THE BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING
2023/18(2)

ISSN 1822-427X/eISSN 1822-4288
2023 Volume 18 Issue 2: 190–204
https://doi.org/10.7250/bjrbe.2023-18.603

SUPERPAVE PAVEMENT DESIGN TEMPERATURES IN ESTONIA

KARLI KONTSON*, KRISTJAN LILL, ANDRUS AAVIK

Dept of Civil Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia

Received 15 December 2022; accepted 13 March 2023

Abstract. This paper introduces the maximum and minimum pavement temperatures of Estonian asphalt pavements in accordance with calculation models developed for North America and Norway. Historical meteorological data from 1992 to 2021 obtained from 25 different weather stations in Estonia were used as an input for the respective models. Comparison between the calculation models demonstrated high variability of the pavement design temperatures, thus significantly impacting the bitumen grade selection. Based on the road weather stations data, the Norwegian and Canadian models provide the most accurate pavement temperature estimations for Estonian conditions. Calculated upper and lower-bound pavement design temperatures varied between +52 °C to +58 °C and −22 °C to −34 °C, respectively. All models showed milder pavement temperatures and lower seasonal temperature amplitudes for coastal and offshore areas. The results also indicated the importance of validating model suitability as well as correlation with actual pavement temperatures in the Baltic region.

Keywords: bitumen, pavement design, pavement temperature, penetration grading, performance grading, Superpave.

* Corresponding author. E-mail: karli.kontson@taltech.ee

Karli KONTSON (ORCID ID 0000-0002-4029-3245)
Kristjan LILL (ORCID ID 0000-0002-2095-806X)
Andrus AAVIK (ORCID ID 0000-0002-8672-0345)

Introduction and background

On average, asphalt mixtures consist of 94–96 wt% (aggregate) and 4–6 wt% (bitumen). Although the content of the bitumen in asphalt mixtures is seemingly low, it has a vital role in ensuring performance and durability of asphalt pavements. Bitumen is a thermoplastic and viscoelastic construction material and its in-service behaviour is greatly influenced by environmental and loading conditions, i.e., temperature and forces induced by traffic.

Bitumen owes its unique properties to a complex chemical composition, consisting mainly of hydrocarbons with a variable structure, molecular weight and polarity, heteroatoms such as oxygen, sulphur, nitrogen and trace metals (Lesueur, 2009).

The rheological behaviour of bitumen varies with respect to temperature. As temperatures increase, the viscosity of bitumen decreases and asphalt pavements can become susceptible to plastic deformation and rutting caused by traffic induced loads (see Figure 1) (Delgadillo & Bahia, 2010). At low temperatures, the viscosity of bitumen increases, causing a transition to a solid-elastic state which leads to a reduced strain tolerance and more brittle behaviour. This, combined with temperature shrinking inherent to asphalt pavements, can lead

Figure 1. Extreme case of asphalt rutting on E67 Pärnu bypass. Rutting occurred on completely new asphalt pavement soon after paving in summer 2012

Figure 2. Typical pavement low temperature cracking with secondary fatigue cracking adjacent to transverse cracking

to premature pavement cracking, known as thermal cracking or low temperature cracking (see Figure 2) (Hesp et al., 2009).

Both rutting and low temperature cracking are among the most relevant types of pavement failure. Rutting results in a reduced service life of the pavement and can also negatively affect the safety of road users' due to the presence of pooled water increasing the risk of hydroplaning or ice formation (EC, 1999). Low temperature cracking is one of the main types of pavement failures in cold regions (Hesp, 2003). Cracks in the pavement allow water to penetrate into the pavement structure and when combined with seasonal freeze-thaw cycles, often leads to progressive pavement failure thereby reducing the service life of roads (Dawson, 2009).

It has been estimated that approximately 30–40% of the rutting and more than 90% of low temperature cracking can be attributed to the properties of bitumen (Dawley & Pulles, 1996; Hesp et al., 2009; Saarela, 1992). To ensure the durability of asphalt pavements, the bitumen and its properties must be carefully selected to meet the environmental conditions of the pavement.

In Europe, both unmodified paving grade bitumen and modified bitumen properties are selected based on widely employed empirical specifications known as penetration grading (CEN, 2009, 2010). The penetration grade for a given road or region is usually selected by the designer or user agency based on previous experience with given grade. Penetration grading relies mainly on the penetration test which measures bitumen consistency at 25 °C. The test is conducted by measuring the penetration depth of a specific 100 g needle after 5 s loading time in decimillimetres (CEN, 2015). Penetration grading is often supplemented with additional tests, such as the Ring and Ball (R&B) softening point and Fraass breaking point to measure and specify bitumen properties at high and low temperatures, respectively. The latter is the only option in European bitumen product specifications to specify the low temperature performance of the bitumen and is therefore often adopted in cold regions such as the Baltic and Nordic countries. However, penetration and Fraass breaking point tests are not related with fundamental physical properties of the bitumen and have shown to have somewhat inaccurate correlation with in-service pavement performance (Kennedy et al., 1994; Lill et al., 2020). Criticism towards penetration grading became more dominant after the crude oil crisis in 1970s in the USA, when crude sources used for fuel and bitumen production diversified. This was perceived by road industry as leading cause of variable in-service performance between bitumen with similar penetration grade (Adams & Holmgreen, 1986; Petersen et al., 1993).

1. Superpave Performance Grading and pavement temperature models

In the late 1980s, the government of the USA initiated the Strategic Highway Research Program (SHRP) to increase the durability and performance of asphalt pavements. The SHRP researchers concluded that bitumen properties should be generally selected based on two aspects: 1) *traffic load characteristics*, i.e., traffic speed and equivalent single axle load (ESALs) and 2) *environmental conditions* (temperatures) of the road to be constructed or remediated. One of the many SHRP outcomes was Superpave™ (**Su**perior **Per**forming Asphalt **Pave**ments) bitumen specification framework known as Superpave Performance Grading currently widely used in North America as the AASHTO M 320 specification. This adopted a completely new approach to specify bitumen. Penetration, softening point and Fraass breaking point tests were replaced with testing methods having a better correlation with pavement in-service performance (Kennedy et al., 1994).

Environmental conditions were divided into two criteria: 1) pavement high design temperature and 2) pavement low design temperature. Pavement high and low design temperatures refer to maximum and minimum pavement temperatures considered in selecting the appropriate bitumen grade. According to the Superpave Performance Grading, bitumen grades are denoted as "PG HT-LT", where "PG" stands for *Performance Grade* and "HT-LT" stands for *high temperature grade* and *low temperature grade,* respectively. PG grade indicates the range of temperatures, also known as Useful Temperature Interval (UTI), in which the bitumen is assumed to provide adequate resistance to both environmental and loading conditions. For example, bitumen with a grade PG 58-28, indicates that this bitumen is suitable to be used in asphalt pavements where the maximum and minimum pavement temperatures (pavement design temperatures) remain within the range: +58 °C to −28 °C. Both HT and LT grades are defined with 6 ºC increments. It is important to note that PG HT is determined by testing the short-term aged or unaged bitumen. Whereas PG LT is determined based on tests conducted on long-term aged bitumen (Asphalt Institute, 2011).

The lower-bound pavement design temperature, PG LT, was estimated to be equal to lowest 1-day minimum air temperature of the region (Kennedy et al., 1994). In this paper, this temperature boundary is denoted as SHRP PG LT.

$$\text{SHRP PG HT} = (T_{air} - 0.00618\varphi^2 + 0.2289\varphi + 42.2) \times 0.9545 - 17.78, \quad (1)$$

where SHRP PG HT – pavement high design temperature at the depth of 20 mm, °C;

T_{air} – 7-day average high air temperature, °C;

φ – latitude of the specific road section under design or examination, °.

Both the maximum and minimum design temperature methodology was later reviewed based on factual data collected from 30 road test sections throughout North America, based on monitoring data as a part of the Seasonal Monitoring Program (LTPP-SMP) of the Long-Term Pavement Performance study. New pavement design temperature calculation models according to Equations (2) and (3) were proposed (Asphalt Institute, 2011; Mohseni, 1998). In this paper, these temperatures are denoted as LTPP PG HT and LTPP PG LT, respectively.

$$\text{LTPP PG HT} =$$
$$= 54.32 + 0.78T_{air} - 0.0025\varphi^2 - 15.14\log_{10}(H + 25) + z\sqrt{9 + 0.61\sigma_{air}{}^2}, \quad (2)$$

where LTPP PG HT – pavement high design temperature below surface, °C;

T_{air} – 7-day average high air temperature, °C;

φ – latitude of the specific road section under design or examination, °;

H – depth to surface, mm (for PG HT calculations, H = 20 mm is adopted);

σ_{air} – standard deviation of the 7-day average high air temperatures;

z – from the standard normal distribution table, z = 2.055 for 98% reliability.

$$\text{LTPP PG LT} =$$
$$= -1.56 + 0.72T_{air} - 0.004\varphi^2 + 6.26\log_{10}(H + 25) - z\sqrt{4.4 + 0.52\sigma_{air}{}^2}, \quad (3)$$

where LTPP PG LT – pavement low design temperature below surface, °C;

T_{air} – 1-day average low air temperature, °C;

φ – latitude of the specific road section under design or examination, °;

H – depth to surface (for PG LT calculations, H = 0 mm is adopted), mm;

σ_{air} – standard deviation of the 1-day low air temperatures;

z – from the standard normal distribution table, z = 2.055 for 98% reliability.

In Canada, a separate minimum pavement design temperature methodology was derived during the Canadian Strategic Highway

Research Program (C-SHRP). Pavement temperature measurements compared with air temperature indicated that SHRP PG LT assumption would lead to an overly conservative minimum pavement design temperature. Therefore, a separate Equation (4) was adopted, which gave reasonable correlation with real pavement low temperatures (Mohseni, 1998). In this paper, this temperature is denoted as C-SHRP PG LT.

$$\text{C-SHRP PG LT} = 0.859T_{air} + 1.7, \tag{4}$$

where C-SHRP PG LT – pavement low design temperature, °C;
T_{air} – 1-day minimum air temperature, °C.

From 1994 to 1998, the Norwegian road industry conducted a series of studies to adopt the Superpave principles in Norway. One of the products of these studies was the further development of the maximum pavement design temperature calculation methodology according to Equation (5), which is more compatible with environmental conditions for Norwegian pavements. In this paper, this temperature is denoted as NOR PG HT. The PG LT calculation method for Norway was kept the same as proposed by C-SHRP (Lerfald et al., 2004; Vegvesen, 2014).

$$\text{NOR PG HT} = T_{\text{20mm}} = \left(T_{\text{air}} - 0.0055\varphi^2 + 0.15\varphi + 36\right)0.9545 - 0.8, \tag{5}$$

where T_{20mm} – pavement high design temperature (PG HT) at depth of 20 mm, °C;
T_{air} – 7-day average high air temperature, °C;
φ – latitude of the specific road section under design or examination, °.

The Superpave Performance Grading enables users to adopt different levels of confidence (reliability) by considering the standard deviations of the *7-day average high air temperatures* and *1-day minimum air temperatures* within the measured period. At least 20 years of air temperature data are needed to ensure reliable results (Asphalt Institute, 1996, 2011). According to the Asphalt Institute (1996), Superpave defines reliability as the "*percent probability in a single year that the actual temperature (7-day average high temperature or 1-day minimum air temperature) will not exceed the design temperatures*". For example, the mean 7-day average high air temperature in Tallinn, Estonia for a period between 1992 and 2021 was T_{air} = 26.8 °C with a standard deviation of ±2.5 °C. However, there is a 50% chance that mean 7-day average high air temperature will be exceeded in an average year. Assuming a normal distribution as well as the standard deviation of the mean 7-day average high air temperature, there is a 2% chance that 7-day average high temperature will exceed 26.8 + 2 × 2.5 = 31.8 °C.

Equations (2) and (3) of LTPP PG HT and PG LT design temperature have already included an option for reliability.

2. Objective

Currently, there is no information available in literature about bitumen Superpave Performance Grades suitable for Estonia and which calculation model provides the most accurate correlation with measured road surface temperatures. The objective of this paper is to calculate pavement design temperatures of Estonia according to models officially adopted in North America (LTPP and C-SHRP) and Norway, to compare the calculated temperatures with the highest and lowest pavement temperatures measured at randomly selected road weather stations and to select the most accurate calculation models for Estonia. The results are then used to develop pavement design temperature maps that can be used to select bitumen Superpave Performance Grades in different parts of Estonia.

3. Geographical location and climate

Estonia is located in Norther-Eastern Europe, bordering the Baltic Sea to the West and Gulf of Finland to the North. The total area of Estonia is 45 339 km^2 and the geographical coordinates range from 57°30’ N to 59°49’ N and from 28°13’ E to 21°46’ E. The country is situated in temperate climate zone and is influenced by both maritime and continental climate. The average annual air temperature (1991–2020) is 6.4 °C with the absolute maximum and minimum recorded air temperatures of 35.6 °C (11 August 1992) and −43.5 °C (17 January 1940), respectively. The warmest months are July–August and the coldest are January–February for all years (Estonian Environmental Agency, 2021).

4. Temperature data and analysis

4.1. Historical meteorological data

Recorded daily minimum and maximum air temperatures for 37 different weather stations were provided by the Estonian Environmental Agency. The period included in this study is from 1992 to 2021 (30 years). Therefore, weather stations with less than 30 years of daily temperature data were excluded from the analysis. This reduced the total number of suitable stations to 25. The global temperature data density resolution is one station per approximately 1800 km^2, the stations are fairly evenly distributed over the territory of Estonia (Figure 3).

For every weather station, the annual highest 7-day average air temperatures and lowest 1-day minimum air temperatures (incl. dates) were extracted for the PG HT and LT calculations, respectively. The daily minimum and maximum air temperature data from every station were subjected to verification to ensure that provided information was sufficient to be included in the PG HT and PG LT calculations. The most critical period for the pavement PG HT calculations was selected from June to September (incl.) and for the PG LT calculations from October to March (incl.). Additionally, the standard deviation of the 7-day average maximum air temperature and 1-day average low temperature was calculated.

In the rare cases where the daily minimum and maximum temperatures were missing for a limited period e.g., for a week or a month, the measurements from the nearby weather stations were analysed to assess the sensitivity of the PG HT and LT calculations due

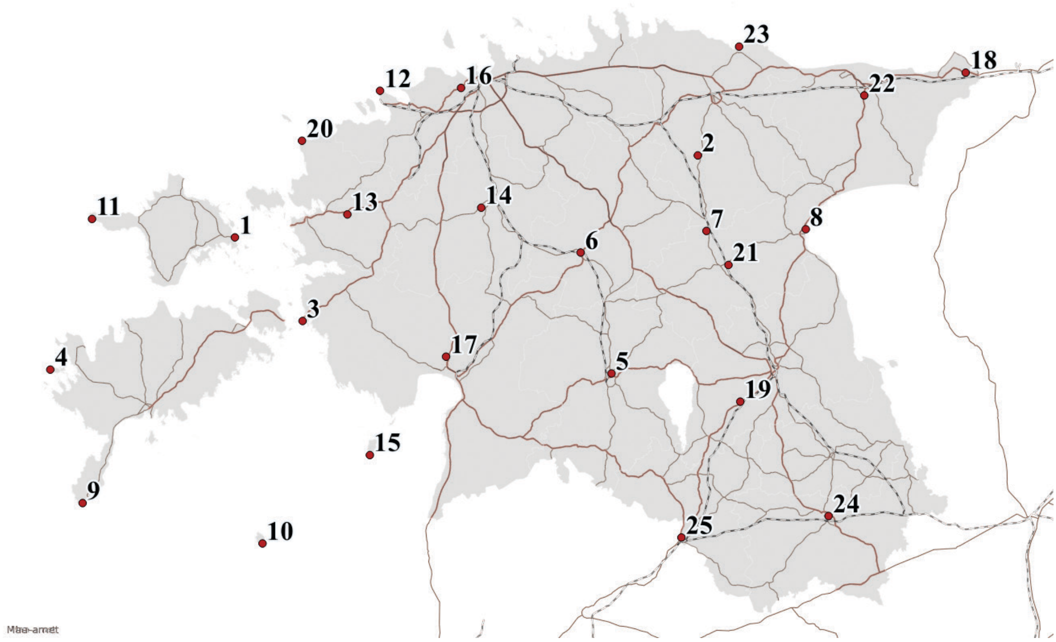

Figure 3. Locations and numbering of the weather stations included in the study

to the missing data. For example, if a weather station was missing the daily minimum air temperatures for a period between 1 December to 15 December and a nearby weather station indicated that the coldest temperatures for given year did not overlap with the period of missing data, then the data from the weather station were still included in the analysis.

4.2. Data from the road weather stations

Daily minimum and maximum recorded road surface and air temperatures from 2020 to 2022 from seven randomly selected road weather stations were collected to allow for comparison with the calculated pavement design temperatures. The highest 7-day average air temperatures and lowest 1-day minimum air temperatures leading to maximum and minimum recorded surface temperatures were extracted for the PG HT and LT calculations, respectively. Road weather stations included in this paper are described in Figure 4.

Figure 4. Locations and numbering of the road weather stations included in the study

5. Results and discussion

5.1. Calculated pavement design temperatures

Pavement high design temperatures (PG HT) were calculated based on LTPP (Equation (2)) and the Norwegian (Equation (5)) models. Pavement low design temperatures (PG LT) were calculated using LTPP (Equation (3)) and C-SHRP (Equation (4)) models. SHRP PG HT and LT results were included for comparison purposes only. All calculations accounted for reliability level of at least 98%. PG HT and LT calculation results have been rounded to the nearest whole number and are presented in Figures 5 and 6.

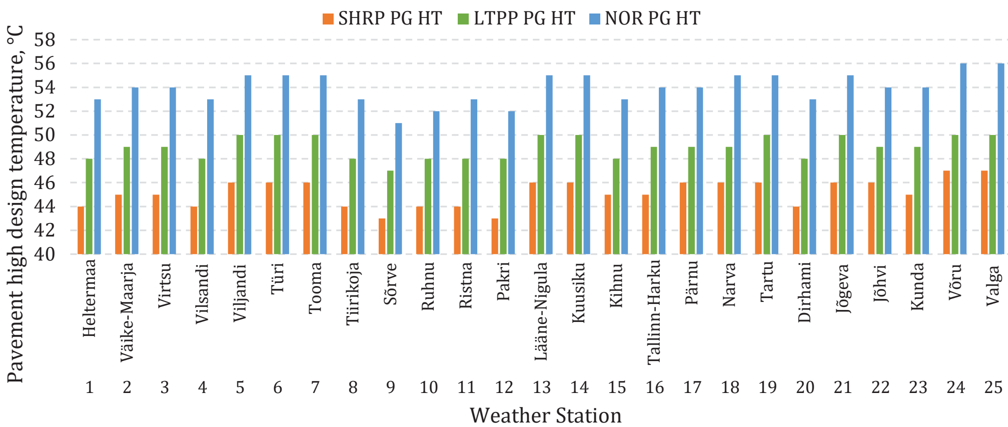

Figure 5. High pavement design temperatures according to SHRP, LTPP and Norwegian calculation models (98% reliability)

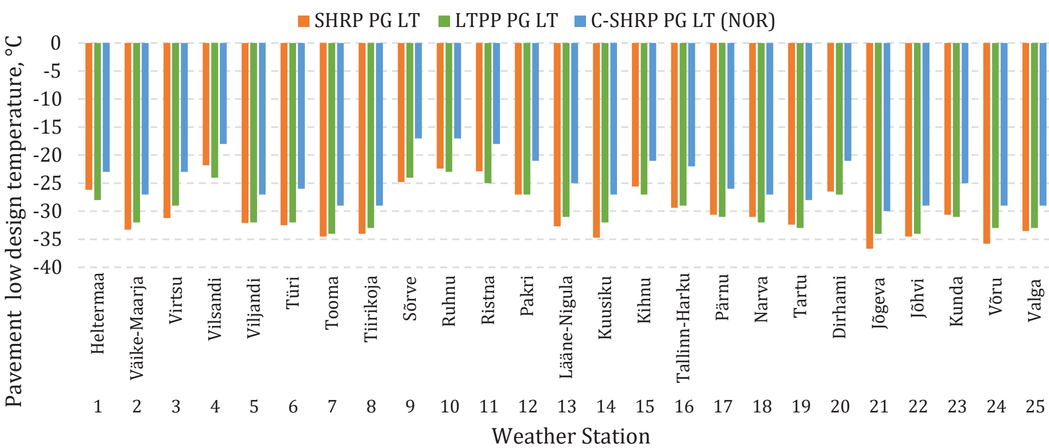

Figure 6. Low pavement low design temperatures according to LTPP and C-SHRP calculation models (98% reliability). SHRP temperature given based on lowest 1-day air temperature

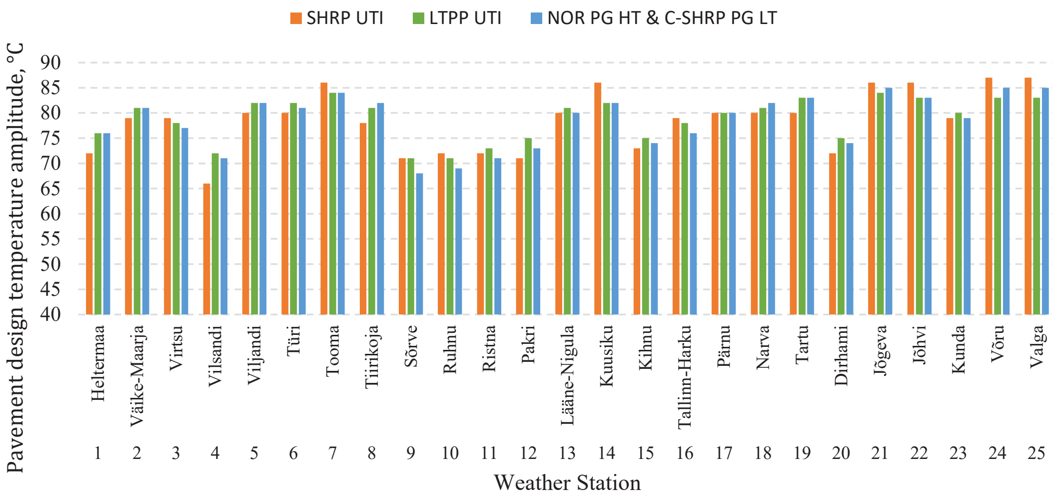

Figure 7. Absolute pavement design temperature differences based on respective calculation models

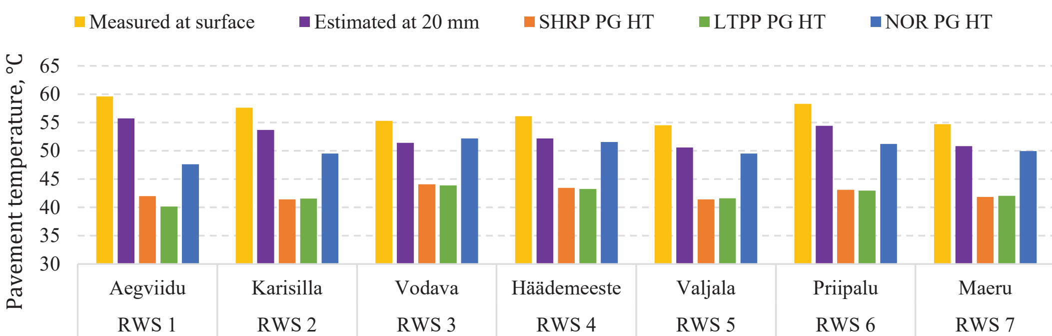

Figure 8. Highest pavement temperatures recorded at road weather stations compared with calculated temperatures

5.2. Calculated vs measured pavement temperatures

The highest recorded road surface temperatures and calculated pavement high design temperatures for every included road weather station with respective calculation models are presented in Figure 8. Pavement temperature at the depth of 20 mm was assumed to be 4 °C lower from surface temperature. This assumption is based on temperature-depth relationship adopted in Equation (2). Norwegian model shows the closest results with estimated temperatures at the depth of 20 mm. SHRP and LTPP models significantly underestimate pavement high temperatures and are not suitable for Estonian conditions.

The lowest recorded road surface temperatures and calculated pavement low design temperatures with respective models are presented in Figure 9. C-SHRP model provides reasonable pavement low temperature estimation compared with recorded temperatures. SHRP and LTPP models lead to significantly lower pavement temperature estimates compared with measured values, resulting in too conservative pavement low design temperatures and would significantly affect the Superpave bitumen low temperature grade selection.

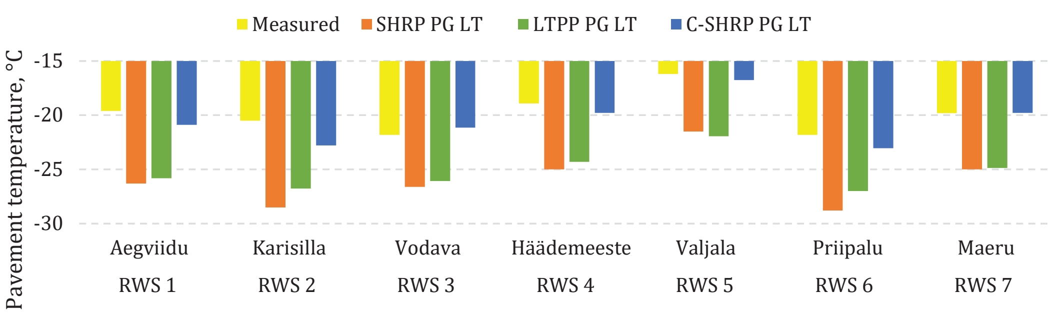

Figure 9. Lowest pavement temperatures from 2020 to 2022 recorded at road weather stations compared with calculated temperatures

5.3. Superpave pavement design temperature maps of Estonia

The pavement maximum and minimum temperature maps were developed based on Norwegian and C-SHRP models, respectively. According to the Superpave methodology, the bitumen grade is specified with 6 °C increments. Required bitumen PG HT and LT grades according to respective models with the aforementioned increments is displayed in Figure 10.

Pavement high design temperatures according to Norwegian model varies from 52 °C to 58 °C. Whereas pavement low design temperatures according to C-SHRP model varies from −22 °C to −34 °C. Results indicate milder pavement design temperatures for islands and coastal areas, i.e., colder pavement temperatures are expected inland, while milder temperatures are dominant near coastal areas and on islands.

Conclusions

This paper introduced maximum and minimum pavement temperatures for Estonian asphalt pavements in accordance with Superpave Performance Grading principles. Historical meteorological data from 1992 to 2021 obtained from 25 different weather stations in Estonia were used as an input for the respective pavement design temperature models. Different calculation models demonstrated variability of the pavement design temperatures, thus impacting the bitumen Superpave Performance Grade selection. Data from road weather stations indicate that LTPP models are unsuitable for Estonian conditions, leading to significantly underestimating maximum pavement

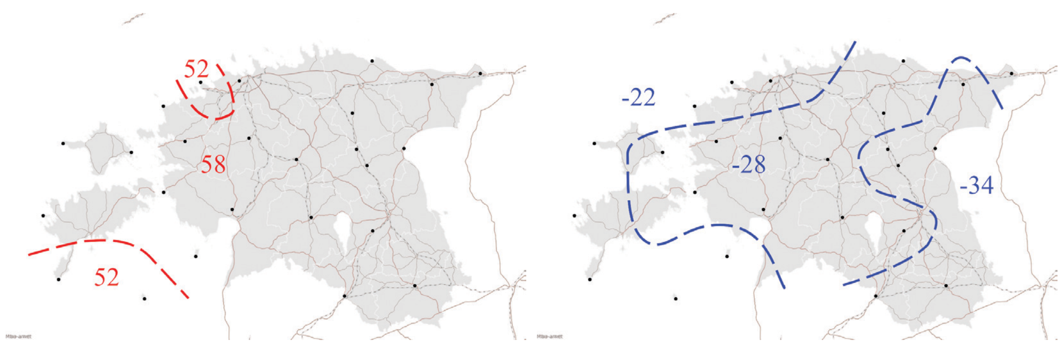

Figure 10. PG HT and LT grades according to the Norwegian PG HT and C-SHRP models with 6 °C increments (98% reliability)

temperatures and overestimating minimum pavement temperatures. Norwegian and C-SHRP models provide reasonable correlation with recorded pavement temperatures in Estonia and are therefore recommended to be used for pavement design temperature calculations. All included models indicate that milder pavement temperatures and smaller seasonal temperature amplitudes are expected for coastal areas and islands.

Estonian Superpave Performance Grades, according to Norwegian and C-SHRP models (≥98% reliability), are as follows:

– Pavement high design temperature (PG HT) varies from 52 °C to 58 °C.
– Pavement low design temperature (PG LT) varies from −22 °C for coastal areas and islands bordering the Baltic Sea and −28 °C to −34 °C for mainland area.

Acknowledgments

The authors would like to express appreciation to Dr Christopher Davies for proofreading and providing valuable input regarding structuring and formatting of the article and to the Estonian Environmental Agency and Estonian Transportation Administration for providing meteorological and road weather station data.

REFERENCES

Adams, C. K., & Holmgreen, R. J. (1986). *Asphalt properties and pavement performance*. Texas A&M University.

Asphalt Institute. (1996). *Performance graded asphalt binder specification and testing.* Superpave Series No. 1 (SP-1).

Asphalt Institute. (2011). *The asphalt binder handbook.* Manual Series No. 26 (MS-26).

CEN. (2009). *EN 12591:2009. Bitumen and bituminous binders – Specifications for paving grade bitumens*.

CEN. (2010). *EN 14023:2010. Bitumen and bituminous binders – Framework specification for polymer modified bitumens*.

CEN. (2015). *EN 1426. Bitumen and bituminous binders – Determination of needle penetration*.

Dawley, C., & Pulles, B. (1996). *Guide to the Characteristics, Performance and Selection of Paving Asphalts* (Research report 1996).

Dawson, A. (2009). *Water in road structures: Movement, drainage & effects*. Springer. https://doi.org/10.1007/978-1-4020-8562-8

Delgadillo, R., & Bahia, H. U. (2010). The relationship between nonlinearity of asphalt binders and asphalt mixture permanent deformation. *Road Materials and Pavement Design*, *11*(3), 653–680. https://doi.org/10.1080/14680629.2010.9690298

EC. (1999). *Development of a new bituminous pavement design method* (COST 333 Final Report). European Comission. https://orbit.dtu.dk/en/publications/development-of-new-bituminous-pavement-design-method-cost-333-fin

Estonian Environmental Agency. (2021). *Eesti Meteoroloogia Aastaraamat (in Estonian)*.

Hesp, S. A. M. (2003). *An improved low-temperature asphalt binder specification method* (Final Report, NCHRP-IDEA Contract 84 and Ministry of Transportation Ontario Contract 9015-A-000190).

Hesp, S. A. M., Soleimani, A., Subramani, S., Phillips, T., Smith, D., Marks, P., & Tam, K. K. (2009). Asphalt pavement cracking: Analysis of extraordinary life cycle variability in eastern and northeastern Ontario. *International Journal of Pavement Engineering*, *10*(3), 209–227. https://doi.org/10.1080/10298430802343169

Kennedy, T. W., Huber, G. A., Harrigan, E. T., Cominsky, R. J., Hughes, C. S., Quintus, H. V., & Moulthrop, J. S. (1994). *Superior performing asphalt pavements (Superpave): The product of the SHRP asphalt research program*. Strategic Highway Research Program. National Research Council. https://www.trb.org/publications/shrp/SHRP-A-410.pdf

Lerfald, B. O., Andersen, E. O., Aurstad, J., Bragstad, R., Jørgensen, T., & Lange, G. (2004). *PROKAS. Proporsjonering og kontroll av asfalt. Sluttrapport. (in Norwegian)*. SINTEF Teknologi um samfunn.

Lesueur, D. (2009). The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification. *Advances in Colloid and Interface Science, 145*(12), 42–82. https://doi.org/10.1016/j.cis.2008.08.011

Lill, K., Khan, A. N., Kontson, K., & Hesp, S. A. M. (2020). Comparison of performance-based specification properties for asphalt binders sourced from around the world. *Construction and Building Materials*, *261*, Article 120552. https://doi.org/10.1016/j.conbuildmat.2020.120552

Mohseni, A. (1998). *LTPP seasonal asphalt concrete (AC) pavement temperature models* (Report No. FHWA-RD-97-103). https://www.fhwa.dot.gov/publications/research/infrastructure/pavements/ltpp/97103/97103.pdf

Petersen, J. C., Robertson, R. E., Branthaver, J. F., Harnsberger, P. M., Duvall, J. J., Kim, S. S., Anderson, D. A., Christiansen, D. W., & Bahia, H. U. (1993). *Binder characterization and evaluation, Volume 1* (Report No. HRP-A-367). Strategic Highway Research Program, National Research Council. https://onlinepubs.trb.org/onlinepubs/shrp/SHRP-A-367.pdf

Saarela, A. (1992). *Asfalttipäällysteiden tutkimusohjelma, ASTO 1987-1994. Asfalttipäällysteet. Osa I: Suunnittelu*. Valtion teknillinen tutkimuskeskus, tie-, geo- ja liikennetekniikan laboratorio.

Vegvesen. (2014). *Håndbok N200. Vegbygging (In Norwegian)*. Statens vegvesen. www.vegvesen.no/handboker