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Predicting the Maximum and Minimum Asphalt Pavement Temperatures on Abuja to Kaduna Railway Line in Nigeria

[1]Apeh Adejoh S., [2]Adeyeri Joseph B., [3]Amu Olugbenga O.

[1,2,3]Faculty of Engineering, Department of Civil Engineering, Federal University of Oye-Ekiti, Nigeria

Corresponding Author: engrsamapeh@gmail.com

ABSTRACT : *The subject of temperature variations in asphalt pavement layers has been studied at various times in the past, because asphalt pavement layer is very sensitive to temperature. The ability to predict temperature variations at any depth in asphalt pavement at a construction site is critical to its performance and behaviour. The aim of this study was to predict the maximum and minimum asphalt pavement temperatures on Abuja-Kaduna railway line. Meteorological data of daily air temperatures for 31 years (1990-2021) were obtained at Abuja and Zaria NIMET weather stations for this research. In this study, the maximum air temperature, being the average hottest 7-day temperature for each year, and the minimum air temperature, being the coldest one-day temperature for each year were determined, and the values of maximum air temperature being the highest value in 31 years and minimum air temperature being the coldest day in 31 years, together with the days the hottest and coldest temperatures were recorded in 31 years were substituted in the Diefenderfer regression equation at three different depths. The predicted maximum and minimum asphalt pavement temperatures were taken at mid-depths. These represent temperatures the asphaltic sub-ballast is expected to withstand in the railway substructure environment. This study found that the maximum and minimum asphalt pavement temperatures on Abuja to Kaduna railway line were 24.53 0C and 15.44 0C respectively.*

KEYWORDS: *Meteorological data, Diefenderfer Regression Models, Asphalt Pavement Temperatures, Abuja to Kaduna Railway Line, Nigeria*

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I. INTRODUCTION

One of the most important environmental variables influencing the mechanical characteristics of flexible asphalt paving mixtures and the carrying capacity of the asphalt pavement structure is temperature distribution (Arangi and Jain, 2015,Matic et al. 2013). According to Nizetic and Papadopoulous (2018) and Van-dam et al. (2015), pavement temperature is a function of changes in pavement surface temperature with variations in weather parameters over time as influenced by the paving materials and direct solar reflectance, thermal conductivity, thermal emittance, specific heat, and surface convection. It should be mentioned that because asphalt mixtures are made of temperature-sensitive components, changes in temperature affect their modulus and strengths. This means that flexible pavements may sustain a variety of problems. For instance, cracks may result from the temperature dropping.

Hot-mix asphalt (HMA) is also a viscoelastic material, which means that it exhibits the properties of both an elastic and a viscous material. At low temperatures, HMA acts as an elastic solid in which low amounts of applied strain are recoverable; consequently, permanent deformation is not likely to occur until this low strain limit is surpassed. At high temperatures, HMA acts as a viscous fluid in which the material begins to flow with an applied stress. Moreover, extensive research on temperature prediction models has been conducted in several regions with diverse climates to formulate pavement temperature prediction models that offer the highest accuracy (Matic et al. 2013).

Temperature fluctuations within the upper layers of a pavement are caused by a variety of factors, such as ambient temperature, solar radiation, wind speed, and pavement surface reflectance, with temperature being the major contributor. For this reason, it is critical to determine the temperature distribution within the pavement cross section when examining the in-situ characteristics of different pavement designs. Environmental factors have a significant impact on the mechanical properties of asphalt mixtures, and temperature is one of the most important environmental factors that affects these properties.

Since pavement is a viscoelastic material, its structural or load-carrying capacity varies with temperature; therefore, accurate prediction of the temperature distribution within the pavement structure is crucial. To ascertain the in-situ strength characteristics of flexible pavement, one must predict the temperature distribution within the HMA layers. To ascertain the pavement temperature profile, one must comprehend the influence of seasonal variations and ambient temperature in order to quantify the effects of heating and cooling trends within the pavement structure.

Recent studies have proved that by knowing the maximum or minimum ambient temperatures, the depth at which the pavement temperature is desired, and the day of year at a specific location, the asphalt pavement's maximum and minimum temperatures can be predicted.

II. MATERIALS AND METHODS

A. MATERIALS

The required daily surface air temperature data (January 1990 to December 2021) were obtained at Abuja and Zaria NIMET meteorological stations, and used in determining the annual maximum and minimum air temperatures. These annual maximum and minimum air temperatures were used to model or predict the maximum and minimum asphalt pavement temperatures on Abuja to Kaduna railway line.

B. METHODS

Because asphalt mixtures change their properties with temperature, exhibiting more rigid behaviour at lower temperatures while showing a softer response when the temperatures increase (Rose et al., 2011), the influence of this parameter on the behaviour of asphaltic sub-ballast was evaluated in this study. This assessment was conducted to determine the feasibility of using the sub-ballast under the range of temperatures that this material can be expected to withstand when used in railway tracks, including both standard and adverse conditions.

- **Determination of the maximum and minimum air temperatures for each year** (the average hottest 7-day consecutive maximum air temperature for each year was calculated. Then the highest value from year 1990-2021 was taken as the maximum air temperature), and the minimum air temperature for each year (the coldest one-day temperature for each year was determined. Then, the lowest value from year 1990-2021 was taken as the minimum air temperature). (Results are shown in Fig.s 2 - 7).

- **Determination of the maximum and minimum asphalt pavement temperatures** (average hottest seven day consecutive maximum air temperature for each year) was converted to asphalt pavement temperatures at Abuja and Zaria by substituting it in the Diefendefer regression equation at three different depths (Fig. 1) (Gedafa et al. 2014, Li et al. 2018) (Results are shown in Table 1).

The Diefenderfer Regression Models:

$$Tpmax = 3.2935 + 0.6356\ max + 0.1061Y - 27.7975d_b \quad \text{......................Eq. 1a}$$

where Tpmax – Maximum air temperature, Y – Day of the year that produced the maximum air temperature (1-365), d_b – The depths (top, middle, and bottom).

- **Calculations to determine the maximum pavement temperatures at Abuja and Zaria:**

The maximum pavement temperature at Abuja

Maximum air temperature = 32.09 ^{0}C, d_b= 0.31, 0.40, 0.49 (m), Y = 116

Substituting the values in Table 1, into Equation 1a

$$Tpmax = 3.2935 + 0.6356\ max + 0.1061Y – 27.7975d_b$$

@ 0.31m; Tpmax = 3.2935 + 0.6356 (32.09) + 0.1061(116) – 27.7975db

= 3.2935 + 20.396404+ 12. 3076 – 8.617225 = 27.38 ^{0}c

@ 0.40m; Tpmax = 3.2935 + 20.396404 +12.3076 -11.119 = 24.88 ^{0}C

@0.49m; Tpmax = 3.2935 +20.396404 +12.3076 – 13.620775 = 22.38 ^{0}C (Results shown in Table 2).

The maximum pavement temperature in Zaria

Substituting the values in Table 1, into Equation 1b,

Maximum air temperature = 32.09 ^{0}C, d_b= 0.31, 0.40, 0.49 (m), Y = 108

$$Tpmax = 3.2935 + 0.6356\ max + 0.1061Y – 27.7975d_b \text{……….......Eq. 1b}$$

@0.31m; Tpmax = 3.2935 + 0.6356 (32.32) + 0.1061 (108) -27.7975(0.31) = 26.68 ^{0}C

@0.40m; Tpmax = 3.2935 + 0.6356 (32.32) + 0.1061 (108) -27.7975 (0.40m) = 24.18 ^{0}C

@0..Tpmax = 3.2935 + 0.6356 (32.32) +0.1071 (108) -27.7975 (0.49) = 21.67 ^{0}C (Results shown in Table 2).

- Determination of Minimum air temperature (one-day minimum temperature in a year) and its conversion to asphalt pavement temperatures at Abuja and Zaria by substituting it in the Diefenderfer regression equation at three different depths (Gedafa et al. 2014, Li et al. 2018) (Table 1).

$$\mathbf{Tpmin = 1.6472 + 0.6504\ min + 0.0861Y + 7.2385d_b} \text{………………Eq. 2a}$$

where TpMin – Minimum air temperature, Y – Day of the year that produced the minimum air temperature (1-365), d_b – The depths (top, middle, and bottom).

- **Calculations to determine the minimum pavement temperatures at Abuja and Zaria:**

The minimum pavement temperature at Abuja

Substituting the values in Table 1, into Equation 2a,

Minimum air temperature = 18.32 ^{0}C, db = 0.31, 0.40, 0.49 (m), Y = 5

From equation 2a,

$$Tpmin = 1.6472 + 0.6504\ min + 0.0861Y + 7.2385$$

@0.31m; Tpmin = 1.6472 + 0.650 (max) + 0.0861Y + 7.2385db

= 1.6472 + 0.650 (18.32) + 0.0861 (5) + 7.2385 (0.31)

1.6472 +11.915328 + 0.4305 + 2.243935 = 16.24 ^{0}C

@0.40m; Tpmin = 1.6472 + 11.915328 + 0.4305 +2.8954 = 16.89 ^{0}C

@ 0.49M; Tpmin = 1.6472 + 11.915328 + 0.4305 + 3.546865 = 17.54 ^{0}C (Results shown in Table 2)

The minimum pavement temperature in Zaria

Substituting the values in Table 1, into Equation 2b,

Tmin = 13.60 ^{0}C, db = 0.31, 0.40, 0.49 (m), Y =7

Tpmin = 1.6472 + 0.6504 min + 0.0861Y + 7.2385d…………….Eq. 2b

@0.31m, Tpmin = 1.6472 + 0.6504 (13.60) +0.0861 (7) +7 2385 (0.31) = 13.34 ^{0}C

@0.40m, Tpmin = 1.6472 + 0.6504 (13.60) +0.0861 (7) +7.2385 (0.40) = 13.99 ^{0}C

@0.49m, Tpmin = 1.6472 + 0.6504 (13.60) +0.0861 (7) +7.2385 (0.49) = 14.64 ^{0}C (Results shown in Table 2).

- Determination of Average Maximum Asphalt Pavement Temperature recorded at mid-depths was taken as the maximum asphalt pavement temperature (Mohsen et al. 2019).

24.88 ^{0}C + 24.18 ^{0}C =24.53 ^{0}C (Result shown in Table 3).

- **Determination of Average** Minimum Asphalt Pavement Temperature recorded at mid-depths (As contained in Fig.1) was taken as the minimum asphalt pavement temperature (Mohsen et al. 2019) (Results are shown in Table 3).

16.89 ^{0}C + 13.99 ^{0}C = 15.44 ^{0}C.

III. RESULTS AND DISCUSSION

A. RESULTS

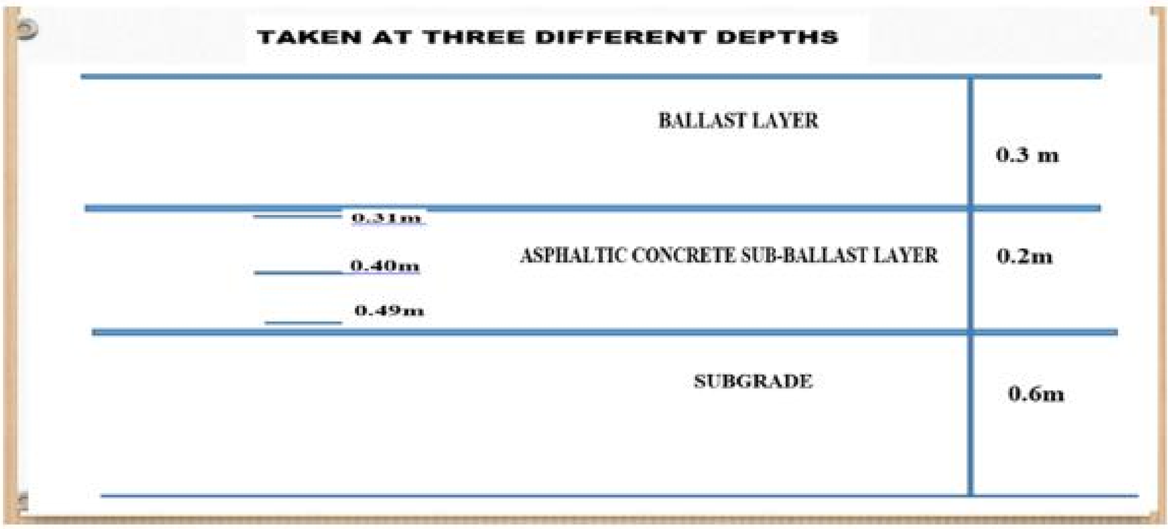

Fig. 1. Diagram showing different depths below the surface where asphalt pavement temperature is desired.

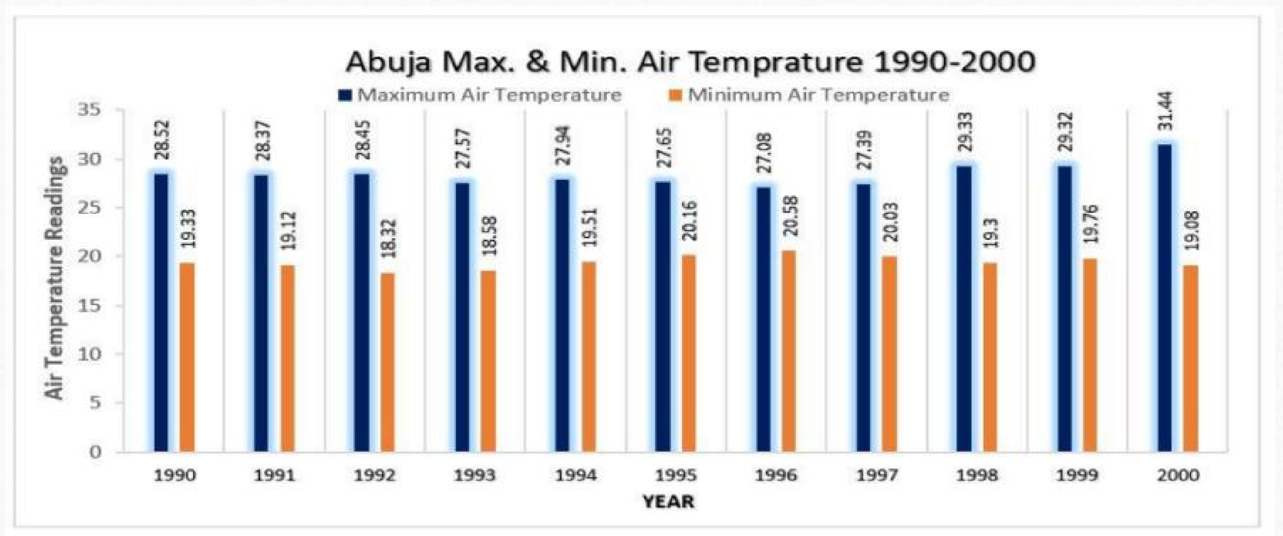

Fig. 2. Abuja Maximum and Minimum Air Temperatures from 1990 – 2000

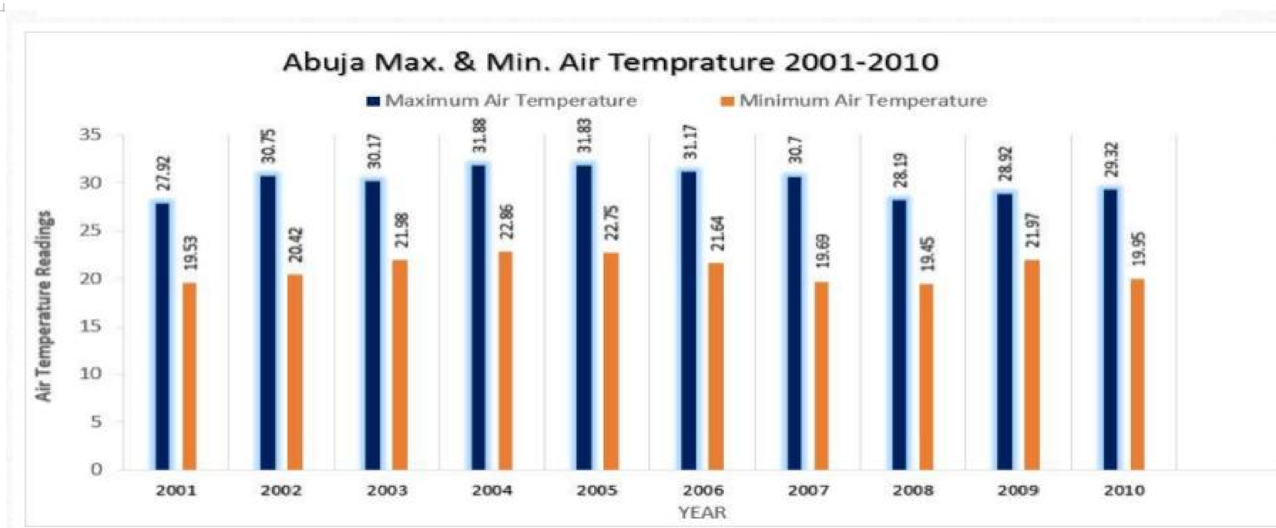

Fig. 3. Abuja Maximum and Minimum Air Temperatures from 2001 – 2010

Fig. 4. Abuja Maximum and Minimum Air Temperatures from 2011 - 2021

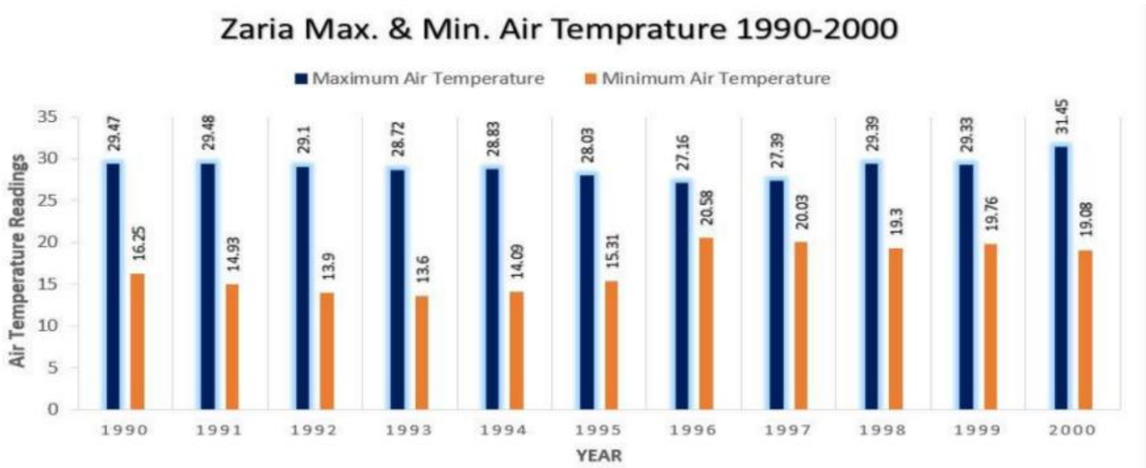

Fig. 5. Zaria Maximum and Minimum Air Temperatures from 1990 – 2000

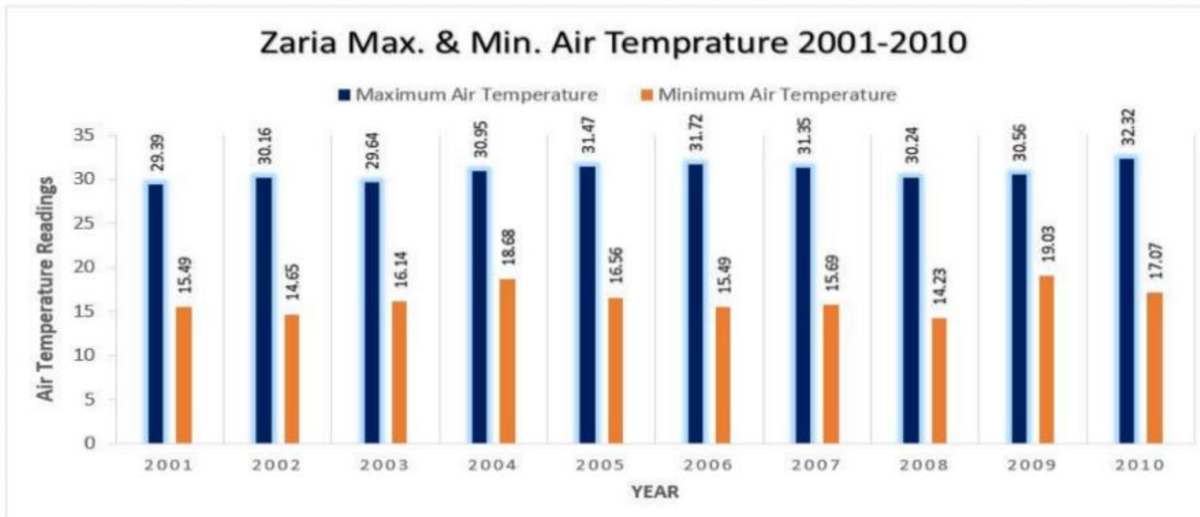

Fig. 6. Zaria Maximum and Minimum Air Temperatures from 2001 – 2010.

Table 1. Summary of Maximum and Minimum Air Temperatures at Abuja and Zaria Weather Stations.

Abuja Weather Station	Maximum Air Temperature (^{0}C)	Minimum Air Temperature (^{0}C)
	32.09	18.32
Zaria Weather Station	Maximum Air Temperature (^{0}C)	Minimum Air Temperature (^{0}C)
	32.32	13.60

Table 2. Values of predicted maximum and minimum asphalt pavement temperatures at Abuja and Zaria.

Abuja	0.31 m	**0.40 m**	0.49 m
Maximum	27.38	24.88	22.38
Minimum	16.24	16.89	17.54
Zaria	0.31 m	0.40 m	0.49 m
Maximum	26.68	24.18	21.67
Minimum	13.34	13.99	14.64

Table 3. Average Maximum and Minimum Asphalt Pavement Temperatures at Abuja and Zaria.

Maximum Asphalt Pavement Temperature	24.53 ^{0}C
Minimum Asphalt Pavement Temperature	15.44 ^{0}C

B. DISCUSSIONS

The model developed with the objective of predicting pavement temperature at any depth is based on the regression data analysis. Regression equations are formed to predict maximum and minimum pavement temperatures at any depth, depending on the maximum and minimum surface pavement temperatures and depth.

In this study, the maximum air temperature at Abuja was 32.09 ^{0}C and this was recorded in the year 2016, while the minimum air temperature was 18.32 ^{0}C and it was recorded in the year 1992.The maximum air temperature recorded at Zaria was 32.32 ^{0}C in the year 2010, while the minimum air temperature recorded was 13.60 ^{0}C in the year 1993. These records show that Zaria has higher maximum air temperature and therefore hotter than Abuja during the dry season, and it has lower minimum air temperature than Abuja and therefore colder during the rainy season.

IV. CONCLUSION

The results of pavement temperature variations at Abuja and Zaria (Table 3) in Nigeria reveal a continuous variability that is seasonally dependent on each of the years. In general, the temperatures were observed to be higher in the north western parts of the country than in the north central parts. This could be due to the consequence of the nearby Sahara desert, which has less cloud cover and is therefore more exposed to solar irradiance.

The models are useful for determining the range of pavement temperatures. Based on the results obtained by this research, it is obvious that the models will perform well in predicting the temperature of flexible pavements at various depths in tropical and subtropical climate conditions.

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