PalArch's Journal of Archaeology of Egypt / Egyptology

Development of Asphalt Pavement Temperature Models for Mediterranean Climate Condition

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Adwan Ibrahim A. I, Nur Izzi Md. Yusoff, Abdalrhman Milad: Development of Asphalt Pavement Temperature Models for Mediterranean Climate Condition -- Palarch's Journal Of Archaeology Of Egypt/Egyptology 17(9). ISSN 1567-214x

Keywords: Asphalt Pavement Temperature; MLR; Prediction moded; Air temperature; Temperature Variation.

ABSTRACT

This paper examines the models for predicting pavement temperatures at specific depths and formulates new models for the four seasons by using Multiple Linear Regression (MLR) to predict pavement temperature by using specific depths, time, and air temperature as the independent variables. The dataset for this study contains 7200 measured pavement temperatures. Thermal instruments were used to measure asphalt pavement temperature and other variables every two hours during the four seasons of the year in an attempt to model pavement temperature by utilising MLR. The prediction aims to establish a pavement temperatures model for the four seasons. Furthermore, the regression square (R2) values predicted by the MLR model are 0.84, 0.83, 0.84 and 0.92 for the summer, winter, spring, and autumn, respectively. All the models presented in this study have a significantly high coefficient of correlation. The models were validated using the data collected in the Gaza strip for the period from March 2012 to February 2013, and the results are satisfactory. Therefore, the resulting models can be used to predict asphalt temperature at varying depths and time.

1. Introduction

Asphalt concrete is the upper layer of a flexible pavement structure and is the most important layer as it is the primary determinant of the performance of flexible pavements. Al-Suhaibani, Sharaf and Al-Abdullatif, (1997). Climate impact is one of the critical factors causing the deterioration of flexible pavements, where thermal factors are induced by high pavement temperature

Alkaissi, (2020). Temperature has a strong influence on the performance of asphalt pavements (Chao and Jinxi, 2018; Verani et al., 2020). Heat distribution is a critical factor in the structural design of pavements and has a significant effect on the indirect tensile stiffness modulus (ITSM). Aggregate binder is very temperature-dependent (Alawi and Helal, 2014). Temperature variation and thermal stress are of significant interest to engineers who are concerned with the formation of cracks under different traffic load conditions (Al-Sanea, 1995). The climate of a particular region is influenced by latitude, depending on whether the region has a tropical, sub-tropical, moderate or cold climate (Ariawan, Subagio and Setiadji, 2015a). In general, Bituminous materials are rheologic by nature, which means that their stress-strain relationship is both time and temperature-dependent. Such a relationship is considered the stiffness of the mix and approaches elastic modulus at high loading and low temperatures (Al-Suhaibani, Sharaf and Al-Abdullatif, 1997 and .Alkaissi, 2020). Pavement temperature ranges between 10 and 65 ^{o}C, and this causes several common types of pavement distress, such as rutting and bleeding at high temperatures and fatigue cracking at low temperatures Milad et al.(2018); Nivitha and Krishnan (2014). The difference in pavement temperature with location, time (daily and seasonal), and depth is significant in determining the physical properties of the asphalt and the expected pavement performance (Hassan et al., 2004; Hermansson, 2004; Nivitha and Krishnan, 2014). Accurate prediction of the temperatures of asphalt pavement layers during different seasons is important to engineers and researchers since this information is critical in designing a rapid and low-cost method for evaluating pavement performance at any time and in any location (Alavi, Pouranian and Hajj, 2014). Several approaches have been proposed for predicting asphalt pavement temperature (Ariawan et al., 2015a).

Barber (1957) is one of the first researchers to develop and calculate the internal temperature profile of maximum asphalt pavement temperature using the thermal conductivity model. Rumney and Jimenez (1970) proposed a nomograph model for predicting the maximum temperature of asphalt pavements at a depth of 50 mm in a hot desert climate. Dempsey and Thompson (1970) used a 1-D heat transfer model and finite element method to improve numerical simulation based on the heat transfer theory and its ability to achieve a balance between the surface layer and other layers of asphalt pavement. (D. A. Anderson et al., 1994) investigated four types of asphalt pavements in western Canada by performing two trial regressions and using theoretical methods to determine the pavements' performance in low-temperature climate. Lytton et al., (1990) developed an enhanced integrated climatic model (EICM) for predicting the temperature of the pavement caused by climate change. The user may set the temperature and rainfall parameters to be as severe as required. In 1987 the Strategic Highway Research Program (SHRP) developed the Long-Term Pavement Performance Program (LTTP) as a 20-year research project to improve pavement characterisation at a particular site. Sixty-one LTPP sites were chosen to be a part of the Seasonal Monitoring Program (SMP) to address the challenges of studying climatic conditions precisely (Diefenderfer et al., 2003; Kennedy et al., 1994; Matic et al., 2013; Sun, 2016)

Several pavement temperature models were developed during the initial SHRP testing, and the SMP data facilitates the selection of the appropriate asphalt binder performance grade, which depends on the weather at a particular location. The pavement data gathered during the LTTP facilitates the selection of an appropriate asphalt pavement Bosscher et al., (1998); Diefenderfer et al., (2003, 2006); Lukanen, Han and Skok (1998); Mohseni (1998); Mohseni and Symons (1998). Solaimanian and Kennedy (1993) used energy transfer theory and heat theory to develop a validation model for the summer based on the highest pavement surface temperature in combination with the measured hourly solar radiation and air temperature. (Hermansson, 2000**)** developed a model for predicting pavement temperature at specific depths of pavement layers in the summer. Yavuzturk and Ksaibati (2002) used a two-dimensional Finite Element Method (FEM) to describe the thermal response of multi-layer asphalt pavements towards environmental conditions on an hour-by-hour basis. However, this model cannot be used with ease by pavement engineers. Since then, researchers have also developed models for the winter season Hermansson (2004).

Hassan et al. (2008) developed a regression relationship of the environmental conditions used to predict the high and low temperatures of asphalt pavement in Oman. Minhoto, Pais and Pereira (2006**)** created a FEM for determining the temperature of asphalt rubber pavements. The model was verified using the hourly solar radiation, air temperature, and average daily wind speed obtained from a meteorological center. Velasquez et al. (2008) proposed an MLR equation for predicting the temperature of flexible pavements by using the least square method. Wang (2011) used the thermodynamic properties of HMA to improve an algorithm as a function of surface temperature and depth to obtain a one-dimensional prediction model (1D) in a multi-layer system. Khadrawi, Al-Shyyab and Abo-Qudais (2011**)** developed a thermal transfer model for predicting HMA transit thermal conductivity based on solar radiation, thermal characteristics of asphalt concrete and peripheral and surface temperatures. MATIĆ et al. (2012) developed a model for predicting pavement temperature at a particular depth by using air temperature and other climate parameters. Islam, Ahsan and Tarefder (2015) developed a series of statistical models for predicting the average, minimum, and maximum pavement temperatures by employing the field-work data gathered from a road fitted with devices in New Mexico. Taamnehb (2016) conducted a study in Ashtabula County, Ohio, and used regression models to make a very accurate prediction of the daily maximum and minimum pavement temperatures. Khan, Islam and Rafiqul (2016) developed and validated a regression profile for determining the mean temperature in asphalt pavement layers. In Canada, Asefzadeh, Hashemian and Bayat (2017) collected data from a field-based test for two years. The researchers then performed a stepwise regression analysis to develop regression models based on the deletion of ineffective factors with a high coefficient of correlation. Li et al. (2018) developed a statistical model for predicting temperature at depths of more than 30cm. A temperature prediction model as a function of air temperature, depth and solar radiation in cumulative time was then developed.

A comparison of the categories mentioned above of research methods indicates that theoretical and analytical methods can demonstrate how different climatic factors influence the temperature distribution of asphalt pavements. These methods have reliable predictability and a wide range of applications. However, the developed equations are too complicated and require a large number of variables to predict pavement temperatures. Therefore, these models are not suitable for practical routine use (Asefzadeh et al., 2017). In recent years, many researchers have employed statistical methods to develop regression prediction models considering that statistical methods are relatively easy to develop and are more effective than prediction models. However, the current research is utilising different modern statistical methods to determine temperature distribution and predict asphalt pavement temperature (Li et al., 2018). MLR was used to model the value of the dependent variables, i.e., asphalt pavement temperature, based on its linear relationship with multiple predictors such as air temperature, depth and time, and environmental factors (Taddesse, 2013). The accuracy of an analytical method is established only within the range of the original data used to develop the (MLR) models (Xu, Dan and Li, 2017). Hence, this study aims to determine the effect of air temperature change on asphalt pavement during the four seasons. This is the first attempt to develop pavement temperature prediction models for Mediterranean climate conditions using MLR.

2. METHODOLOGY

The development of MLR consists of three steps. In the first step, the test site and the data sorting for the prediction model were determined. The second step is the development of the temperature profile prediction model. MLR analyses were carried out to define the relationship between measured climate data and measured pavement temperature. The third step involves the development and validation of the MLR models as well as the determination of temperatures at different depths by using the most appropriate model. MLR equation models can be utilised to calculate the predicted model for pavement temperature concerning depth in the pavement, air temperature, and time. The development of model requires a large amount of data to be gathered in the Gaza strip throughout the four seasons, and more than 7200 measurements were made. Three variables were supposed in a linear relation by taking into account the effect of pavement depths, time, and air temperature. In this study, the prediction of asphalt temperature was made for different depths, with greater focus being given to the summer and winter seasons since the maximum and minimum temperatures occur during these seasons. A thermocouple was used to record the temperature at three different depths of 0, 2, 5.5 and 7 cm. The data for air temperature, asphalt pavement, and time was used to develop the temperature model

Observation Location and Data Acquisition

The pavement temperature measurement was made in the Beit Hanoun region in the Gaza Strip, as shown in Figure. 1. The measurements were made manually using the HI-935005 device (Hanna Instrument, 2002). The sensor was placed at a specific depth in the asphalt pavement and touched the bottom of the hole. The time is taken to measure the temperature at each hole until a stable temperature reading was obtained 5 minutes; this is to ensure that an accurate pavement temperature was obtained. Since asphalt pavement temperature varies significantly across the depth of the pavement, different pavement depths have been chosen to record the temperature. The holes must be free of sand, aggregates and water during temperature measurement to ensure that impurities do not influence the measured temperature. For this reason, the holes are tightly closed with a convenient stopper after completing each measurement process to prevent pollutants from entering the hole and reduce the impact of sunlight and other climatic factors, such as rain and dust on asphalt pavement hole. The diameter and length of hole cover are smaller than those of hole to ensure that it does not touch the wall or the bottom of the hole. The total thickness of the asphalt layers ranges from 60 to 90 mm, and a decision was made to measure the temperature at the bottom, middle and upper parts of the pavement. Multiple holes were drilled to measure the thermal gradient (Gedafa, Hossain and Romanoschi, 2014). A thermometer was used to measure the air temperature about 1.5 m above the surface of asphalt pavement. Measurements were made every two hours, between 6.00 am to 12.00 am the next day. The asphalt pavement temperature was measured at the surface and three different depths of 2, 5.5 and 7 cm (Figure 2). Shows a detailed illustration of the measurement depths. The temperature data were collected from March 2012 to February 2013. The measurement locations must be determined, and the conditions of the data collection site must be known before performing the analysis (Li et al., 2018). The data were obtained from data measuring stations in the Gaza strip and comprises three independent variables (air temperature, time and depth) and one dependent variable (asphalt pavement temperature).

Multiple Linear Regression (MLR) Models

The main advantage of using a multiple regression model is its ability to determine the relative influence of one or more predictor variables on the criterion value. The current study introduces temperature as an hourly measurement based on the differences in seasonal prediction. In this model, stepwise regression analysis was used to determine and identify the value of variables that add considerable explanatory power to each regression model. The results of one way ANOVA, such as RMSE, were used to evaluate the pavement temperature prediction model at different time and depths. RMSE is inversely correlated with the model's accuracy. However, the coefficient of determination (R^2) is directly correlated with the model's accuracy to develop a model for prediction of Multiple Linear Regression based on pavement temperature. Firstly, It is necessary to have the pavement temperature database and a few other related parameters .The data for pavement temperature and other relevant data were collected from the sites chosen for the pavement temperature measurement. The formula for (MLR) was determined using equation 1, where i=n observations, yi=dependent variable, xi=explanatory variables, β0=y-intercept (constant term), βp=slope coefficients for each explanatory variable, and ϵ =the model's error term (also known as the residuals).

$$yi = \beta 0 + \beta 1xi1 + \beta 2xi2 + \ldots + \beta pxip + \epsilon$$

3. RESULTS AND DISCUSSION

Temperature Variation

Pavements are heated to varying depths during the day, and the heat seeps out at night. Thus, as can be seen in (Figures. 3 and 4), the temperature of pavement materials continually fluctuates. The (Figure 4) illustrates a winter chart for one day, which represents the seasonal behavior of air temperature and pavement temperature at various depths. The maximum air temperature occurred at around 1.00 pm and the minimum temperature occurred at about 6.00 am. However, the maximum temperature of the lower layer of flexible asphalt concrete was recorded at around 12:00 am and the minimum temperature was recorded at around 6.00 pm. The same condition was observed daily even though the maximum and minimum temperatures vary. (Figures. 3 and 4) also show that the maximum or minimum pavement temperature occurred after air temperature has reached its maximum or minimum, respectively. The average pavement temperature may occur at 8.00 pm or 1.00 am. Maximum and minimum temperatures can be used in combination with pavement depth to determine the desired asphalt grade. The correlation between pavement temperature and structural applications, such as stress-strain, wheel stress and material properties, can also be used. The determination of maximum, minimum and average temperatures may provide an understanding of the behavior of the continually changing pavement temperature. The temperature inside asphalt pavements at any depth is strongly influenced by surface temperature, air temperature and pavement thickness.
Stepwise regression for MLR was used to develop temperature prediction models by using air temperature, depth and time as the independent variables. Stepwise regression technique for analysis was used to select and identify important variables that are likely to add significant explanatory strength to each regression equation. In stepwise regression, an increase in the value of R^2 requires two significance levels: one for adding the variables and one for removing the variables. The cutoff probability for adding variables should be less than the cutoff probability for removing variables so that the procedure does not get into an infinite loop. The relationships were plotted using air temperature as the independent variable and asphalt temperature with varying pavement depths and time the dependent variables, as shown in (Figure 5 a, b, c and d). The MLR models of the dependent variables and independent variables are shown in (Table 1).

Goodness-of-Fit Statistics

One-way ANOVA was carried out to validate the models developed for summer, winter, spring and autumn. The results of the ANOVA are presented in (Table 2). The P-values for all independent variables are less than 0.5 and are almost (0.000). Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted. The independent variable is influential (different from zero) and is not equal at the 95% confidence interval (CI). (Table 2) shows that the R^2 values for summer, winter, spring, and autumn are 0.843, 0.836, 0.844 and 0.922, respectively. It can be deduced that the predicted asphalt pavement temperature correlates very well with the actual temperature. The high R^2 values indicate the accuracy of the predicted asphalt temperature relative to the field data. The higher R^2 values indicate the usefulness of the models in data prediction and the ability of the model in predicting asphalt temperature using field data. The Root mean square error (RMSE) is a measurement of the difference between the values predicted by the model and the measured values. A small RMSE value indicates that the difference between the predicted and the observed value is small, thus indicating a better fit and better credibility of the model. The RMSE values for summer, winter, spring, and autumn are 0.0316, 0.0316, 0.0632 and 0.0447, respectively. These values indicate that the models are able to accurately predict asphalt pavement temperature at any depth and at any time, as shown in (Table 1).

Model Validation

The asphalt pavement temperatures measured between March 2012 and February 2013 were used to validate the developed models. The verification method employed in this study includes a plot of the predicted temperature versus the actual temperature of the pavement sections used to develop the model**.** A comparison between the measured data, which was made at the sites at different time and depths, and the predicted pavement temperatures at varying depths during the winter, summer, spring and autumn seasons shows that the models for predicting pavement temperatures are sufficiently accurate. It has been noted that the temperatures predicted by the models closely approximate the measured temperature at varying depths. The measured temperatures on the x-axis were plotted against the predicted pavement temperature on the y-axis. A 45° line was drawn through the origin to show the distribution of the measured and predicted pavement temperatures. The measured asphalt pavement temperature was compared with the predicted temperature (Figure 6 a, b, c and d). The relationship between the measured and predicted values shows an asymmetrical trend around the 45 °C diagonal line, which proves the validity of the developed model.

4. CONCLUSION

The study has provided a better comprehension of the development of temperature profile features of the statistical prediction models used to predict the daily temperature of pavement layers during the four seasons. Based on the measured asphalt pavement temperature obtained from the test site, which is expressed as a random sample of asphalt pavement, it can be concluded that the proposed models for predicting asphalt pavement temperature in Gaza are very accurate. The hourly air temperature was measured to improve the accuracy of the asphalt pavement temperature prediction in Gaza. SPSS was used to determine the regression coefficients, which were then tested for significance at the 95 % confidence level. The models achieved a good P-value of 0.000 and an excellent R^2 value of 0.922 with the inclusion of air temperature and pavement depth variables. The models are useful for determining the range of pavement temperatures. Based on the results obtained by this research, it is believed that the models will perform well in predicting the temperature of flexible pavements at various depths of the roads in Mediterranean climate conditions. Hence, verification of the model's performance is recommended by using the field data from different countries within the same region.

5. DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to Universiti Kebangsaan Malaysia for the financial support for this work through grant code No. GUP-2018-094.

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LIST OF FIGURE URES

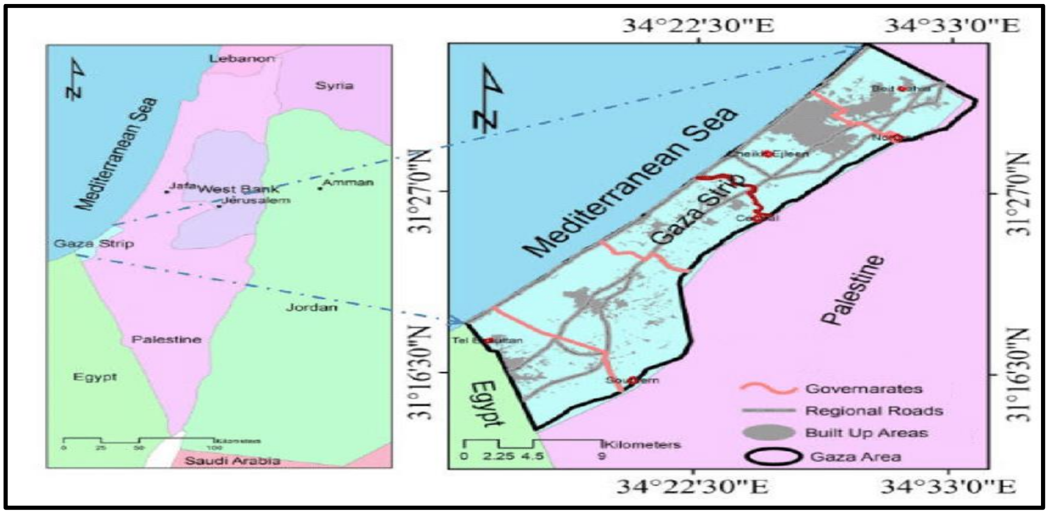


Figure (1): Location of the study area

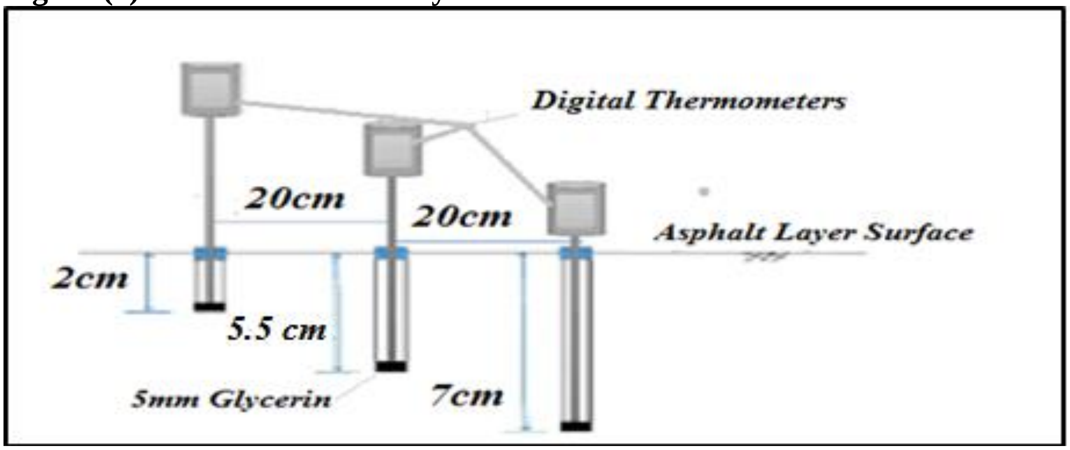


Figure (2): Measurement depths of asphalt pavement temperature

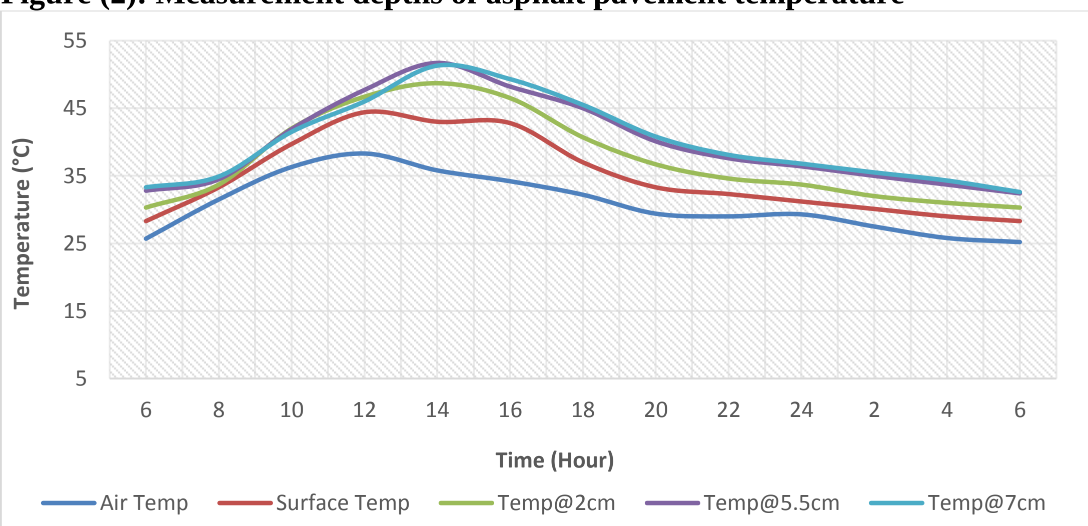


Figure (3): Temperature variation on 23rd July 2012

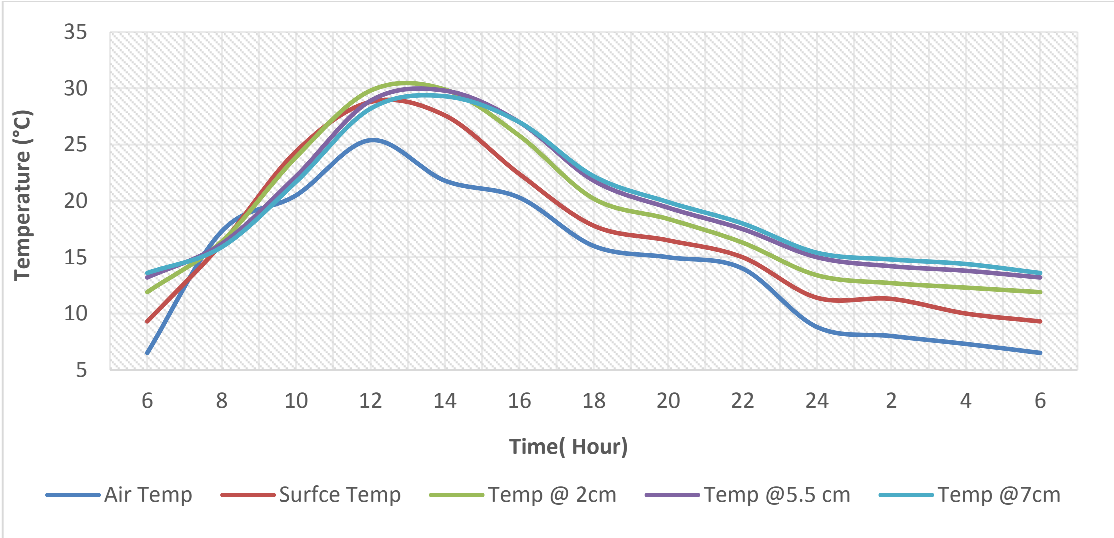
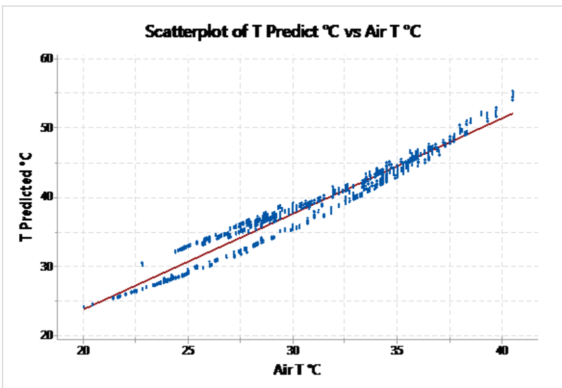
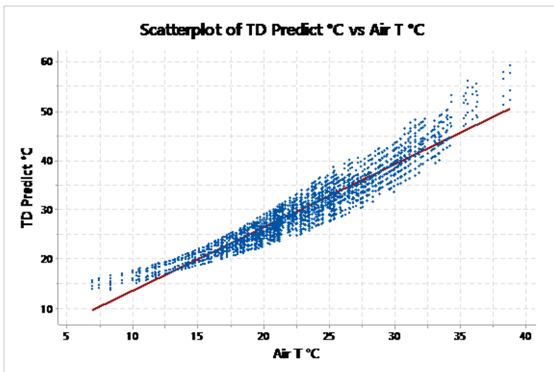


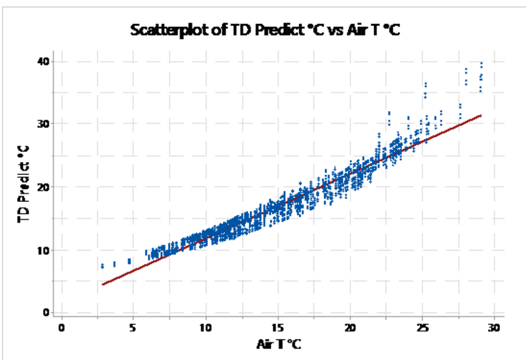
Figure (4): Temperature variation on 20th March 2012



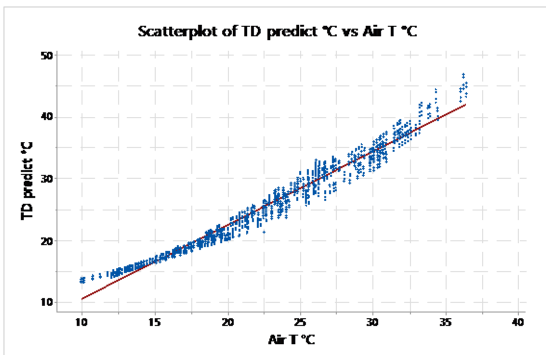
a- Scatterplot points for summer



b- Scatterplot points for winter

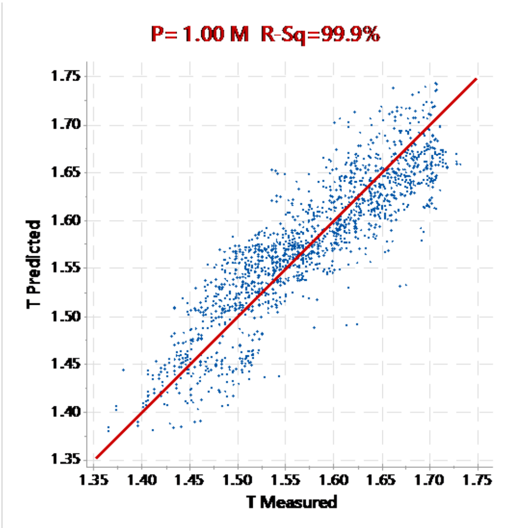


c- Scatterplot points for spring

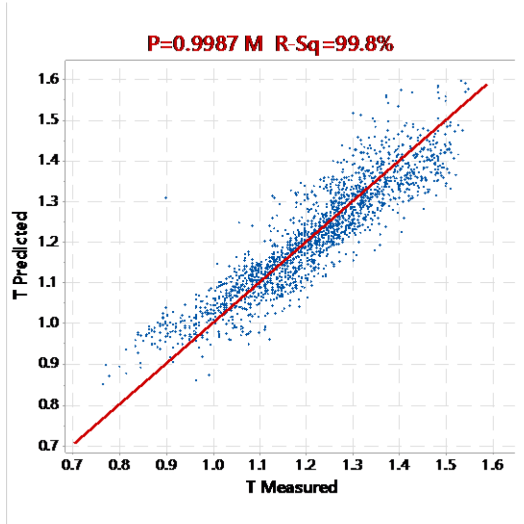


d- Scatterplot points for autumn

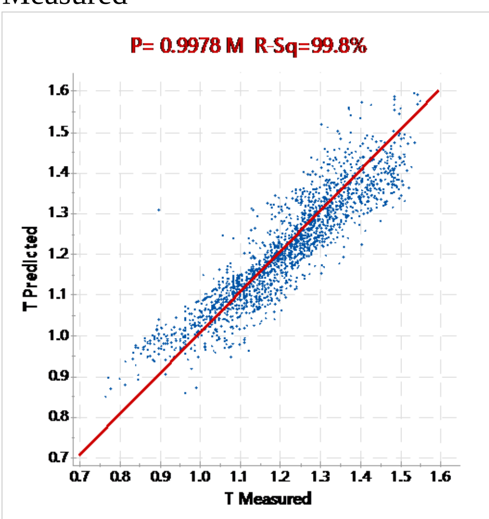
Figure (5): Scatterplot points for the four seasons at different time and depths



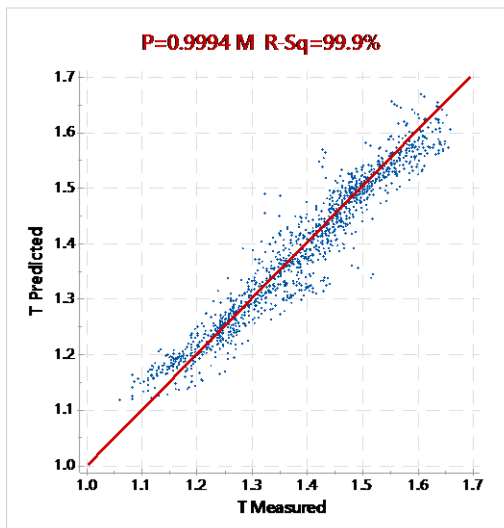
a. validation for Summer: T Predicted vs T Measured



b. validation for Winter: T Predicted vs T Measured



c. validation for Spring: T Predicted vs T Measured



d. validation for Autumn: T Predicted vs T Measured

Figure (6): Validation of the Equations Using Measured Field Data

LIST OF TABLES

Table 1. Model Development for All Seasons.

TD: Temperature at depth d (°C); A: Air Temperature (°C) d: Depth cm T: time (hour)

Season	Period	Model
Summer	21-6/22-9	logTD = 1.04202 + 0.016 A + 0.002 T +0.007d
Autumn	23-9/2 2-12	logTD = 0.97100 + 0.015877 A + 0.000385 AT + 0.003052 depth - 0.005320 T
Winter	23-12/ 20-3	logTD = 0.78399+ 0.022143 A+ 0.003997depth + 0.000347 AT
Spring	21-3/20-6	logTD = 1.0634 + 0.013544 A + 0.007740 depth + 0.000413 AT- 0.005193 T

Table 2. ANOVA of Multiple Regression Analysis Outputs for Season Equations.

Season	Model	Sum of sq.	df	SEE	R	R^2	Means SQ	F	P
Summer	Regression	(SSR)8.360	3	0.0312	0.918	0.84	(MSR)2.787	2846.11	0.0
	Residual	(SSE) 1.562	(n-2)1595				(MSE) 0.001		
	Total	(SST) 9.922	(n-1)1598						
Winter	Regression	(SSR) 35.01	3	0.060	0.916	0.83	(MSR)11.670	3316.66	0.0
	Residual	(SSE) 6.703	(n-2)1905				(MSE) 0.004		
	Total	(SST)41.713	(n-1)1908						
Spring	Regression	(SSR)29.12	4	0.0491	0.919	0.84	(MSR)7.281	3017.32	0.0
	Residual	(SSE)5.393	(n-2)2235				(MSE) 0.002		
	Total	(SST)34.517	(n-1)2239						
Autumn	Regression	(SSR)22.57	4	0.0379	0.964	0.92	(MSR)5.656	4351.06	0.0
	Residual	(SSE)1.702	(n-2)1312				(MSE) 0.001		
	Total	(SST)24.281	(n-1)1316						

Dependent variable : log TD
Predictors (Constant, A, depth, AT, time)
SSR: Sum of Squares Regression, SSE : Sum of squared residuals SST=SSR+SSE
MSR: mean square due to regression = SSR/df , MSE: mean squared error SSE/df
RMSE: Root Mean Squared Error $=\sqrt{MSE}$, n :Number of sample. R^2: (R-squared) Coefficient of Determination; SEE: Std. Error of the Estimate