Binder performance and testing

ESTIMATION OF HIGH TEMPERATURE PERFORMANCE GRADE USING RUTTING DAMAGE AND IMPROVED FUNCTIONS FOR PG VARIABILITY

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Abstract

The Superpave performance grading asphalt bitumen classification method relies on climate historical data to predict the environmental conditions for a location where the bitumen will be used. In 2005 the basis for calculating the Performance Grade high temperature (PGHT) grade changed from the use of a 7-day high temperature to a temperature determined from a damage-based approach. The damage-based temperature was then correlated to the degree-days, defined as the summation of days with a maximum temperature greater than 10 degrees Celsius in a year. Algebraic equations then linked this value to the PGHT grade with consideration of the rut depth and latitude. The variation in the PGHT grade was related to latitude via a power law equation. However, this functional fit is only valid over a limited range, greater than 20 degrees of latitude and less than approximately 50 degrees of latitude. This does not create any problems for the USA bitumen grades since the majority of the country lies within this range (excluding Alaska, Hawaii and some tropical territories). However, when applying this power law function to other regions, for example to countries in Northern Europe, Canada or Russia, which are mainly above 50 degrees latitude, as well as other regions of the globe such as the Middle East, etc., problems arise. Work has been conducted to develop a functional fit to the data presented by earlier workers using a geometric law that better describes the variation of the climate coefficient of variation with latitude. A nonlinear optimization method was used to fit an asymmetric sigmoid describing the PGHT coefficient of variability. Updated equations calibrated for the European continent are provided for estimation of PGHT grade. This methodology is implemented in software that calculates the PGHT for any location in the world for which there is available climate data of sufficient quality and quantity.

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1. INTRODUCTION

The Superpave bitumen performance grading methodology was developed as part of the SHRP project [1] and implemented using a climate-based approach for defining temperatures of testing for rheological parameters [2, 3]. More recently the temperatures used for defining two distinct parameters, a damaged weight high pavement temperature and a minimum pavement temperature were changed using a damage weighted method [4]. These represent the higher and lower temperatures to which the pavement will be exposed and is determined by a statistical analysis of the data regarding the last twenty years for the location for which the bitumen grade is to be determined. The bitumen's and mixture's properties must therefore relate to these two parameters in order to guarantee an adequate performance grade is specified.

The variable that determines the low temperature, designated as T_{PAV}, is defined as follows:

$$T_{PAV} = -1.56 + 0.72\ T_{air} - 0.004\ Lat^2 + 6.26\ \log_{10}(H+25) - z\ (4.4 + 0.52\ Sair^2)^{0.5} \qquad (1)$$

where:

T_{PAV}	Low pavement temperature below surface, ºC
Tair	Absolute low air temperature yearly average, ºC
Lat	Latitude of the section, degrees
H	Depth to surface, mm
S_{air}	Standard deviation of the mean low air temperature, º C
z	Standard normal dist. table, z = 2.055 for 98% reliability

The variable that determines the high temperature, is designated as P_{GD}, and is defined as follows:

$$P_{GD} = 48.2 + 14\ DD - 0.96\ DD^2 - 2\ RD \qquad (2)$$

where:

P_{GD}	PG Damage at a Rut Depth
DD	20 year period days > 10 °C (x 1000)
RD	Rut depth (between 5 and 13 mm)

One of the key factors in establishing these two distinct parameters is the site's latitude, given the fact that with its variation both the number of daylight hours and the average/maximum temperatures will change significantly.

The current Superpave methodology applies a latitude correlated statistical adjustment to the higher magnitude temperatures that are determined by the mathematical analysis of the historical climate data in order to increase the reliability of the calculated higher temperature value. To this purpose, the yearly P_{GD} coefficient of variation (CVPG) is calculated by the following expression:

$$CVPG = 0.000034(Lat-20)^2 * RD^2 \qquad (3)$$

where:

CVPG	Yearly P_{GD} Coefficient of Variation, %
Lat	Latitude of Site, Degrees

The performance grade high temperature (at a reliability), is then determined as:

$$PGrel = P_{GD} + Z * P_{GD} * CVPG/100 \qquad (4)$$

where:

PGrel	P_{GD} at a reliability, ºC
Z	2.055, from Standard Probability Table for 98% reliability

As noted, the SuperPave methodology is a product of the Strategic Highway Research Program (SHRP) which was a major United States of America (USA) congress funded study whose goal was to find solutions to the problems that highway agencies in that country face and consider as being of major priority [1, 2, 3]. Naturally, the research efforts of this program were based on the USA experience and geographical territory. An example of this is the fact that the equation (3) was calibrated and designed to predict the coefficient of variation between 20º and 50º latitude, boundaries that encompass the continental USA except the state of Alaska and part of the state of Hawaii [4]. The functional fit, which includes a latitude term which is squared does not extrapolate to locations beyond the range for which it was developed and if used outside these bounds can produce unreasonable values for CVPG.

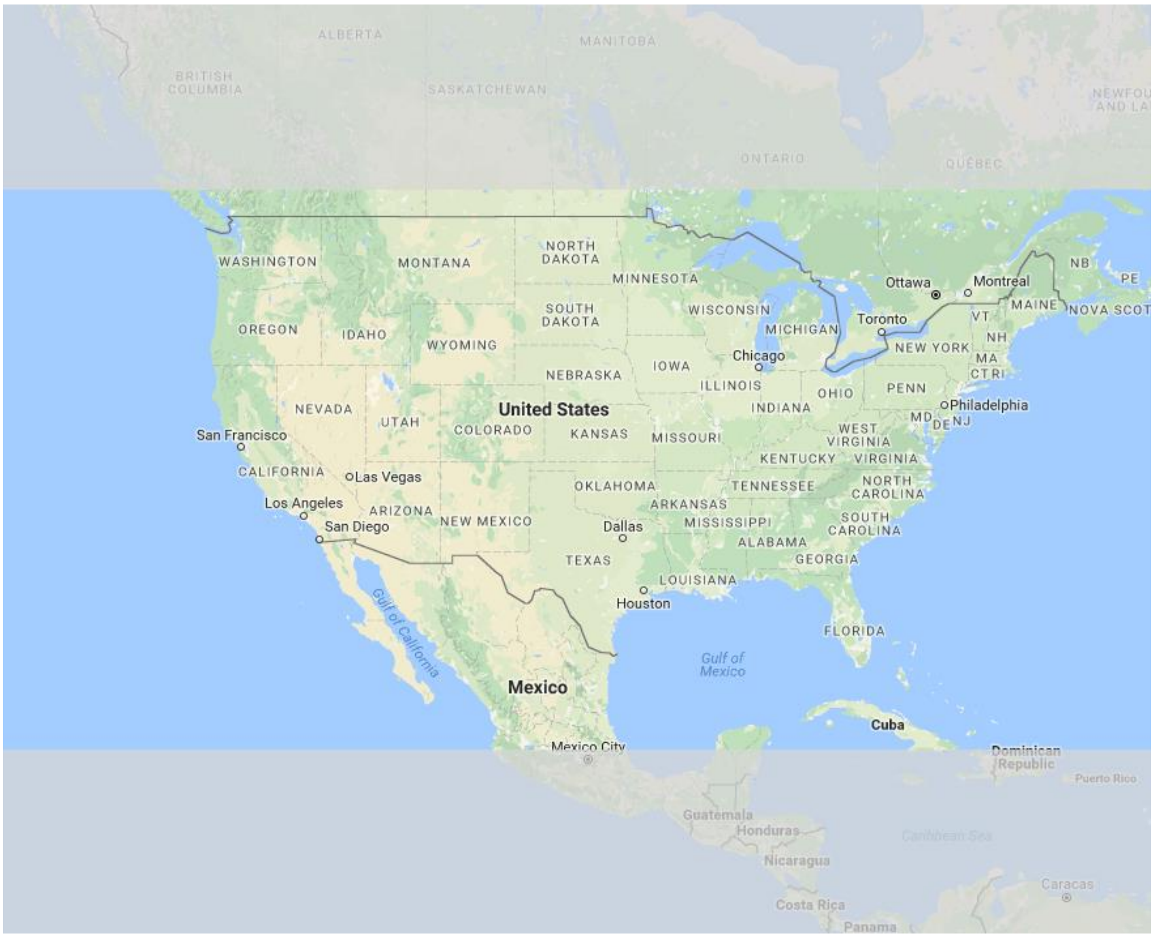


Figure 1: North American territory covered by the CVPG function

2. DATA COLLECTION AND CLASSIFICATION

2.1. Spatial and temporal scope

In order to define a functional fit that is well adapted to represent the Superpave high temperature performance grade coefficient of variation for the European continent, it is first of all necessary to obtain and to process climatic data that is geographically representative of the targeted landmass, and that is also simultaneously a sample of adequate statistical value and significance. It is of added interest that the functional fit to be determined can be applied to as wide a range of latitudes as possible.

The latitudes in the European continent vary between the 29º of the Spanish Canary Islands in the south to over 70º in Norway, Finland and the Russian Federation to the north. The authors decided to include in this analysis the French overseas territories of Guadeloupe, Martinique, French Guiana, Reunion and Mayotte Islands in order to obtain as much data as possible for latitudes between 0º and 29º and to anchor the functional fit at lower latitudes; in the case of southern hemisphere locations, the absolute value of latitude is to be considered. It was also determined to deliberate the limit of the Arctic Circle (66.56º latitude) as the upper boundary of the data to be accepted.

To obtain data for such a wide variety of locations, the National Oceanic and Atmospheric Administration (NOAA) weather station database available online at https://www.ncdc.noaa.gov/cdo-web/datatools/selectlocation was consulted. From this platform, information was acquired on the maximum, average (when existing) and minimum temperatures that were recorded each day in the period that spans from January 1st January 1998 to 31st December 2017, accounting for exactly 20 years of information. This data was obtained for all European countries; the number of available weather stations is 1422.

2.2. Software development

In order to process the data that relates to the referred weather stations and time span, a software designated as STAT-TEMP was developed. This computer program aims at accomplishing two main objectives:

- To implement the SuperPave performance grading procedure automatically for any given location in the world for which climate data is available
- To analyse the climate historical records and produce the intended results and as much related information as possible, while separating adequate data from incomplete or erroneous information

Given the large amount of information that results of the analysis process, and to facilitate the interpretation of the calculated parameters, the software was added with the capability of generating graphic outputs. Figure 2 is one example of such outputs, making it possible to visualize the location of the available weather stations (apart from the French overseas territories), but also to differentiate each location accordingly to a STAT-TEMP determined parameter expressed in terms of percentiles, in this specific case, the Performance Grade low temperature T_{PAV}. As expected, the main observed tendency is that the T_{PAV} parameter magnitude evolves in an inverse order in regard to latitude.

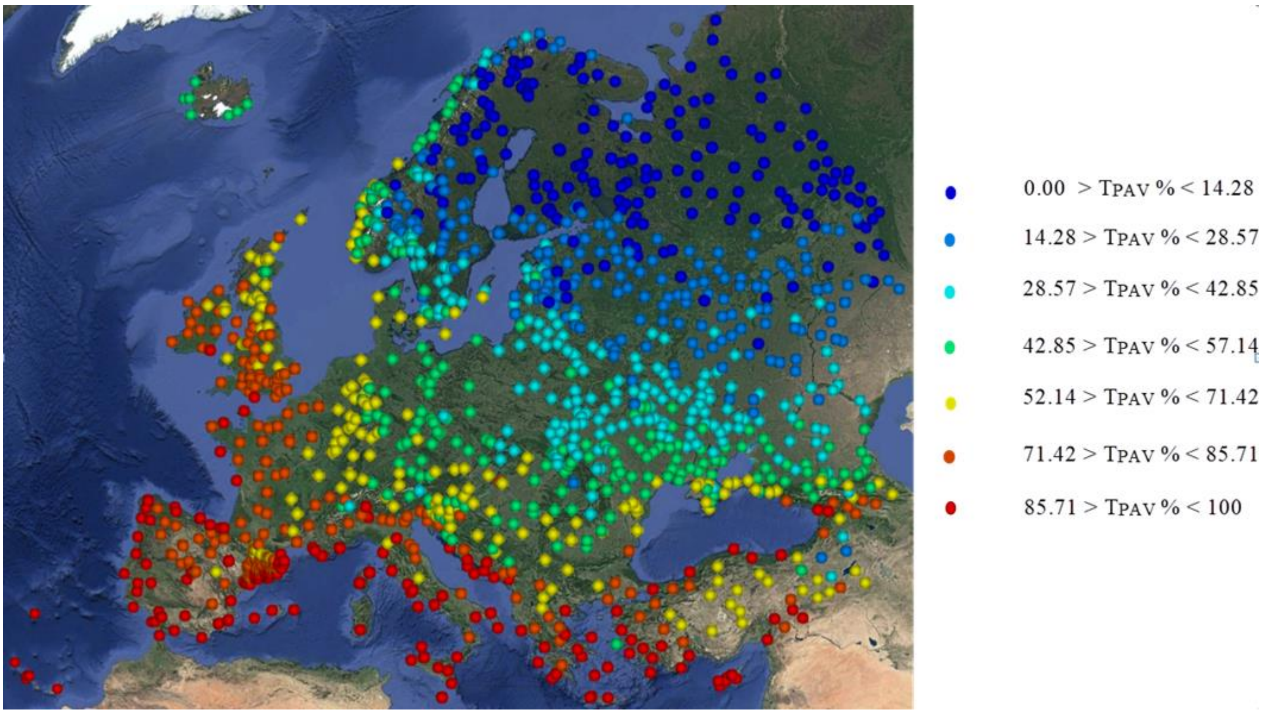
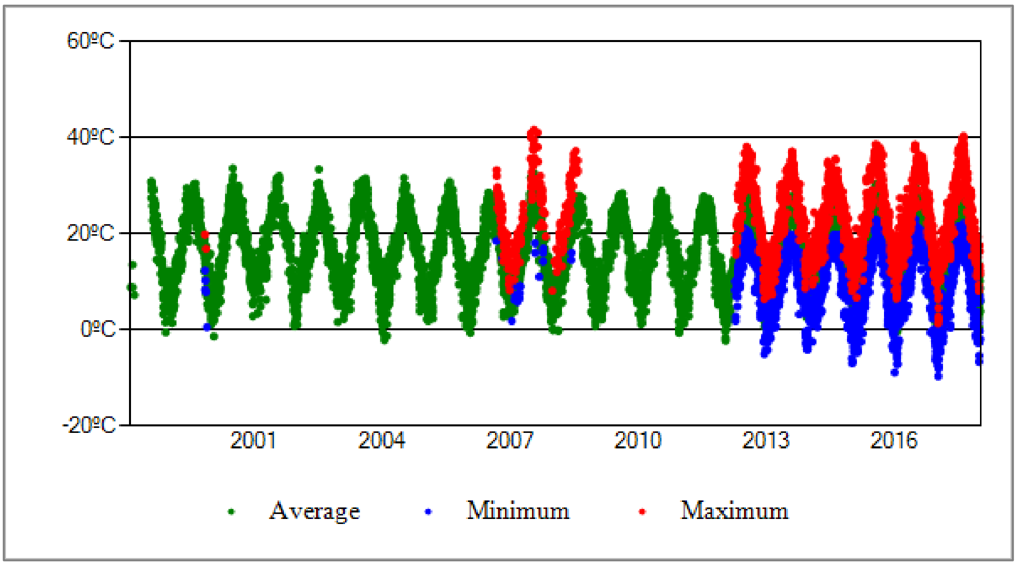


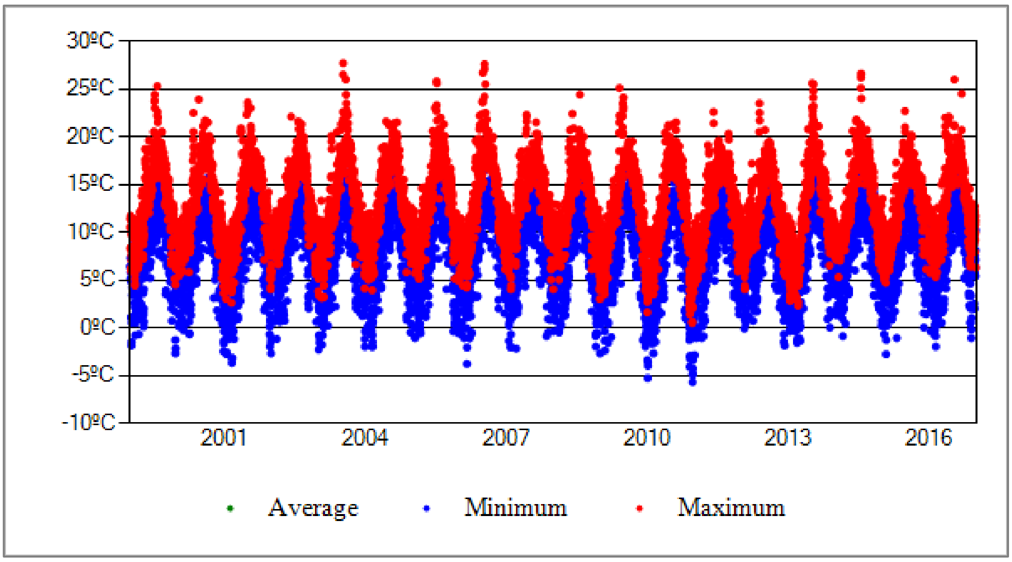
Figure 2: Available weather station locations and T_{PAV} percentile differentiation

The robustness of the data that relates to each of the locations/weather stations is affected by several constraints, such as possible equipment malfunction, number and type of recorded parameters, level of automation of the measuring and recording process, etc.

The determination of the Performance Grade high temperature parameter as described by the Superpave methodology is related to a variable designated as degree days [4], variable that measures the number of days over a 20-year period in which the maximum measured temperature is equal or higher than 10ºC. In order to rectify the existence of isolated days, or even periods of time for which the maximum temperature was not recorded in any of the studied locations, STAT-TEMP applies a correction factor to the initial sum of degree days that result from the statistical analysis of weather station data, more specifically it multiplies the degree days variable with the ratio between the expected number of daily maximum temperatures and the actual number of listed maximum temperatures.



a) Incomplete data



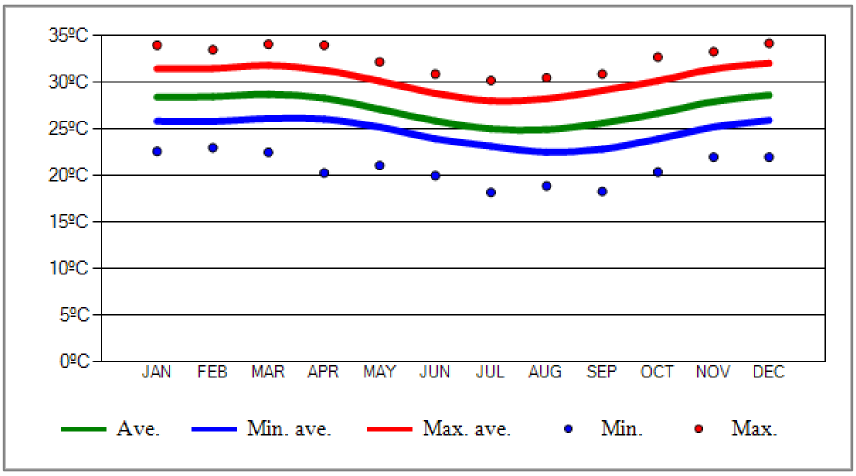
b) Complete data

Figure 3: Example of weather stations with incomplete/complete temperature data over a 20 period

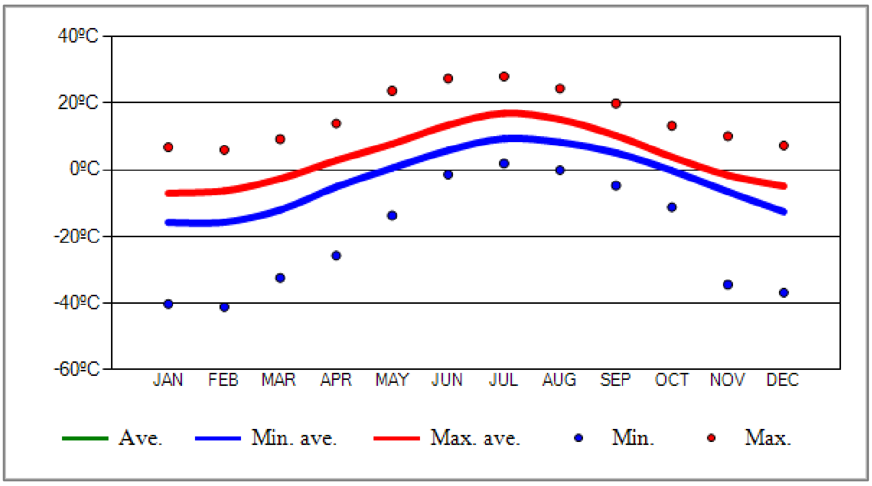
However, despite this correction, in order to maintain an adequate degree of reliability and value, STAT-TEMP discards weather stations in which the number of daily maximum temperatures is less than 85% of the expected value. By applying this quality filter, the number of available weather stations dropped from the initial 1422 to 968.

3. ANALYSIS METHODOLOGY

To the 968 weather stations that verify the 85% coverage of the daily maximum temperature data criteria, correspond 19360 years of accumulated data, spread over latitudes that have the Rochambeau weather station located in the French Guiana as their lower limit, and the Swedish Liliviken Roparudden weather station at the higher latitude boundary.



a) Rochambeau, French Guiana (latitude = 4.8º)



b) Liliviken Roparudden, Sweden (latitude = 66.5º)

Figure 4: Considered European latitude and weather extremes

The database formed by the information of the sum of the weather stations constitutes a comprehensive source of information. In order to determine the yearly SuperPave high temperature performance grade variation with climate conditions in the European continent, for each weather station/location, twenty different P_{GD} values were determined using expression (2), one for each of the years in the initially admitted period. The coefficient of variation for any given individual weather station is then determined as [5]:

$$CV(\%) = \sigma/X*100 \tag{5}$$

where:

σ	Standard deviation
X	Average

The weather stations were then grouped together accordingly to their latitude, in incremental clusters representative of one degree each. The considered coefficient of variation of any given latitude is equalled to the average coefficient of variation of the corresponding group. This process was performed at the rut depths of 5, 7.5, 10 and 12.5 mm. Once the evolution of the coefficient of variation in regard to latitude and depth was established, two distinct mathematical expressions were considered as functional fits of the coefficient of variation [6], namely the generalized logistic model (Equation 6) and the modified geometric function (Equation 7).

$$CV(\%) = \frac{A}{(1+Te^{-\beta(latitude\text{-}lm)})^{T}} \tag{6}$$

$$CV(\%) = c * latitude^{(d / latitude)} \tag{7}$$

where;

A, *T*, *B*, *lm*, *c* and *d* are the functional fit parameters to be determined.

A custom version of the STAT-TEMP software implementing the Levenberg-Marquardt numerical routine [6] (also known as damped squares optimization) was developed. This version was created in order to fit the calculated and measured coefficients of variation, for both the logistic and geometric model functional fits. The objective function to be minimized with the Levenberg-Marquardt optimization [7] is the sum of the squared differences between the weather analyses inferred coefficients of variation and the corresponding functional fits calculated values.

$$f = \sum_{i=1}^{n} (cv_w - cv_c)^2 \tag{8}$$

Table 1 gives the values obtained from Equation 8 for both functional fits, at the four different considered rut depths. Despite having a lower error sum for the twelve and a half millimetres rut depth, the modified geometric function is on average, the fit that demonstrates to possess a lower correlation to the calculated coefficient of variation for the considered depths, therefore, the generalized logistic function as described in (6), is selected to represent the evolution of the SuperPave performance grading high temperature coefficient of variation parameter calibrated for Europe.

Table 1. Sum of the squared differences for both functional fits at different depths

	5 mm	7.5 mm	10 mm	12.5 mm
Logistic	2.57	3.00	3.61	4.50
Geometric	2.69	3.12	3.70	4.43

The final form of the logistic model equation that describes the coefficient variation of the SuperPave high temperature performance grade as a function of latitude and rut depth (between 5 and 13 mm) adjusted for the European continent is as depicted in Equation 9. We have included the magnitude term for expression of the latitude since this equation can then be applied to both northern and southern latitudes.

$$CV(\%) = \frac{3.367e^{(\frac{RD}{23.41})}}{(1 + (0.50 - 0.021\ \mathrm{RD})e^{-0.0615*(|latitude|-41.25)})^{1/(0.50-0.021\ \mathrm{RD})}} \tag{9}$$

An example of this coefficient of variation prediction for a rut depth of 5 mm is given in Figure 5.

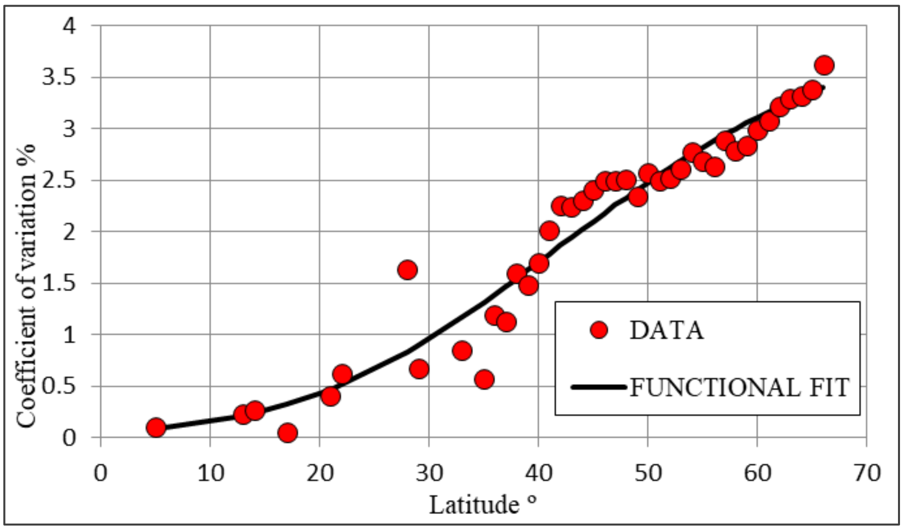


Figure 5: Correlation between data and functional fit at a rut depth of 5 mm

4. CONCLUSIONS

Based upon this work and analysis we can draw conclusions as follows:

- The original expression of coefficient of variation for development of HTPG grade is based upon limited latitudes of approximately 20 to 50 degrees north. this works well for the continental USA and other regions within this range but can give misleading results to higher or lower latitudes.

- The coefficient of variation can be better expressed by a sigmoidal function which would then provide a robust method for extrapolation of the function to more northern and southerly latitudes, including the southern hemisphere.

- A software STAT-TEMP was developed to enable access to the data in the NOAA database thus enabling the analysis of locations around the globe.

We anticipate as additional data sets become available the software and this analysis technique can be used to re-analyse locations thus considering trends in climate pattern. The functional forms adopted enable easy incorporation into software-based systems for selection of binder grade such as LTPP Bind [8] and/or pavement design system such as the MEPDG [9] or others [10], since a robust analysis can be applied to all geographic regions around the globe.

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