has an open-wire termination at one end and a battery connector termination at the other. Incorporating a connector into a project is a highly recommended practice due to its numerous advantages. These benefits include preventing short circuits, eliminating the possibility of polarity mismatches as wires are color-coded in red and black, optimizing battery usage, and connecting and disconnecting the battery to the application, among others.

Figure 11: 9V Battery and Battery Cap

3.2.12

3.2.13 Thermal Paste

Thermal paste, commonly known as thermal compound or grease, is a specialized substance utilized to enhance the heat transfer process between two surfaces. Commonly, it is utilized to connect a heat-generating module, such as a microprocessor, with a heat sink. The significance of thermal paste is attributed to its capacity to occupy microscopic crevices and flaws in the interface areas, guaranteeing optimal contact and enhancing thermal conductivity. Thermal paste is crucial in mitigating temperature fluctuations and facilitating effective heat dissipation by minimizing thermal resistance and eliminating air pockets. Maintaining optimal operating temperatures for electronic components is crucial in preventing overheating, which is imperative for enhancing their performance and longevity.

Figure 12: Thermal Paste

3.3 Calibrating the Sensors

In order to guarantee the precision and dependability of the temperature measurements obtained from the six thermocouple sensors integrated within the apparatus, a thorough calibration procedure was executed. The calibration process is deemed crucial to compensate for any intrinsic measurement inaccuracies and fluctuations that may arise in the thermocouple sensors.

The calibration process entailed comparing the readings obtained from the thermocouple sensors with the established temperature of the water. The outcome was attained by using calibrated thermometers as reference devices. A set of controlled experiments were carried out to measure the temperature of the water using calibrated thermometers and six thermocouple sensors simultaneously.

The thermocouple sensors and calibrated thermometers were submerged in water at a predetermined temperature in each calibration trial. Following an appropriate duration for thermal equilibrium, data was collected from both the thermocouple sensors and the calibrated thermometers. Subsequently, the recorded values were compared in order to evaluate any potential inconsistencies or divergences.

Through the process of comparing the readings obtained from the calibrated thermometers with those acquired from the thermocouple sensors, it is possible to identify any potential systematic errors or deviations. The data was subsequently utilized to compute calibration factors or correction coefficients for the thermocouple sensors. The calibration factors were utilized to enhance the precision of the temperature readings acquired from the thermocouple sensors and to bring them in line with the reference measurements obtained from the calibrated thermometers.

The calibration procedure was iterated several times to guarantee the uniformity and dependability of the acquired calibration coefficients. The calibration factors were meticulously recorded and linked with their corresponding thermocouple sensors, facilitating accurate modifications to be performed during the process of data analysis.

Figure 13: Calibration of the sensors

3.4 Location of Data Collection

To ensure the acquisition of data that accurately reflects pavement temperature, a precise selection process was followed to identify an appropriate location. The pavement selection process involved the consideration of various factors, such as sunlight exposure and traffic loading, to accurately capture the realistic conditions experienced by the pavement.

One crucial factor was to ascertain a site with unobstructed access to sunlight throughout the daytime. Solar radiation is a crucial determinant of pavement temperature, as it directly elevates the surface temperature. Hence, a site with abundant solar irradiance was chosen to encompass the complete spectrum of temperature fluctuations encountered by the pavement over the course of the day. This measure was taken to ensure that the data gathered accurately represented the thermal conditions experienced by the pavement in the presence of natural sunlight.

Furthermore, the study considered the proximity of a roadway with a high volume of traffic. Traffic loading significantly impacts pavement temperature, which is a critical determinant. The heat generated from the weight and movement of vehicles impacts the thermal behavior of pavement. The selection of a site in close proximity to a heavily trafficked road would enable the apparatus to record the impact of traffic loading on pavement temperature effectively. The utilization of this dataset resulted in a more comprehensive and representative analysis, which took into consideration the dynamic impact of vehicles on temperature fluctuations.

Selecting an appropriate site was crucial in guaranteeing the dependability and inclusiveness of the gathered information. The study facilitated a holistic comprehension of the temperature fluctuations encountered by the pavement, considering the collective impact of solar radiation and vehicular activity. The inclusion of this representative dataset would make a significant contribution towards the precise validation of current pavement temperature prediction models. Additionally, it would offer valuable insights for enhancing pavement design and maintenance strategies in comparable settings.

Figure 14: Data collection location

3.5 Probe Insertion

Five vertical holes next to one another were dug methodically to record temperature readings at various depths within the pavement layers. The selection of the depths of these holes was based on a thorough literature review, which aimed to ensure an accurate depiction of the temperature profiles within the pavement.

The depths chosen for the incisions were 10, 25, 50, 75, and 100 mm. The determination of these particular depths was based on prior research that emphasized the importance of these intervals in examining temperature fluctuations in flexible pavements. The literature review assisted in determining the depths that would provide significant insights into the thermal characteristics of the pavement layers.

In order to enhance the precision of temperature measurements and mitigate the influence of recurrent temperature fluctuations, a layer of thermal paste was administered onto the tips of every temperature sensor prior to their insertion into the orifices. The thermal paste acted as a conductive barrier between the sensors and the surrounding pavement material, promoting effective heat transmission and enhancing thermal conductivity. Applying thermal paste minimized air gaps or inconsistencies between the sensor and the hole, leading to more accurate temperature readings.

Thermal paste application was vital in reducing temperature variations and improving the accuracy of the data gathered. It assisted in establishing a solid and dependable thermal link between the temperature sensors and the pavement, reducing the impact of outside influences and variations in thermal conductivity. This allowed for accurate measurements of the temperature profiles across various depths within the pavement layers. The study made sure that the temperature data gathered from the various depths gave a thorough understanding of the thermal behavior of the flexible pavements by combining the careful selection of hole depths and the application of thermal paste.

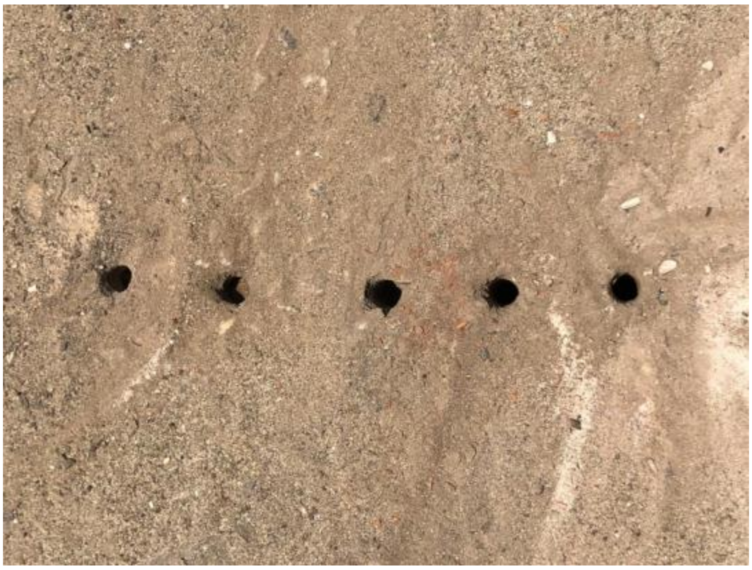


Figure 15: Holes for sensor insertion

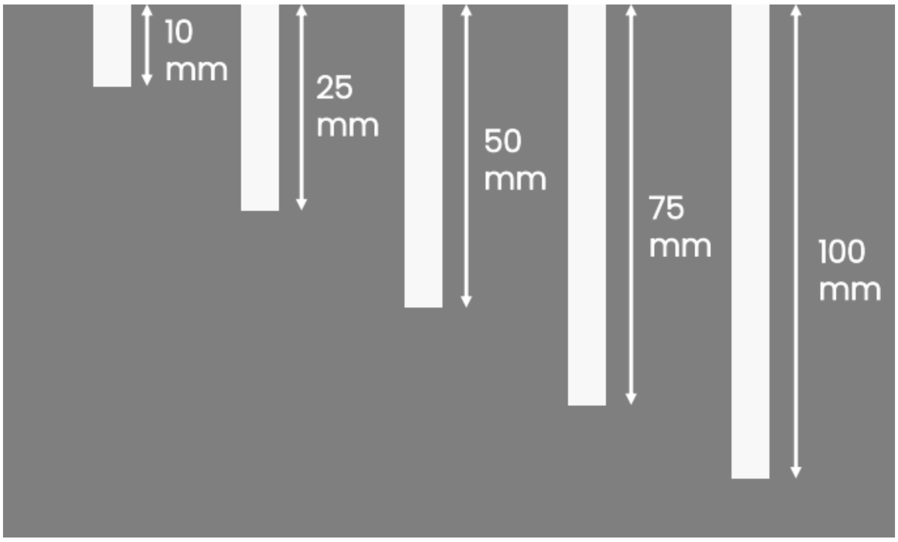


Figure 16: Various depths of sensor insertion

3.6 Insulating the Holes

After the insertion of temperature sensors at different depths within the pavement layers, an essential step was taken to guarantee the accuracy and reliability of the gathered data. Using Styrofoam to cover each hole served as a thermal insulator to impede the impact of external heat on the temperature measurements and to preserve the authenticity of the pavement temperature data.

Styrofoam, recognized for its thermal insulation characteristics, was chosen as a fitting substance for this objective. The material in question is characterized by its low weight and low thermal conductivity, efficiently reducing heat transfer. A thermal barrier was established using Styrofoam to cover each aperture, thereby effectively isolating both the sensors and the pavement from any potential external heat sources.

The Styrofoam served as a protective barrier, safeguarding the sensors and the adjacent pavement from direct contact with ambient temperatures and external thermal variations. The insulation utilized in this study served to mitigate the impact of atmospheric conditions and other environmental variables, thereby preserving the accuracy and representativeness of the temperature measurements obtained from the sensors concerning the actual temperature of the pavement.

The Styrofoam covering impeded the ingress of external heat through the apertures, thereby preserving a consistent and regulated thermal milieu in the vicinity of the sensors. Isolating the pavement was essential to procure precise and dependable temperature measurements without extraneous thermal influences.

The incorporation of Styrofoam as a thermal insulator introduced an additional level of precautionary measures and quality assurance to the process of data collection. Including this data has augmented the precision and soundness of the gathered information, thereby amplifying the research's capacity to authenticate the current pavement temperature prediction models and acquire a deeper understanding of the thermal characteristics of flexible pavements in Bangladesh. Using Styrofoam as a thermal insulator proved to be efficacious in preserving the sensors and the gathered data from extraneous thermal influences, thereby guaranteeing the conservation of the authentic temperature profiles of the pavement. The insulation process was crucial in preserving the accuracy and dependability of the research results.

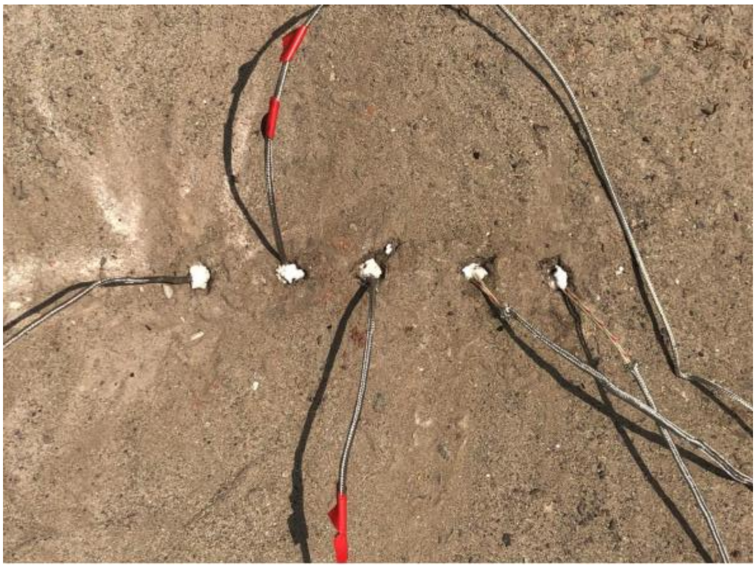


Figure 17: Placing Styrofoam on the holes to act as heat insulator

3.7 Sealing the Holes

To further improve the protection of the temperature sensors and uphold the accuracy of the gathered data, a concluding measure was implemented to seal the apertures with bitumen. The selection of bitumen for pavement construction was based on its sealing properties, which are widely recognized in the field. Bitumen is a viscous and hydrophobic material that creates a resilient barrier upon application to various surfaces. The application of bitumen as a sealant effectively established a protective barrier, impeding the infiltration of extraneous substances into the sensor apertures. The application of bitumen to seal the holes served various functions. Initially, it functioned as a tangible obstruction, impeding the entrance of dust and minute particles into the apertures and potentially compromising the accuracy of temperature measurements.

Furthermore, the hydrophobic properties of bitumen served to prevent the infiltration of precipitation or any other form of moisture into the sensor apertures. The moisture intrusion could disturb the sensors' thermal equilibrium, leading to inaccuracies in the temperature readings.

Using bitumen as a sealing agent provided an additional level of preservation for the temperature sensors and the gathered data. Implementing measures to prevent the impact of extraneous elements, such as dust, delicate particulate matter, and precipitation, ensuring that the temperature readings of the pavement were not compromised, thereby maintaining the precision and dependability of the data. Through the application of bitumen to seal the sensor holes, the study established a controlled environment that safeguarded the integrity of the collected data. The systematic methodology employed in this study has augmented the research's capacity to authenticate the prevailing pavement temperature forecasting models. It has furnished significant discernments into the thermal attributes of flexible pavements in Bangladesh without being influenced by extraneous interferences.

Figure 18: Sealing the holes with bitumen

3.8 Process of Collecting the Data

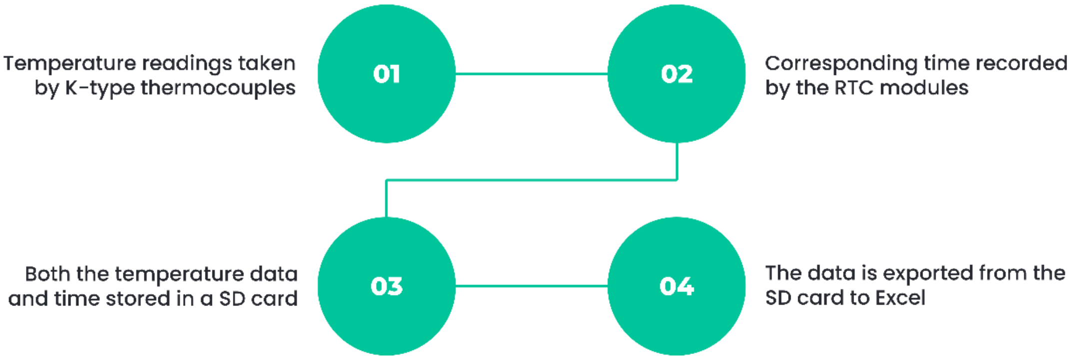


Figure 19: Full process of data collection

Chapter 4: Analysis & Results

4.1 Data Interpretation

The thorough data collection on pavement temperature and matching air temperature gave essential insights into the thermal behavior of the pavement layers. Six sensors were used in a setup, with one sensor recording the air temperature, and the other sensors were positioned at different depths within five holes to collect the data. The temperature distribution within the pavement layers was shown to have several interesting patterns and trends by analysis of the data collected.

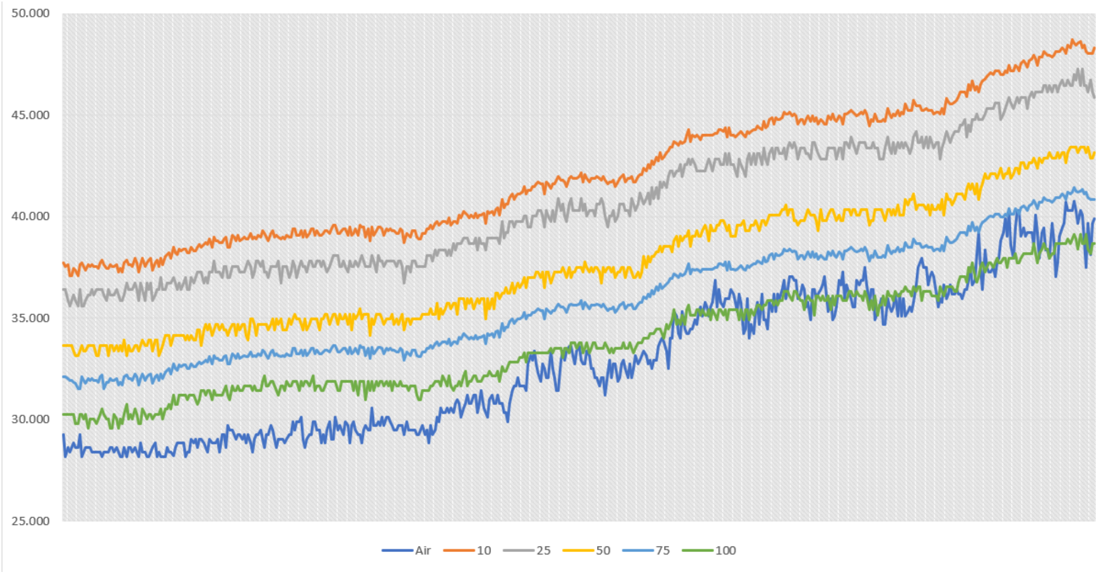


Figure 20: Temperature data across various depths of the pavement

The temperature reading that was highest was recorded at the shallowest depth, specifically at 10 mm. The finding is consistent with expectations given that the pavement's surface layer is more exposed to solar radiation and other outside heat sources, leading to greater temperatures. Sunlight directly affects the surface layer, which absorbs a lot of heat during the day. Therefore, it is not surprising that the 10 mm depth showed the highest temperatures.

A steady trend of dropping pavement temperatures was seen as the depths rose. This is explained by the fact that as the sensors progressed deeper into the pavement layers, the impact of solar radiation and surface heat sources decreased. Lower temperatures are a result of deeper strata being more protected from direct solar radiation and subject to fewer outside influences.

A depth of 25, 50, 75, and 100 mm yielded the second, third, fourth, and fifth highest temperatures. The heat dissipation and attenuation occurring within the pavement layers is demonstrated by the temperature gradually dropping as depth increases. The pavement layers serve as insulating barriers as the sensors descend, preventing heat from being transferred from the surface to the lower depths.

Notably, the pavement temperatures began to converge and became closer to the measured air temperature as the depths grew. A sizable chunk of the data was in good alignment with the air temperature readings at the 100 mm depth. This is explained by how exterior characteristics start to have less of an impact as depths rise. The deeper pavement layers are less affected by elements like sun radiation, traffic volume, and environmental factors. As a result, at deeper depths, the pavement temperatures show a closer likeness to the air temperature.

The fact that the pavement temperatures at deeper depths converge toward the air temperature shows that subsurface factors predominate in controlling the thermal properties of the pavement. The mechanisms of thermal conductivity and heat exchange within the pavement layers have a greater influence on the temperature profiles at these depths. The temperature of the subsurface layers tends to be closer to that of the surrounding air because they transfer heat more slowly and tend to establish thermal equilibrium.

These results emphasize how critical it is to consider depth-dependent temperature changes when examining pavement temperature data. A thorough understanding of the thermal behavior of the pavement layers can be gained from the temperature profiles acquired at various depths. The decrease in temperature as depth increases illustrates how subsurface influences affect the thermal properties of flexible pavements.

The data analysis highlights the importance of pavement design and its capacity to reduce changes in outside temperature. Flexible pavements' layered structure serves as a thermal buffer, regulating the flow of heat between the surface and deeper layers. This thermal regulation lessens the effects of temperature swings outside by helping to maintain stable temperatures inside the pavement structure.

Overall, intensive pavement temperature data collection and analysis and air temperature observations provided insight into the intricate dynamics of temperature distribution within flexible pavements. We can learn a lot about the thermal behavior of the pavement layers from the observed trends of temperature decline with depth and convergence toward air temperature. These results strengthen our knowledge of the thermal properties of flexible pavements, which is essential for building and maintaining Bangladesh's resilient road infrastructure. They also add to the validation of current pavement temperature forecast models.

4.2 Validating Different Models

4.2.1 LTPP High Temperature Model

The main objective of the SHRP bitumen research program was to create performance-based requirements for a wide range of temperatures to recognize the critical impact of temperature on asphalt binder performance. The Long Term Pavement Monitoring Program (LTPP) was created in 1987 by the Strategic Highway Research Program (SHRP) to support a variety of pavement performance assessments leading to improved engineering tools for designing, building, and managing pavements.

In order to measure and assess the impacts of temperature and moisture changes on pavement performance and validate the current models, the Seasonal Monitoring Program (SMP) was established as a component of the LTPP in 1991 (Diefenderfer et al., 2002). Several pavement temperature models were created using the original SHRP tests and SMP data to aid in the right choice for the asphalt binder performance grade. One of these models that was developed was the LTPP model. For the conversion from air to pavement temperature, the LTPP model is applied.

The LTPP formula is as follows-

$$T(pav) = 54.32+0.78\,T(air) - 0.0025\,Lat^2 - 15.14\,\log_{10}(H + 25) + z\,(9+0.61\,Sair^2)^{1/2}$$

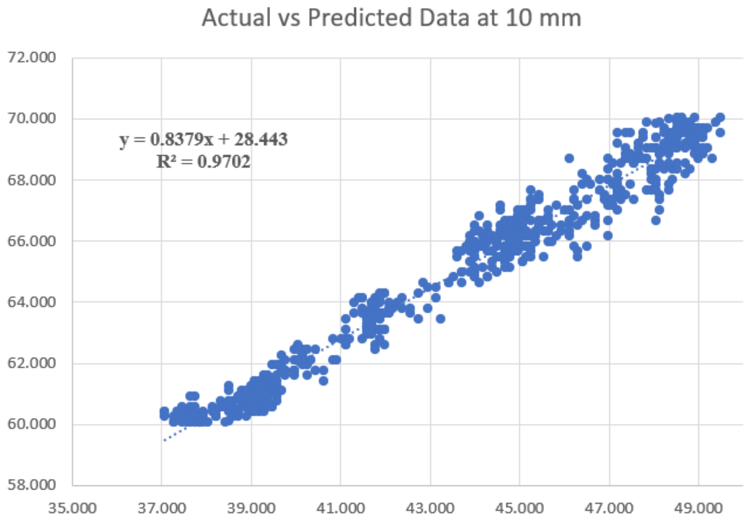
Where,

T(pav)	Pavement temperature (°C)
T(air)	Air temperature (°C)
Lat	Latitude
H	Depth of measurement (mm)
z	Reliability coefficient
Sair	Standard deviation of average air temperature

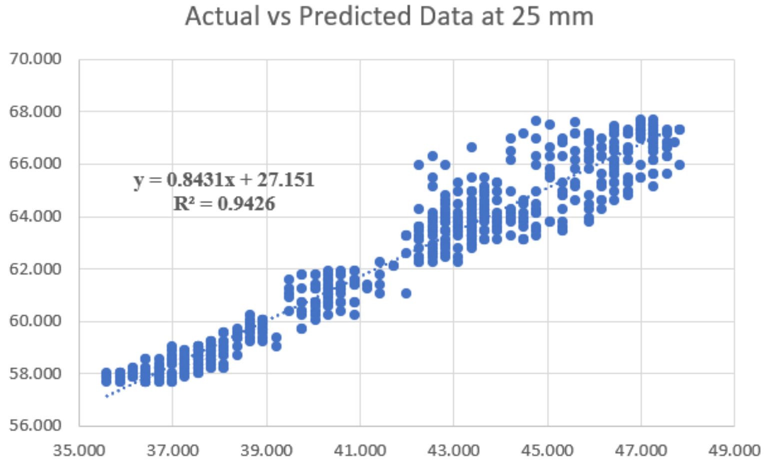
The data we got from our sensors was validated against this formula. The variables we used in our formula are-

T(air)	Respective Air temperature (°C)
Lat	23.947021
H	10, 25, 50, 75, 100 respectively
z	2.055 (For 98 percentile)
Sair	4.0714847

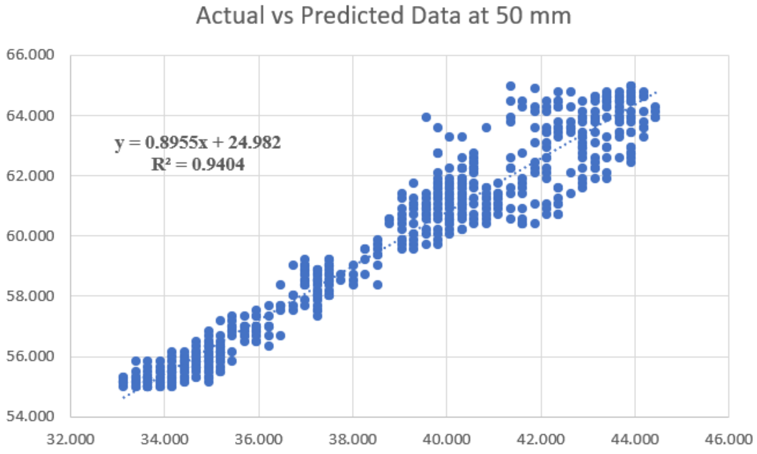
The obtained results are depicted below:



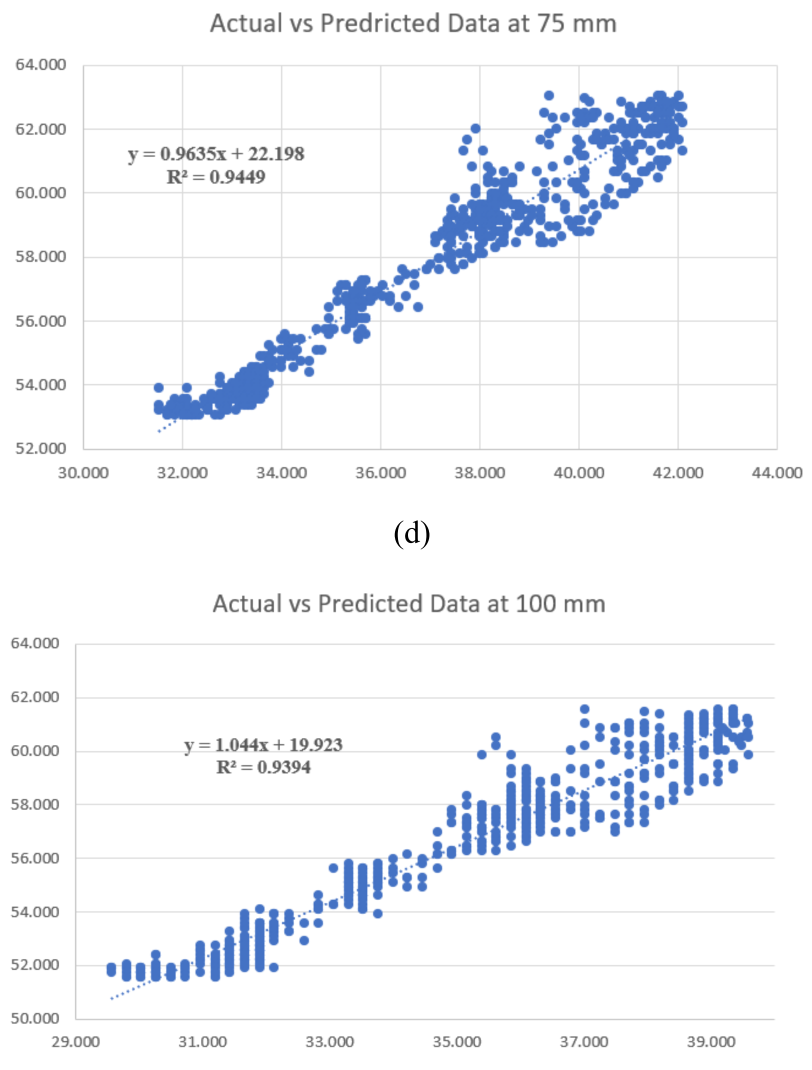
(a)



(b)



(c)



(d)

(e)

Figure 21: Validation of LTPP model at (a) 10 mm, (b) 25 mm, (c) 50 mm (d) 75 mm, (e) 100 mm

The summary of the findings from this model:

Table 4: LTPP Model Summary

LTPP High	
Data	**R-Squared**
10 mm	0.9702
25 mm	0.9426
50 mm	0.9404
75 mm	0.9449
100 mm	0.9394

4.2.2 Abdul Al-Wahhab et al. Model

The Abdul Al-Wahhab et al. Model, created especially for Saudi Arabia, is an important step in pavement engineering, especially in arid environments with little seasonal variation in ambient temperature. The model focuses on forecasting maximum and minimum temperatures, which are essential for determining how well asphalt pavements operate.

For asphalt pavements to be designed and built to last in Saudi Arabia's desert climate, where temperature extremes are typical, it is crucial to understand how they behave thermally. The Abdul Al-Wahhab et al. model accurately predicts the temperature changes experienced by pavements by considering the area's distinctive environmental characteristics, such as high temperatures and limited rainfall.

The model enables engineers and researchers in Saudi Arabia to make well-informed judgments regarding pavement materials, thicknesses, and design approaches by offering trustworthy estimates of maximum and minimum temperatures. This lowers the danger of early pavement distress and failure by enabling the selection of suitable asphalt mixes and construction methods that can endure harsh environmental conditions.

A localized model like the one created by Abdul Al-Wahhab et al. is essential since it considers the unique traits and needs of the area. The model makes sure that pavement designs in Saudi Arabia are suited to specific thermal conditions, increasing their longevity and performance. It does this by using local statistics and climatic information.

The Abdul Al-Wahhab et al. formula is as follows-

$$\boldsymbol{T(d) = 3.714 + 1.006T(a) - 0.146d}$$

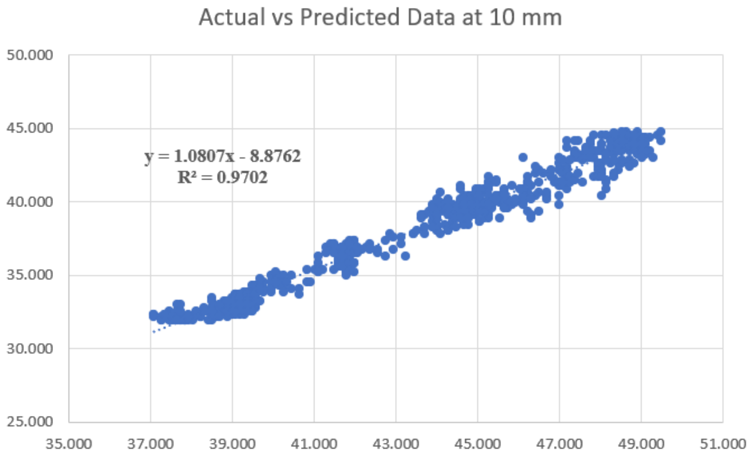
Where,

T(d)	Pavement temperature at depth d
a	Air temperature
d	Depth below pavement surface (cm)

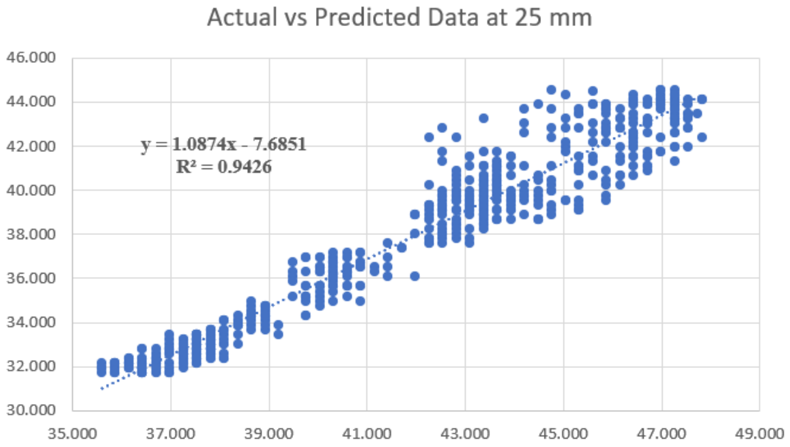
The data we got from our sensors was validated against this formula. The variables we used in our formula are-

a	Respective Air temperature (°C)
d	1, 2.5, 5, 7.5, 10 respectively (cm)

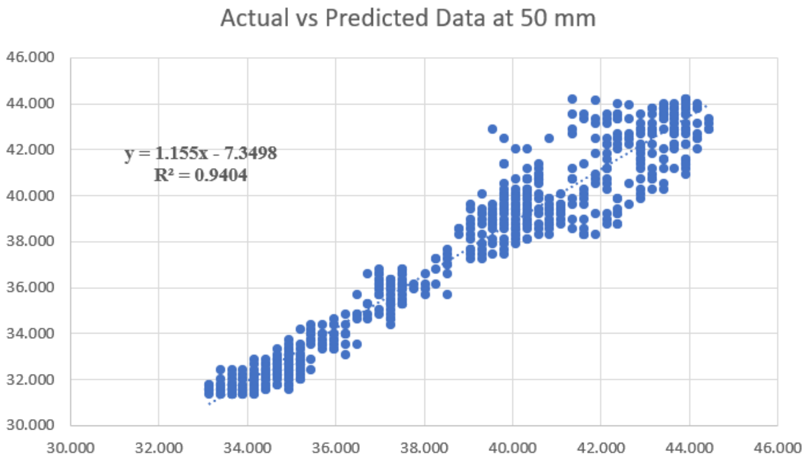
The obtained results are depicted below:



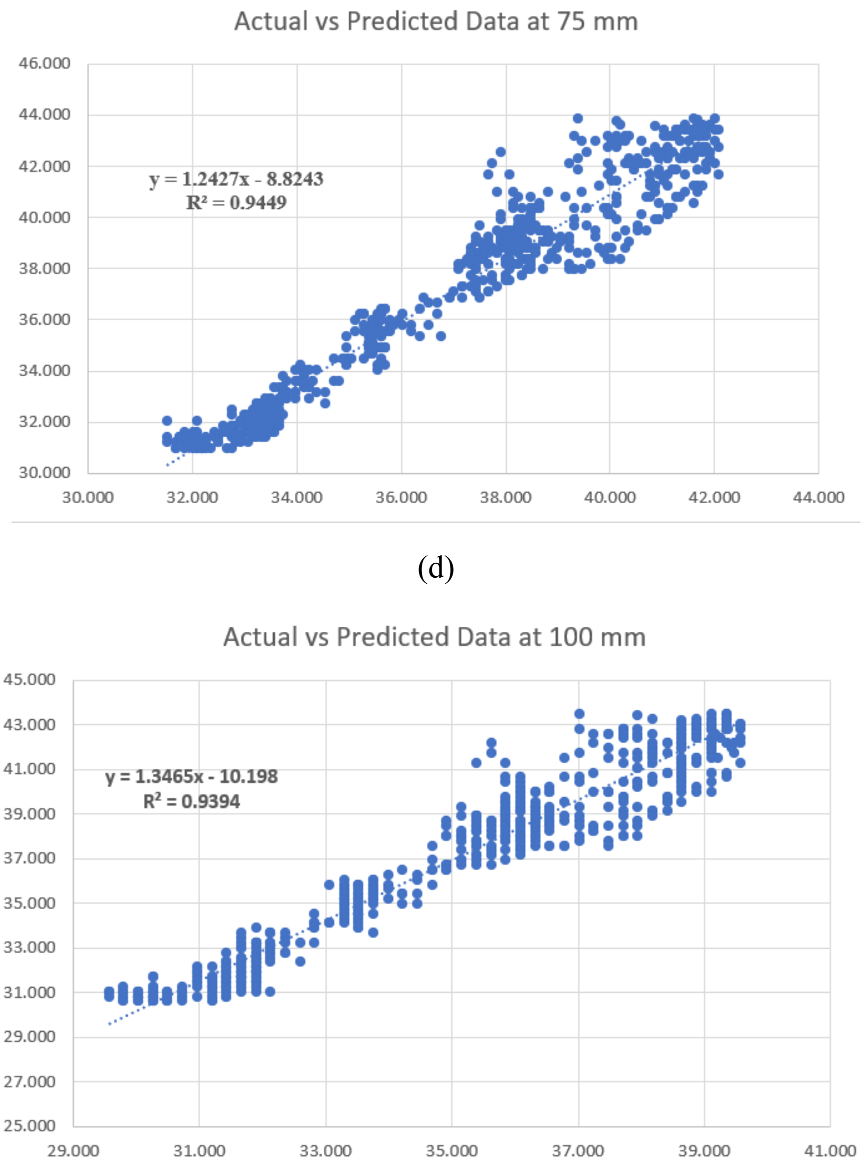
(a)



(b)



(c)



(d)

(e)

Figure 22: Validation of Abdul Al-Wahhab et al. model at (a) 10 mm, (b) 25 mm, (c) 50 mm (d) 75 mm, (e) 100 mm

The summary of the findings from this model:

Table 5: Abdul Al-Wahhab et al. Model Summary

Abdul Al-Wahhab et al. (2001)	
Data	**R-Squared**
10 mm	0.9702
25 mm	0.9426
50 mm	0.9404
75 mm	0.9449
100 mm	0.9394

4.2.3 Zheng et al. Model

Prediction models with greater adaptability and usability can determine pavement temperature at any depth. Because of this, multivariate regression between asphalt concrete temperature, air temperature, and pavement structure depth was carried out by Zheng et al. in China using the least squares approach, and the following prediction models are developed based on different air temperature changing periods:

$$T_{pave\text{-}falling} = 1.085T_{air\text{-}falling} - 0.07h + 4.3$$

$$T_{pave\text{-}rising} = 1.170T_{air\text{-}rising} - 0.50h + 3.55$$

$$T_{pave} = 1.118T_{air} - 0.23h + 4.1$$

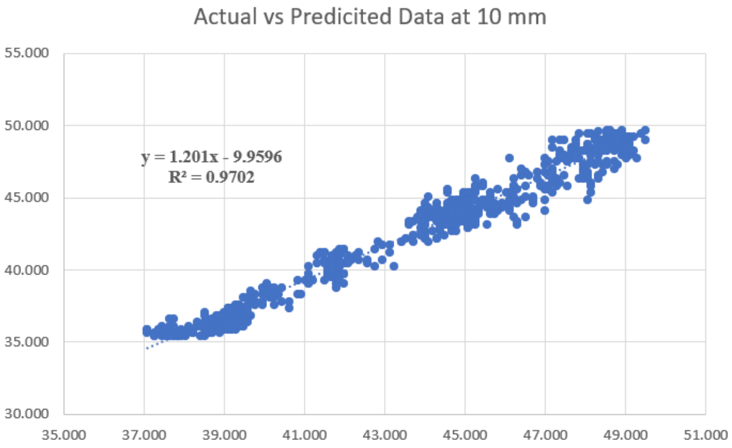
Where,

$T_{pave\text{-}falling}$	Temperature of asphalt pavement during the period of rising air temperature
$T_{pave\text{-}rising}$	Temperature of asphalt pavement during period of falling air temperature
T_{pave}	Temperature of asphalt pavement
$T_{air\text{-}falling}$	Falling air temperature
$T_{air\text{-}rising}$	Rising air temperature
T_{air}	Air temperature
h	Depth

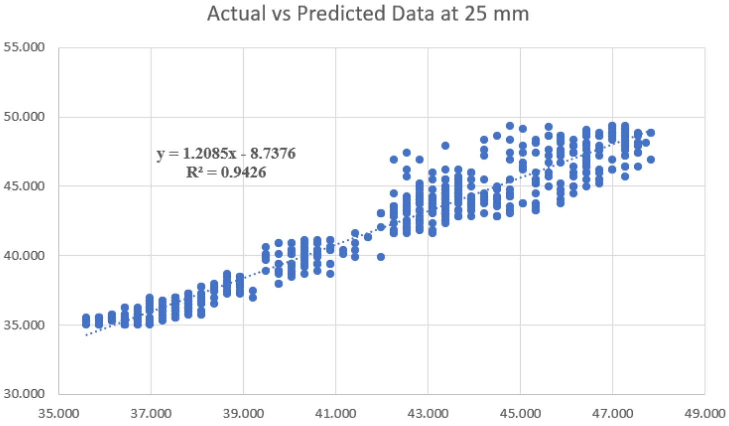
The data we got from our sensors was validated against this formula. The variables we used in our formula are-

T_{pave}	Temperature of asphalt pavement
T_{air}	Respective Air temperature
h	1, 2.5, 5, 7.5, 10 cm

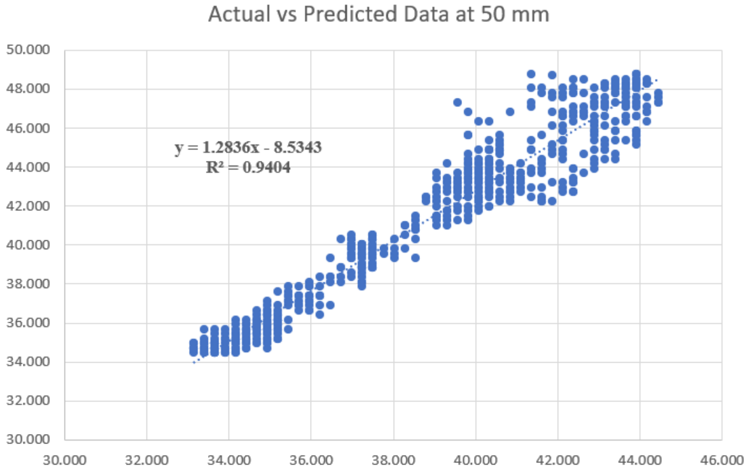
The obtained results are depicted below:



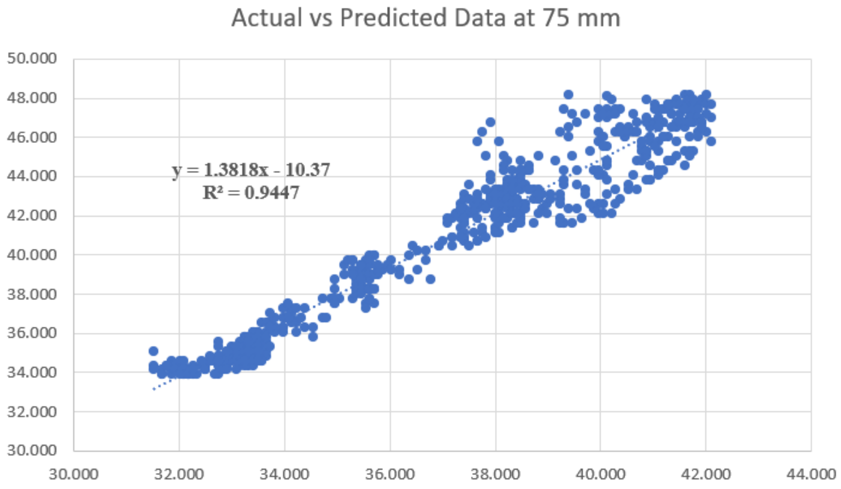
(a)



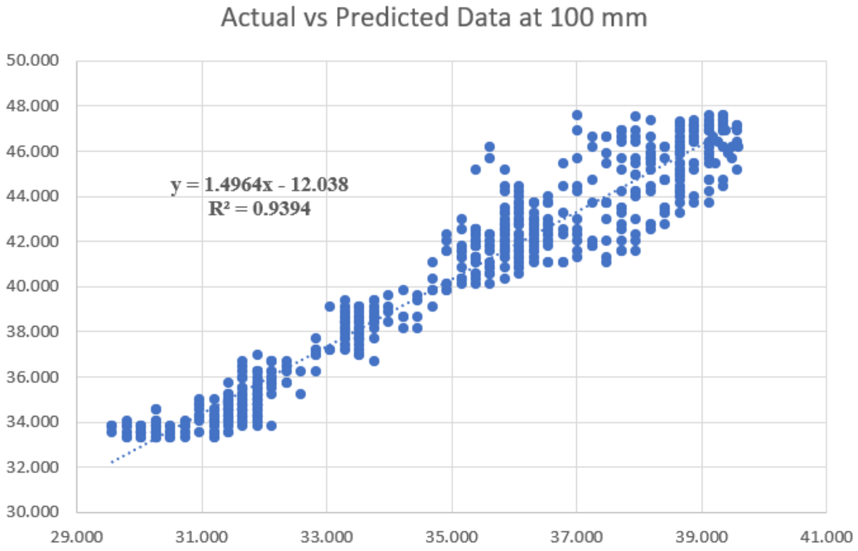
(b)



(c)



(d)



(e)

Figure 23: Validation of Zheng et al. Model at (a) 10 mm, (b) 25 mm, (c) 50 mm (d) 75 mm, (e) 100 mm

The summary of the findings from this model:

Table 6: Summary of Zheng et al. Model

Zheng et al. (2011)	
Data	**R-Squared**
10 mm	0.9702
25 mm	0.9426
50 mm	0.9404
75 mm	0.9449
100 mm	0.9394

4.2.4 Al-Hamed and Maryam Model

A model for predicting pavement temperature as a function of air temperature and depth below the pavement surface was created using linear regression. The equation below, developed for Iraq, displays the statistical model that has been created. R2 is 0.923, and SE is 2.7725 for this model.

$$T_{Pave} = 3.175 + 0.0\ 4866Z + 0.946\ T_{air}$$

Where,

T_{Pave}	Pavement Temperature °C
Z	Depth below the pavement surface (cm)
T_{air}	Air Temperature °C

Based on the results of the research, the following key conclusions were drawn, within the constraints of the materials and testing program employed in this work:

1. A model is created to forecast the resilient modulus of asphalt concrete under various test settings and mix parameters based on the results of the indirect tensile test using the pneumatic repeated load apparatus.:

$$M_R = 763480.93 - 173341.49AC + 16835.719$$

$$n - 3793.643\ Av - 8778.963T + 88084.\ 523S.A$$

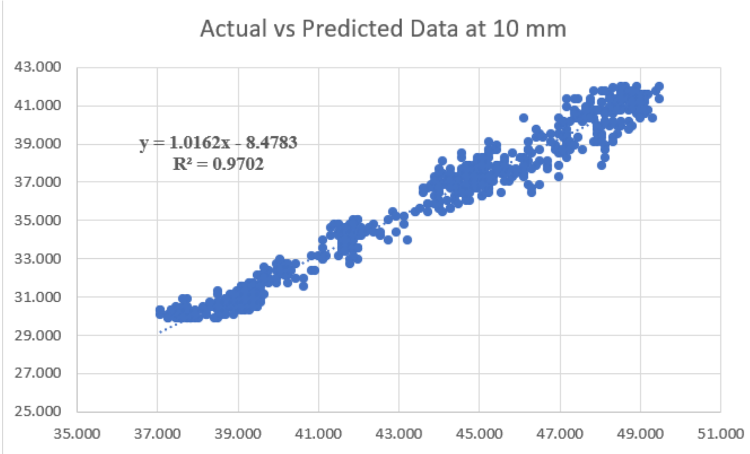
2. When temperature rises, robust modulus typically decreases at a rate of 8.78 x 10 Psi/C for wearing courses and 8.72 x 10 Psi/C for leveling courses.

3. The robust modulus is negatively impacted by deviations from the ideal value of asphalt cement content. At 10 C, 25 C, and 40 C, an increase in asphalt content of 0.1% (by weight of the whole mixture) results in a decline in resilience modulus of 5.1%, 8.3%, and 22%, respectively.

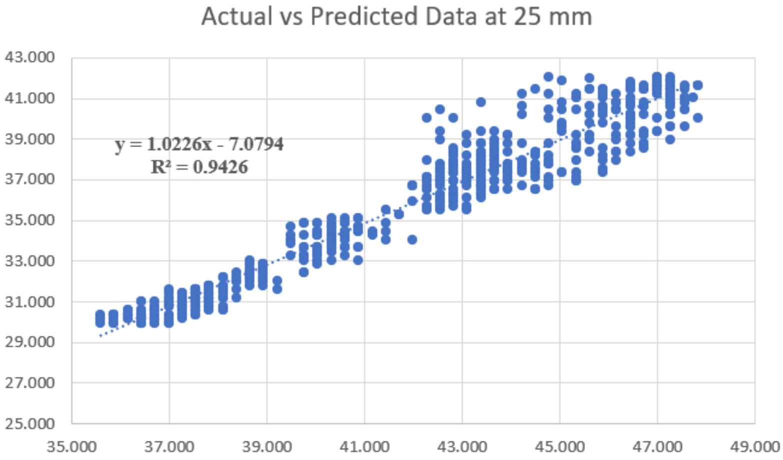
The data we got from our sensors was validated against this formula. The variables we used in our formula are-

Z	1, 2.5, 5, 7.5, 10 cm
T_{air}	Respective Air Temperature °C

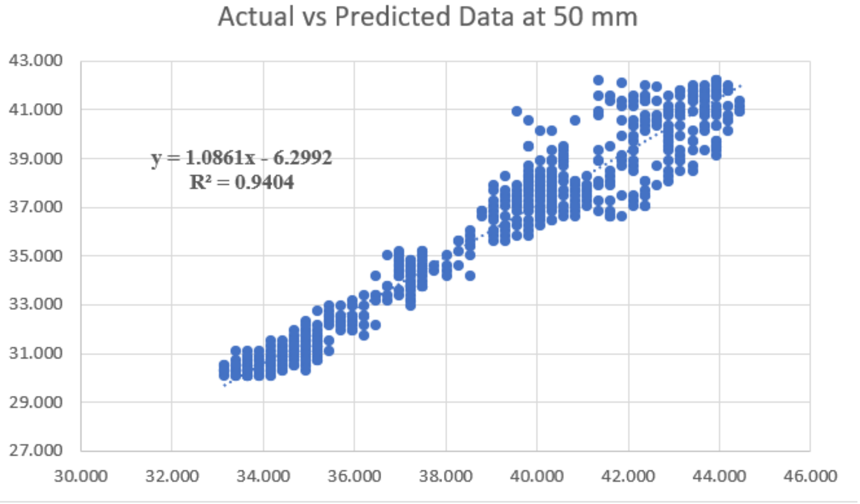
The obtained results are depicted below:



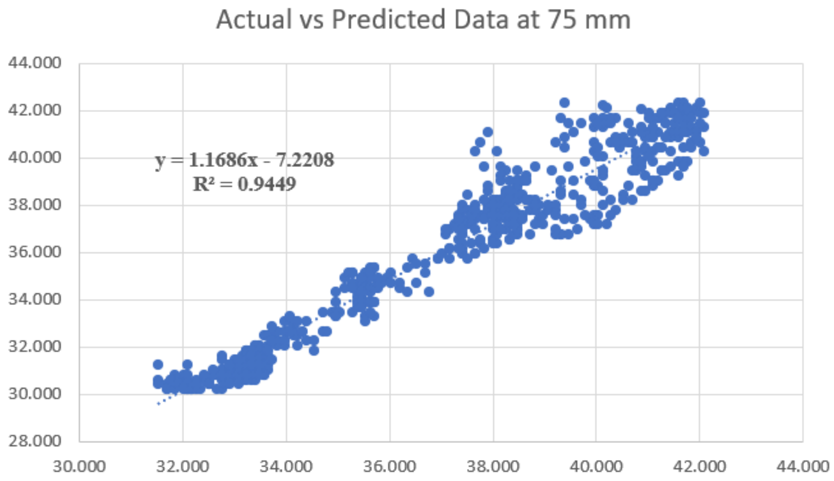
(a)



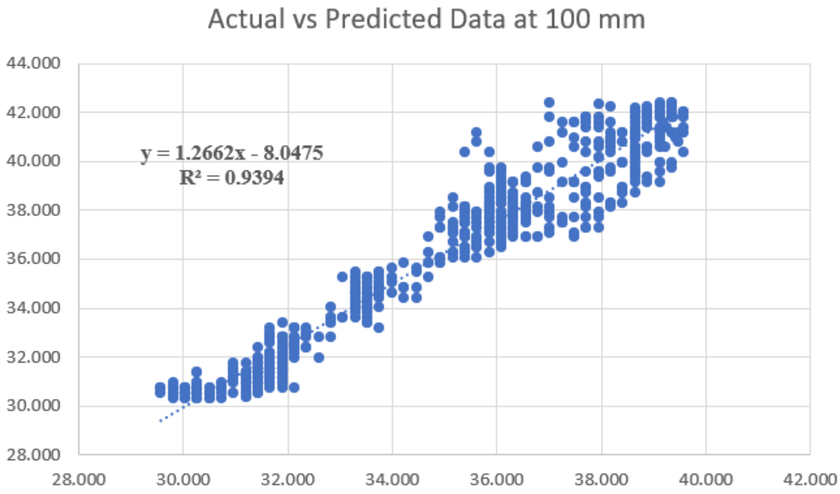
(b)



(c)



(d)



(e)

Figure 24: Validation of Al-Hamed and Maryam Model at (a) 10 mm, (b) 25 mm, (c) 50 mm (d) 75 mm, (e) 100 mm

The summary of the findings from this model:

Table 7: Summary of Al-Hamed and Maryam Model

Al-Hamed and Maryam (2011)	
Data	**R-Squared**
10 mm	0.9702
25 mm	0.9426
50 mm	0.9404
75 mm	0.9449
100 mm	0.9394

4.2.5 Diefenderfer et al. Model

The Diefenderfer et al. (2003) model, which offers applicability across several climate zones and seasons, is a thorough pavement temperature forecast model. One of its key advantages is this model's capacity to produce precise temperature predictions across various geographic regions with varying climatic traits. Significant data from Strategic Highway Research Program (SHP-R) Maintenance Project (SMP) sites in the United States confirmed the model's dependability. These SMP sites are an excellent source for evaluating and fine-tuning the model's equation because they span an array of climate zones and environmental circumstances.

The Diefenderfer et al. model benefits from an assortment of temperature profiles observed in different locations and seasons by including data from SMP sites around the United States. As a result, the model can accurately represent the specific thermal behavior of pavements across a range of climate zones, including those that experience significant seasonal temperature variations.

The intensive data analysis produced a proven equation strengthening the model's dependability and credibility. The model's equation accurately depicts the temperature characteristics of existing pavement systems in various climate zones because of the stringent validation procedure using SMP sites. Beyond the detailed data utilized for validation, this validation procedure increases the model's usability and broadens its application potential.

$$Tp_{max} = 3.2935 + 0.6356T_{max} + 0.1061Y - 27.7975d_b$$

$$Tp_{min} = 1.6472 + 0.6504T_{min} + 0.0861Y + 7.2385d_b$$

Where,

Tp_{max}	Predicted maximum temperature (◦C)
Tp_{min}	Predicted minimum temperature (◦C)
T_{max}	Maximum daily temperature (◦C)
T_{min}	Minimum daily temperature (◦C)
Y	Day of the year
d_b	Depth (m)

Table 8: Results from the Diefenderfer et al. Model

	Max Temp	Max Predicted Temp	Min Temp	Min Predicted Temp
Air	40.966	-	28.178	-
10 mm	49.494	42.316	37.070	30.809
25 mm	47.833	41.899	35.596	30.917
50 mm	44.446	41.204	33.140	31.098
75 mm	42.095	40.509	31.527	31.279
100 mm	39.584	39.814	29.569	31.460

Chapter 5: Discussion & Conclusion

Several significant findings were made while validating pavement temperature prediction models for Bangladesh's climate and environment. The goal was to evaluate the models' accuracy at various depths within the pavement structure.

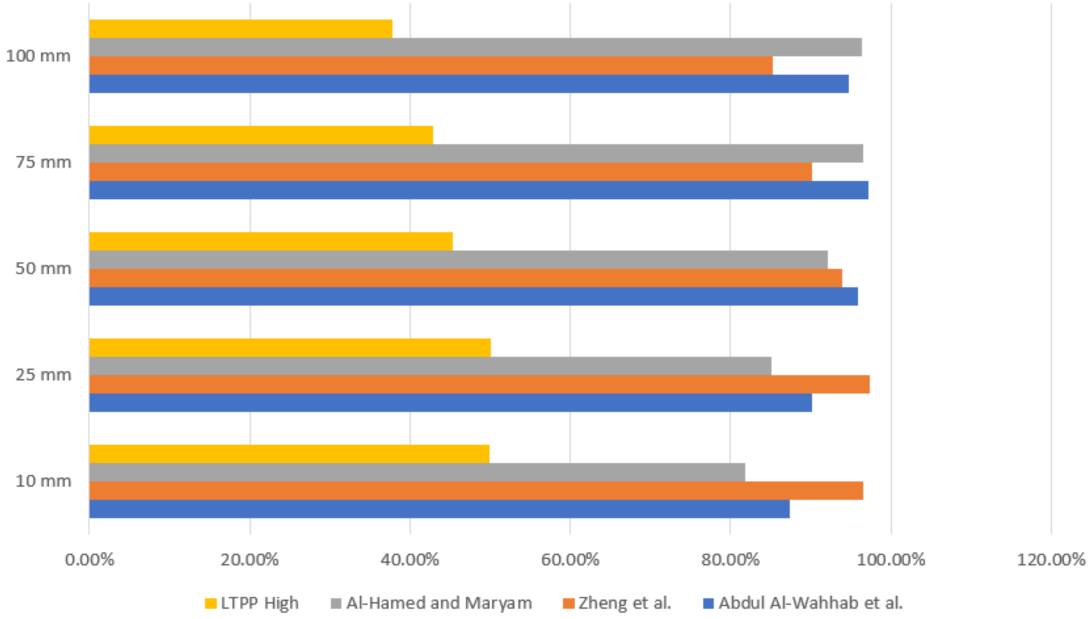


Figure 25: Comparison of the different models

The Zheng et al. model consistently showed the highest accuracy at shallower depths among the models tested. In particular, the Zheng et al. model showed the highest accuracy compared to the other models at depths of 10 mm and 25 mm. This suggests that the pavement temperatures close to the surface layers, essential for comprehending surface discomfort and performance, were particularly well predicted by the Zheng et al. model.

The Abdul Al-Wahhab et al. model performed well at intermediate depths inside the pavement structure. The Abdul Al-Wahhab et al. model produced the maximum accuracy at depths of 50 mm and 75 mm. This implies the model might have accurately estimated the pavement temperatures at these intermediate depths. This is crucial for determining the thermal behavior and probable development of discomfort inside the pavement layers.

Interestingly, the Al-Hamed and Maryam model showed the maximum accuracy at a depth of 100 mm. This model created expressly for predicting pavement temperatures, performed exceptionally well at determining temperatures at deeper levels inside the pavement structure. Understanding the heat transport mechanisms within the pavement layers and how they affect long-term pavement performance depends on this information.

The importance of choosing an appropriate model depending on the desired depth range of interest is shown by the changes in accuracy across various depths. The Zheng et al. model would be appropriate for applications focusing on surface temperatures and distress evaluation because of its excellent accuracy near the surface layers. On the other hand, the Al-Hamed and Maryam model would offer valuable insights for investigations involving deeper layers and thermal behavior evaluation.

It is significant to emphasize that these results are unique to Bangladesh's climate and surroundings. The models were assessed considering the country's particular climatic conditions, which may differ from those in other regions. As a result, care should be taken while using these models in different geographic areas with different climatic traits.

Additional research and validation studies are required to improve and maximize these models' performance in Bangladesh's unique climatic circumstances. This process involves investigating additional variables that could affect accuracies, such as differences in pavement materials, subgrade characteristics, and traffic loading circumstances. It is possible to gain a more thorough grasp of the models' advantages and disadvantages by broadening the research's focus.

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