Transportation Association of Canada

Determining the Winter Design Temperature for Asphalt Pavements

April 1997

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2323 St. Laurent Blvd., Ottawa, ON K1G 4J8
Tel. (613) 736-1350 Fax (613) 736-1395
www.tac-atc.ca

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Author(s) Warren Robertson		Corporate Affiliation(s) W.D. Robertson & Associates	
Sponsoring/Funding Agency and Address Research and Development Council Transportation Association of Canada 2323 St. Laurent Blvd., Ottawa, Canada K1G 4J8		Performing Agencies Names and Addresses W.D. Robertson & Associates 1252 Echo Road, Sarnia, ON N7S 3K3	

Abstract

The U.S. Federal Highway Administration has recognized that the original SUPERPAVE winter design temperature is too conservative for very cold winter climates. The purpose of this study was to develop a method for selecting winter design temperatures for pavement sites in cold winter climates to enable the selection of asphalt binders which resist thermal cracking.

This report describes the development of an algorithm for estimating winter design temperatures for asphalt pavements based on readily available climatic data. The relationship between the minimum pavement temperature and the minimum air temperature for several pavement test sites was studied and at all sites, an excellent correlation was found between minimum air and pavement temperatures. The equation for estimating winter design temperatures for a pavement test site from the local winter temperature history is developed and presented. This equation includes a factor for the desired reliability, and can be used with the SUPERPAVE paving mix design system.

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Auteur(s) Warren Robertson	Affiliation(s) W.D. Robertson & Associates

Nom et adresse de l'organisme parrain

Conseil de la recherche et du développement
Association des transports du Canada
2323, boul. St-Laurent, Ottawa, Canada K1G 4J8

Nom et adresse de l'organisme exécutant

W.D. Robertson & Associates
1252 Echo Road, Sarnia, ON N7S 3K3

Résumé

La Federal Highway Administration des États-Unis a reconnu que la température hivernale de conception des mélanges SUPERPAVE utilisée à l'origine était trop prudente, en ce sens qu'elle ne témoignait pas des très basses températures enregistrées dans certaines régions où le climat hivernal est très rigoureux. L'objet de la présente étude était d'élaborer une méthode de sélection des températures hivernales de conception des revêtements de chaussée exposés à des basses températures pendant l'hiver, le tout à l'appui du choix de liants bitumineux qui résisteront à la fissuration d'origine thermique.

Le présent document traite de l'élaboration d'un algorithme d'estimation des températures hivernales de conception des revêtements de chaussée bitumineux. Cet algorithme a été mis au point à partir de données climatologiques existantes.

Dans ce contexte, le rapport entre la température minimale d'un revêtement de chaussée et la température minimale de l'air a été étudié à plusieurs sites d'essai de chaussée. À chacun de ces sites, on a constaté une excellente corrélation entre ces deux températures. Ce rapport permet en outre de définir l'équation permettant, à partir de données historiques des températures hivernales d'un site, d'estimer la température hivernale de conception du mélange bitumineux à y appliquer. Cette équation comprend un facteur de fiabilité souhaitée et peut être appliquée dans le contexte de la technologie de conception des mélanges SUPERPAVE.

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Project Steering Committee:

Dr. Gerhard Kennepohl (Chair)
Ontario Ministry of Transportation

Jim Gavin
Alberta Transportation & Utilities

Anne-Marie Leclerc
Ministère des transports du Québec

Christopher Hedges (Secretary)
Transportation Association of Canada

Alison Bradbury
Ontario Ministry of Transportation

Leonnie Kavanagh
Manitoba Highways and Transportation

Ludo Zanzotto
University of Calgary

Consultant:

Warren Robertson
W.D. Robertson & Associates

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Executive Summary

This report describes the development of an algorithm for estimating winter design temperatures for asphalt pavements based on readily available climatic data.

Thermal cracking of asphalt pavements is prevalent in most regions of Canada. The most significant factor affecting thermal cracking is the characteristics of the asphalt binder. The U.S. Strategic Highway Research Program (SHRP) has developed a new design system called SUPERPAVE for asphalt paving mixes, and a performance-based asphalt binder specification for use with it. Design for resistance to thermal cracking consists of two steps: determining the winter design temperature for the pavement site, and selecting an asphalt binder having low temperature properties that enable it to resist thermal cracking at the winter design temperature.

The original SUPERPAVE winter design temperature was the lowest expected air temperature at the pavement site during its design lifetime. However, as a result of research conducted under the Canadian Strategic Highway Research Program (C-SHRP), the U.S. Federal Highway Administration has recognized that this design temperature is too conservative for very cold winter climates. The research has suggested that in colder climates the minimum pavement temperature is related to but generally somewhat higher than the lowest air temperature.

Pavement surface temperature data is almost never available. Therefore, for design purposes, it is necessary to estimate the lowest expected pavement surface temperature from available climatic data. An acceptable estimate of the lowest expected surface temperature can be obtained from a regression equation describing the relationship between observed minimum pavement and air temperatures.

In this study, the relationship between the minimum pavement temperature and the minimum air temperature for several pavement test sites was studied by analyzing periodic measurements of the air temperature and the corresponding temperature at several depths in the pavement structures. The test sites were selected to meet the following criteria: 1) pavement thickness was greater than 100 mm; 2) temperature readings were available over at least three winters; and 3) minimum winter temperatures were distributed over the range expected in Canada.

Regression analysis was used to determine the relationship between the minimum air and pavement temperatures at each site. At all of the sites, there was an excellent correlation between minimum air and pavement temperatures.

The equation for estimating winter design temperatures for a pavement test site from the local winter temperature history is developed and presented in this report. The equation includes a factor for the desired reliability, and can be used with the SUPERPAVE paving mix design system.

To further verify the validity of the equation, it is recommended that additional air and pavement temperature data be collected and analyzed. Experience to date at a small number of locations indicates that a binder selected using the winter design equation developed in this study will resist thermal cracking. Further studies should be conducted to confirm this conclusion.

Sommaire

Le présent rapport traite de l'élaboration d'un algorithme d'estimation des températures hivernales de conception des revêtements de chaussée bitumineux. Cet algorithme a été mis au point à partir de données climatologiques existantes.

La fissuration d'origine thermique des revêtements de chaussée bitumineux est un problème bien concret dans la plupart des régions du Canada. Le principal facteur de fissuration d'origine thermique tient aux caractéristiques mêmes des liants bitumineux qui sont utilisés. Le Programme stratégique de recherche routière (SHRP) des États-Unis à permis de mettre au point la nouvelle technologie SUPERPAVE de conception des mélanges bitumineux de pavage routier. Cette technologie est fondée sur les caractéristiques de rendement des liants bitumineux employés dans la fabrication de ces mélanges. La détermination de la résistance à la fissuration d'origine thermique se fait en deux étapes. Dans un premier temps, il faut calculer la température hivernale de conception pour le site auquel est destiné le mélange de pavage; ensuite, il faut choisir un liant bitumineux possédant des caractéristiques de rendement à basse température qui permettront au mélange de résister à la fissuration d'origine thermique à la température hivernale de conception.

À l'origine, la température hivernale de conception des mélanges SUPERPAVE s'entendait de la température de l'air la plus basse que l'on pouvait s'attendre à enregistrer à un site à paver pendant la durée de vie utile de ce dernier. À la lumière des résultats de recherches exécutées dans le cadre du Programme stratégique de recherche routière du Canada (C-SHRP), la Federal Highway Administration des États-Unis a toutefois reconnu que cette température de conception était trop prudente, en ce sens qu'elle ne témoignait pas des très basses températures enregistrées dans certaines régions où le climat hivernal est très rigoureux. Les recherches précitées donnent en effet à entendre que dans ces régions la température minimale d'une chaussée est sans contredit liée à la plus basse température de l'air ambiant mais qu'elle est cependant légèrement supérieure à cette dernière.

Il est plutôt rare que l'on puisse avoir accès à des données concernant la température surfacielle des chaussées. Aussi, aux fins de la conception des mélanges bitumineux, il est nécessaire d'estimer la plus basse température surfacielle d'une chaussée à partir des données climatologiques disponibles. Il est possible d'en arriver à une estimation acceptable de la température surfacielle la plus basse en appliquant une équation de régression fondée sur le rapport dérivé de la mesure de la température minimale du revêtement de chaussée et de la température de l'air à un site donné.

Dans le contexte de la présente étude, le rapport entre ces deux températures minimales a été calculé à plusieurs sites d'essai. À cette fin, on y a mesuré périodiquement la température de l'air et la température correspondante du revêtement à plusieurs niveaux de profondeur de ce dernier. Les sites d'essai retenus aux fins de cette étude ont été choisis en fonction des critères suivants : 1) une épaisseur de revêtement de chaussée supérieure à 100 mm; 2) l'existence de données sur les températures visées couvrant au moins trois hivers; 3) des températures hivernales minimales correspondant à celles que l'on peut s'attendre à enregistrer au Canada.

L'analyse de régression a servi à déterminer le rapport entre les températures minimales de l'air et du revêtement à chaque site. À chacun des sites, on a constaté une excellente corrélation entre ces deux températures.

Ce rapport d'étude définit l'équation permettant, à partir des données historiques des températures hivernales d'un site, d'estimer la température hivernale de conception du mélange bitumineux à y appliquer. Cette équation comprend un facteur de fiabilité souhaitée et peut être appliquée dans le contexte de la technologie de conception des mélanges de pavage SUPERPAVE.

Aux fins de vérifier la validité de l'équation, il est recommandé de recueillir et d'analyser des données supplémentaires concernant les températures minimales de l'air et du revêtement. À ce jour, les expériences exécutées à un petit nombre d'emplacements montrent que les liants choisis par le biais de l'application de cette équation offrent toutes les caractéristiques voulues de résistance à la fissuration d'origine thermique. Ceci dit, des études plus poussées s'imposent aux fins de confirmer cette conclusion.

1. INTRODUCTION

Thermal cracking of asphalt pavements is prevalent in most regions of Canada, the exceptions being the coastal regions of British Columbia and Atlantic Canada. The most significant factor affecting the thermal cracking resistance of these pavements is the characteristics of the asphalt binder. However, until recently, specifications for asphalt cements did not address the thermal cracking problem with requirements related directly to the low temperature properties of the binder.

The U.S. Strategic Highway Research Program (SHRP) has developed a new design system for asphalt paving mixes, known as SUPERPAVE, and a performance related asphalt binder specification for use with it.[1] The U.S. Federal Highway Administration (FHWA) has responsibility for implementing the SUPERPAVE system.

Design for resistance to thermal cracking consists of two steps: determining the winter design temperature for the pavement site, and selecting an asphalt binder having low temperature properties that enable it to resist thermal cracking at the winter design temperature.

The low temperature properties of asphalt binders are addressed in the SUPERPAVE binder specification,[2] which defines the minimum service temperature for the material. Research carried out by the Canadian Strategic Highway Research Program (C-SHRP) has shown that the criteria used to define the minimum service temperature are reasonable.[3] However, greater insurance that cracking does not occur above the binder's critical temperature might be desirable. This could be achieved by reducing the critical stiffness limit slightly.

The original SUPERPAVE winter design temperature was the lowest expected air temperature at the pavement site during the design lifetime.[4] However, as a result of the C-SHRP research, FHWA has recognized that this is too conservative for very cold winter climates. They have issued an interim modification of the SUPERPAVE algorithm to give less restrictive binder grades for minimum air temperatures lower than -28°C.[5] The current SUPERPAVE algorithm and interim guideline will be replaced when research on a new algorithm is completed.

In the SUPERPAVE paving mix design system, the designer may specify the desired reliability for the winter design temperature. This is the probability that the pavement temperature will not fall below it during its design life. This enables the designer to select the winter design temperature with a known risk that the pavement will crack because its temperature fell below the design value.

This report describes the development of an algorithm for determining winter design temperatures for pavements. The objective was to devise a procedure for estimating the lowest expected pavement temperature from readily available climatic data for the pavement site. It was also desired that the design equation include a factor that would enable the designer to specify the design reliability, so it could be used with the SUPERPAVE paving mix design system. The algorithm developed meets these objectives. It is based on observed air and pavement temperatures, and should be suitable for all locations in Canada.

2. THE SUPERPAVE SPECIFICATION

In the SUPERPAVE asphalt binder specification, the limiting values for the binder properties are the same for all grades, but the temperatures at which these requirements must be met are different for each grade. The SUPERPAVE specification is shown in Appendix A.

The grade designations contain two parameters. The first is the maximum service temperature, below which the binder is expected to have satisfactory resistance to permanent deformation. The second is the minimum service temperature, which is the lowest temperature at which the binder is expected to resist thermally induced cracking. For example, the PG 58-22 grade is for use where the maximum service temperature is 58°C, and the minimum service temperature is -22°C. Both the high temperature and the low temperature parameters change by increments of 6°C between grades.

The minimum service temperature in the SUPERPAVE specification is 10°C below the lowest temperature at which the creep stiffness of the binder is less than 300 MPa, and *m*, the absolute value of the slope of the creep stiffness master curve (log *Stiffness* vs log *time*), is greater than 0.3. Both values are determined by measurement using the Bending Beam Rheometer (BBR)[6] at a loading time of 60 s. The limiting stiffness value at the BBR test conditions is a surrogate for the limiting stiffness at the minimum service temperature and a loading time of 7200 s. These are the loading conditions used by Readshaw[7] to define his limiting binder stiffness to avoid thermal cracking of pavements.

A limit for strain tolerance is allowed as an alternative to the maximum stiffness, provided that the stiffness is less than 600 MPa, and the *m* value requirement is met. Binders that have 1% or higher strain at failure when tested in tension are accepted.

The creep stiffness and failure strain are measured on the Pressure Aging Vessel (PAV) residue of the binder.[1] PAV conditioning is intended to emulate changes in the binder resulting from several years of aging of the pavement in service.

3. AIR AND PAVEMENT TEMPERATURES DURING WINTER

The pattern of air temperatures during the year is extremely complex, due to the interaction of the many factors that effect it. The air temperature varies in superimposed cycles.

The longest cycle is seasonal, with a maximum in summer and a minimum in winter. The maximum and minimum temperatures depend on the latitude, which affects the intensity and amount of solar energy reaching the earth's surface. The yearly maximum and minimum temperatures occur some time after the summer and winter solstices, due to the moderating effect of the earth's mass, which absorbs and releases energy more slowly than the air. This moderating effect also affects the range of temperatures during the year. Temperature moderation is greater in coastal regions, because the heat capacity of water is greater, and its resistance to heat transfer is lower than those of the land mass.

Superimposed on the seasonal temperature cycle are much shorter weather related cycles caused primarily by transfer of heat between warmer and colder regions by wind. The length of these cycles is variable, from a few days to more than a week.

The shortest cycles are daily cycles caused by the rising and setting of the sun.

In winter, pavement temperatures change over a smaller range, and more slowly than air temperatures. Sunlight has a smaller effect on pavement temperatures during winter than in summer because the sunlight is less intense in winter. Also, winter days are shorter, and on many of them, sunlight is blocked from reaching the pavement surface by clouds or snow cover.

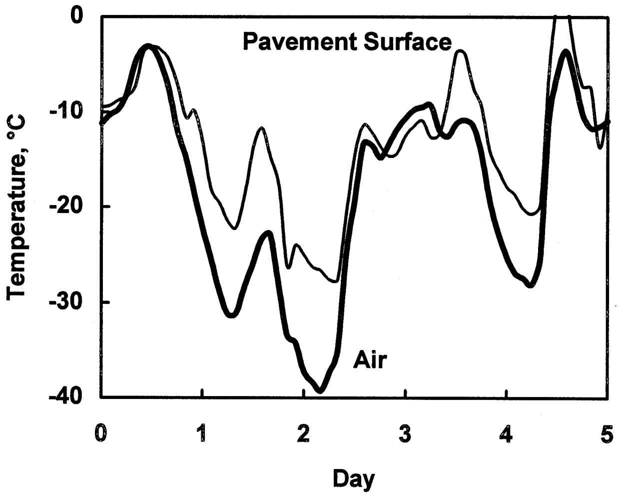

Figure 1. Typical air and Pavement Temperatures During Winter

Pavement temperatures in winter depend not only on the air temperature, which has its greatest effect on the upper surface, but also on the subgrade temperature, which has its largest effect at the pavement/subgrade interface. The subgrade temperature changes slowly, because of its large mass and heat capacity, and because it is insulated from changes in the air temperature by the overlying pavement. As a result, pavement temperatures change more slowly than air temperatures, and their minima and maxima lag behind those in the air temperature. This is illustrated in Figure 1.

The lowest pavement temperature during winter is significantly warmer than the lowest air temperature. The pavement will never experience a temperature as low as the lowest air temperature, as is assumed in the SUPERPAVE winter design algorithm. The difference between the lowest surface temperature and the lowest air temperature is larger for locations with lower minimum air temperatures, because there is greater heat flow from the subgrade to the atmosphere in this situation.

4. WINTER DESIGN TEMPERATURE FOR PAVEMENTS

The winter design temperature should be the lowest temperature that the pavement is likely to experience during its design life. This is the lowest surface temperature associated with the lowest air temperature likely to be observed at the pavement location. These will not occur simultaneously; the lowest pavement temperature will usually occur one or two hours after the minimum air temperature during a daily cooling cycle.

Pavement surface temperature data is almost never available. Therefore, for design purposes, it is necessary to estimate the lowest expected pavement surface temperature from available climatic data. The lowest pavement temperature depends mainly on air temperatures during winter. Therefore, an acceptable estimate of the lowest expected surface temperature can be obtained from a regression equation describing the relationship between observed minimum pavement and air temperatures.

It could be argued that a temperature lower in the pavement structure should be used as the winter design temperature, because a significant thickness of pavement must be cooled to the critical temperature of the binder to enable crack propagation. However, it is uncertain what depth in the pavement should be used to define the design temperature. The use of the surface temperature is more conservative, because it is the lowest temperature experienced by the pavement. It is also the location of crack initiation, without which no cracking can occur. The pavement surface temperature is also supported by observations for thick pavements in the C-SHRP test roads.[3] For these pavements, the average surface temperature at fracture was only 1.5°C below the binder critical temperature, defined as 10°C below the temperature at which the SHRP limiting stiffness and *m* value criteria are met.

The risk of failure associated with designing for the lowest predicted pavement temperature has two elements. One is the risk that the air temperature will fall below the expected minimum air temperature. This is quantified by the standard deviation of the minimum air temperatures at the pavement site, which measures variability of the winter climate. The other risk is that the lowest pavement temperature will be lower than that estimated from the relationship between minimum air and pavement temperatures. This is defined by the standard error of the estimated minimum pavement temperature, which reflects variability in the pavement/air boundary conditions and the temperature history at the pavement site.

This leads to an equation of the following type for the winter design temperature:

$$T_{design} = A(T_{air} - n\sigma_{air}) - n\sigma_{surface} + B \quad \text{...} \quad (1)$$

where T_{design} = winter design temperature, °C;
T_{air} = mean of minimum air temperatures at the pavement site, °C;
σ_{air} = Standard Deviation of the minimum air temperature, °C;
$\sigma_{surface}$ = Standard Error of the estimated minimum pavement temperature, °C;
n = multiplier associated with the desired reliability for the design temperature;
A, B = the slope and intercept of the equation relating the minimum pavement surface temperature to the minimum air temperature.

This equation relates the winter design temperature to the winter climate at the pavement site, and allows the designer to specify the reliability of the design temperature according to the risk he is willing to take that the design will fail and the pavement will crack.

5. RELATIONSHIP BETWEEN MINIMUM PAVEMENT AND AIR TEMPERATURES

In this study, the relationship between the minimum pavement temperature and the minimum air temperature for several locations was obtained by analyzing periodic measurements of the air temperature and the temperature at several depths in the pavement structures.

Table 1

Sites for Pavement Temperature Analysis

Location	Pavement Thickness mm	Minimum Air Temp. °C[1]	Probe Depths, mm	Data Periods
Lamont, AB	100	-48	12,33,66,100	1991-92, 1992-93, 1993-94
Hearst, ON	100	-47	10,35,70,100,175	1991-92, 1992-93, 1993-94
Princeton, BC	203	-45	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Merritt, BC	100	-42	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Sherbrooke, QC	120	-40	13,50,100,163,300,420,540,845,1150,1455,1760	1992-93, 1993-94, 1994-95
Cache Creek, BC	140	-40	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Lumby, BC	150	-36	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Lillooet, BC	102	-32	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95

1. Long term minimum air temperature (97.5% Probability). Data from Huber, G.A., "Weather Database for the SUPERPAVE Mix Design System", SHRP-A-648A, February, 1994.

5.1 Pavement Sites for Temperature Analysis

Analysis of minimum pavement temperature vs minimum air temperature data was carried out for eight Canadian locations. The pavement sites used are described in Table 1. They were selected to meet the following criteria:

- pavement thickness ≥100 mm;
- temperature readings during three winters;
- minimum winter temperatures distributed over the range expected in Canada.

A list of all the sites considered is shown in Appendix B.

The pavement thickness ranged from 100 to 203 mm. The minimum limit was chosen to ensure that the pavements evaluated would be representative of those for which asphalt binder characteristics are a major factor controlling thermal cracking resistance. Asphalt concrete pavements less than 100 mm thick may crack by a mechanism different from that for thick pavements, and not dependent on the minimum service temperature of the binder.[3]

All of the selected sites had temperature data for three winters.

Some sites were rejected for various reasons:

- Data from the Ste Anne Test Road were not used, because only monthly summaries are available. A search of archives at Manitoba Highways and Transportation failed to find the daily temperature measurements. The summary data was used to validate the equation between minimum pavement and air temperatures developed using the other sites.

- Extensive data from a test road at McLean, SK was received in paper form. It was decided not to use it because data for two other sites with similar winter temperatures (Lamont, AB and Hearst, ON) were available in a format suitable for computer analysis. Minimum temperatures selected manually from this data set were used to validate the relationship between minimum pavement and air temperatures.

- Data from Kamloops and Oliver, BC was found to be unacceptable, because significant periods of temperature probe or datalogger malfunction in their temperature histories make the data unreliable.

- Two Long Term Pavement Performance (LTPP) sites in northeastern United States, for which temperature data is being collected by FHWA, were evaluated. They were found to be unsuitable because daily minima at selected depths in the pavement rather than periodic temperature measurements are reported. It is not possible to extract corresponding minimum air and pavement surface temperatures from this data.

The range of historical minimum temperatures at the selected sites is -32° to -48°C. The range of minimum winter temperatures in the populated regions of Canada is about 0° to -54°C. Therefore, low temperature regions are well represented. However, very few sites with mild climates are available. There are no instrumented sites in Atlantic Canada or the coastal region of British Columbia.

The lack of data for very mild winter climates is not considered serious because all the sites used experience mild temperatures during part of the winter. For example, southern and coastal locations never experience the lowest temperatures observed at the sites used in this study. However, conditions in November at northern locations will not differ much from those observed during the coldest part of the winter farther south. Therefore, observations during mild periods at northern locations should provide acceptable estimates of minimum pavement temperatures in areas with mild winters. The range of winter climates represented by the pavement sites selected is broad enough that the relationship between minimum pavement and air temperatures developed should be suitable for all regions of Canada.

Less conservative estimates of minimum pavement temperatures might be desirable for lower latitudes where sunlight is more intense during winter. However, solar energy is not a large contributor to the pavement surface temperature during the coldest part of winter, so the bias due to this effect will be small. The practical effect of using winter design temperatures based on northern data in this situation is that the actual risk of thermal cracking may be slightly lower than the design risk.

5.2 Time Period for Temperature Analysis

Temperature data for the months of November, December, January and February only were used. These months are approximately equally spaced around the winter solstice, when the intensity of sunlight is lowest in the northern hemisphere. During this time, the effect of sunlight on the pavement surface temperature is lowest, and the effect of the air temperature is greatest. These months are also those when almost all thermal cracking of pavements occurs.

5.3 Estimation of Pavement Surface Temperatures

The lowest temperature experienced by a pavement is at the surface, but no direct measurements of pavement surface temperatures are available for the sites used in this study. Therefore, the pavement surface temperature at each time was estimated by extrapolating the top three pavement temperature vs depth measurements using a second degree polynomial. The data sets provided by highway agencies consisted of periodic measurements of the air temperature and the temperature at several depths in the pavement structure. The temperature readings were at one or two hour intervals. At least two of the temperatures were in the asphalt concrete layer. At some locations, the third was in the granular base. This probably had no effect on the estimated surface temperature, because of the similarity in thermal conductivity of asphalt concrete and compacted aggregate.

This is confirmed in Figure 2, which shows typical temperature profiles in 100 mm and 203 mm thick pavements. The shape of the temperature profile in a pavement depends primarily on the air temperature history at the pavement location. It will be different at different times. There could be several inflection points, depending on the air temperature history. However, as shown in Figure 2, there is no abrupt discontinuity in the slope near the pavement/subgrade interface that might affect the estimated surface temperature.

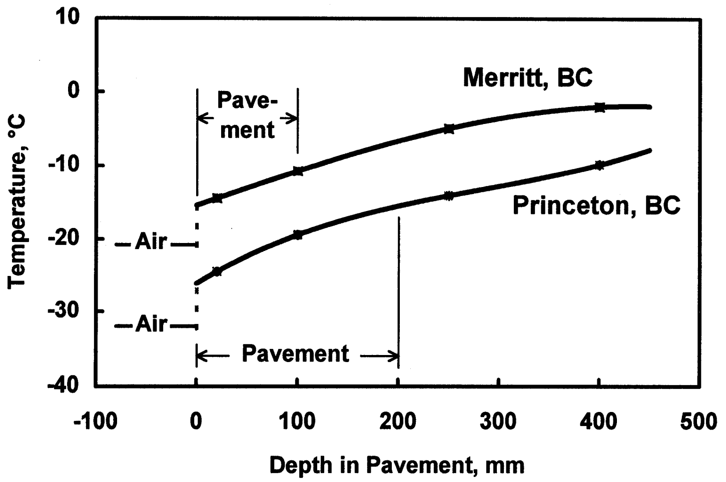

Figure 2. Temperature Profiles in Pavements.

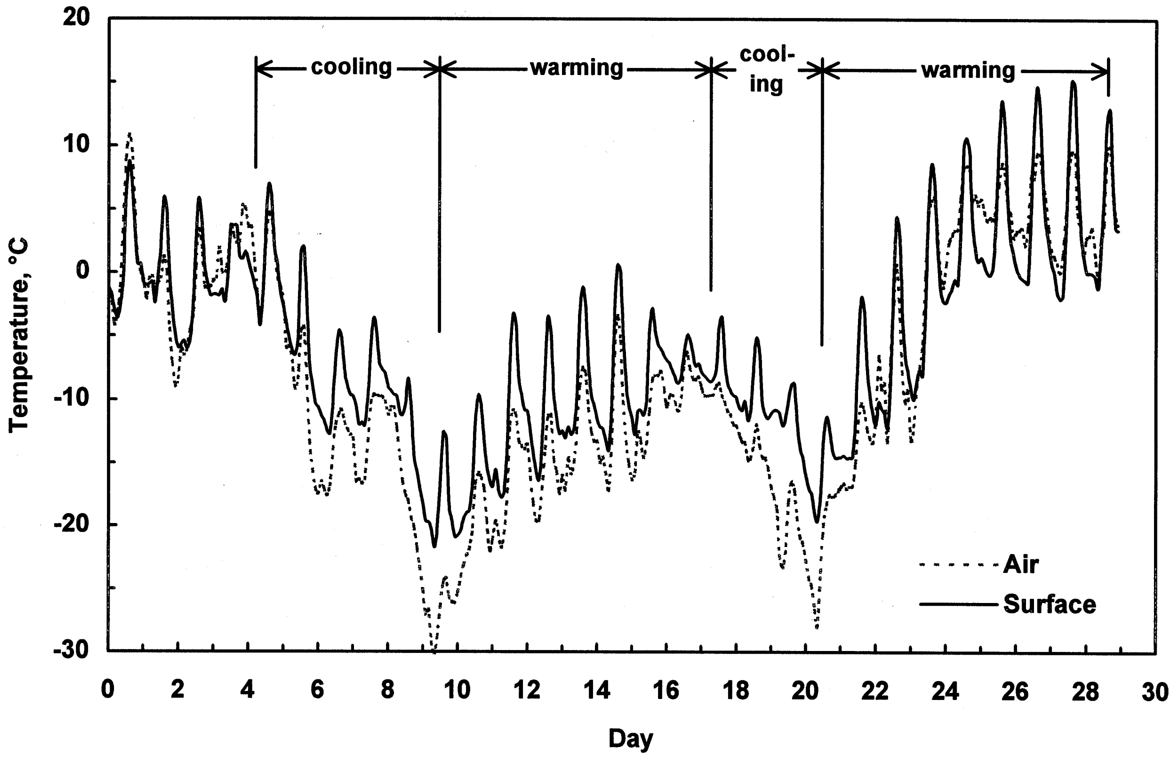

Figure 3. Air and Pavement Temperatures Showing Weather Related Cooling and Warming Periods.

Pavement surface temperatures estimated in this way are not true surface temperatures. The temperature gradient near the surface is affected by the local topography, sunlight, wind, snow cover and precipitation. However, the extrapolation method provides a standardized means of determining the surface temperature for design purposes that gives values not much different from the true temperature. It is also consistent with the method used in the validation of the SUPERPAVE low temperature stiffness criteria.[3]

5.4 Selection of Minimum Air and Minimum Pavement Temperatures

For each site, sets of minimum air and associated minimum pavement temperatures were selected manually from the temperature measurements with the aid of temperature vs time plots. A typical plot for Lamont, AB during February 1992 is shown in Figure 3. Cooling periods were from February 5-10, and from February 18-21. Warming occurred from February 10-18, and February 21-29. The minimum pavement surface temperature usually occurred at the same time, or a few hours after the associated minimum air temperature.

Not all daily minimum temperatures were selected. Only those resulting from weather related cooling cycles lasting more than one day were included. The lowest temperature during winter will always occur at the end of a weather related cooling period. Therefore, the daily minima during cooling periods should be representative of those which occur at the lowest temperatures at other locations during winter.

Minimum pavement temperatures occurring during warming periods were not used because these are unduly affected by the low subgrade temperatures resulting from the previous cooling period. They are sometimes lower than the minimum air temperature. This is due to the large heat capacity of the subgrade, which warms more slowly than the air. Because these minima are affected more by subgrade conditions than by the air temperature, and they are not representative of the behaviour at the lowest temperature, they were not included in the analysis.

Long periods of relatively constant air temperature also result in pavement temperatures that differ little from the air temperature. The temperature minima that occur during these periods are daily minima caused by setting of the sun. They are not related to cooling caused by weather changes, and they are not typical of the minimum that occurs at the lowest temperature during the winter. Therefore, they are of no interest for design purposes, and were excluded from the database.

The number of data points for each site ranged from 131 at the coldest location (Lamont, AB) to 36 at the warmest (Lillooet, BC). This is a reflection of the number of weather related cooling cycles during the three winters for which data was available. Colder climates generally had more and longer cooling periods.

5.5 Correlation of Minimum Pavement and Minimum Air Temperatures

Regression analysis was used to determine the relationship between the minimum air and pavement temperatures at each site. The results are summarized in Table 2. More detailed results are given in Appendix C. A quadratic model did not produce significantly better fit than the linear model used.

Table 2

Summary of Pavement Temperature Analyses

Site	Lowest Air Temp., °C	Regression				
		Data Sets	R^2	Slope	Intercept	SE
Lamont, AB	-52.5	131	0.938	0.743	-0.54	1.97
Hearst, ON	-40.0	105	0.928	0.783	1.03	1.62
Sherbrooke, QC	-39.3	71	0.912	0.703	-0.14	1.71
Cache Creek, BC	-32.2	96	0.951	0.759	0.27	1.17
Princeton, BC	-32.0	84	0.986	0.798	0.15	0.75
Merritt, BC	-31.6	80	0.968	0.784	0.61	1.09
Lumby, BC	-29.0	86	0.967	0.788	1.01	1.07
Lillooet, BC	-25.0	36	0.979	0.955	1.03	0.89
All (except Lillooet)		653	0.954	0.749	0.00	1.52

At all of the pavement sites, there was an excellent correlation ($R^2 = 0.91$ to 0.99) between the minimum pavement surface temperature and the minimum air temperature. Except for Lillooet, BC, the slope of the regression line was in the narrow range of 0.7 to 0.8.

The data from Lillooet, BC is not consistent with that at the other locations. This location is known for deep frost penetration, which may be related to the coarse 'bouldery' subgrade there. This may inhibit heat transfer from lower depths by conduction, resulting in faster cooling near the surface than occurs with more dense graded subgrades. Regardless of the cause, this site is deemed to be an outlier, and was not used in the subsequent data analysis.

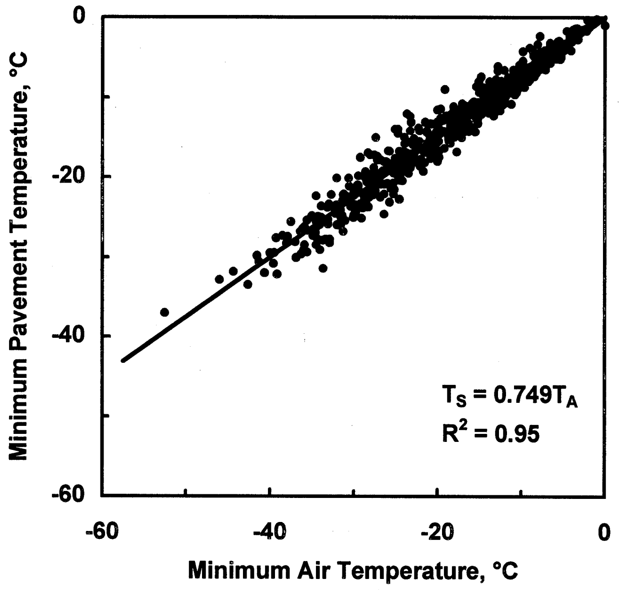

Figure 4. Relationship Between Minimum Pavement and Air Temperatures for Seven Canadian Locations.

The different behaviour at Lillooet compared to the other sites examined suggests that subgrade characteristics might affect the temperature profile in the pavement structure, and the surface temperature. This could be an area for future research.

Regression analysis was also used to determine if the relationship between minimum air and pavement temperatures at the other locations is site dependent. As shown in Table 3, it is not, at the 95% confidence level. This is indicated by the very large values of the standard deviations of the coefficients for the site variables compared to the coefficient values, by the high P-values for these variables, and by the fact that the range between the upper and lower confidence limits for the site coefficients includes the value zero. The P-value is the probability that a t-statistic as large as that shown for the coefficient would be observed by chance. A P-value of 1 indicates that the variable has no statistical significance.

The minimum air temperature variable is highly significant. The standard error of the coefficient is small relative to the coefficient value, the P-value is zero, indicating that there is no probability that the observed t-statistic would be obtained by chance, and the range of the lower and upper confidence limits for the coefficient does not include zero.

The intercept of the equation for all sites is also not statistically significant at the 95% confidence level. Therefore, a single equation with intercept = 0 can be used to represent the relationship between the minimum pavement temperature and the minimum air temperature for all locations. This relationship is shown in Figure 4, and is given by the equation:

$$T_S = 0.749T_A \qquad (2)$$

where T_S = minimum pavement surface temperature, °C;
T_A = minimum air temperature, °C.

This equation is based on 653 data points from seven locations. More than 95% of the variance in the minimum pavement temperature is accounted for by the variance in the minimum air temperature. The Standard Error of minimum pavement temperatures estimated using equation 2 is 1.5°C.

Table 4 shows a comparison of equation 2 with the regression equations for the individual pavement sites for estimating the minimum pavement surface temperature. The minimum pavement temperatures were calculated at the lowest air temperature observed at each site during the time when data was collected. The differences are small, except for Lillooet, BC, where the behaviour is different from that at the other sites. This confirms that the combined equation represents the relationship between minimum pavement and minimum air temperatures satisfactorily.

Table 3

Regression Analysis
Minimum Pavement Temperature vs Minimum Air Temperature and Site

Regression Statistics	
Multiple R	0.979
R^2	0.959
Adjusted R^2	0.959
Standard Error	1.46
Observations	653

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	8	32303.3	4037.9	1896.8	0.0
Residual	644	1371.0	2.1		
Total	652	33674.2			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-167.3	6026283.3	-0.00003	1.00	-11833700.4	11833365. 8
Lamont, AB	167.2	6026283.3	0.00003	1.00	-11833365.9	11833700.2
Hearst, ON	167.8	6026283.3	0.00003	1.00	-11833365.3	11833700.9
Sherbrooke, QC	168. 5	6026283.3	0.00003	1.00	-11833364.6	11833701.5
Cache Creek, BC	167.6	6026283.3	0.00003	1.00	-11833365.5	11833700.7
Princeton, BC	166.9	6026283.3	0.00003	1.00	-11833366.2	11833700.0
Merritt, BC	167.5	6026283.3	0.00003	1.00	-11833365.5	11833700.6
Lumby, BC	168.0	6026283.3	0.00003	1.00	-11833365.1	11833701.1
Minimum Air Temp.	0.762	0.007	107.8	0.00	0.748	0.776

Table 4

Comparison of Minimum Pavement Temperatures
Estimated from Site Specific and Combined Regression Equations

Site	**Lowest Air Temp., °C**	**Estimated Lowest Pavement Temperature, °C**		
		Site	**Combined**	**Difference**
Lamont, AB	-52.5	-39.6	-39.3	0.2
Hearst, ON	-40.0	-30.3	-30.0	0.3
Sherbrooke, QC	-39.3	-27.8	-29.4	-1.7
Cache Creek, BC	-32.2	-24.1	-24.1	0.0
Princeton, BC	-32.0	-25.4	-24.0	1.4
Merritt, BC	-31.6	-24.2	-23.7	0.5
Lumby, BC	-29.0	-21.8	-21.7	0.1
Lillooet, BC	-25.0	-22.8	-18.7	4.1

There are few measurements of pavement surface temperatures in winter. However, some examples from Ste Anne, MB,[8] McLean, SK,[9,10] and several locations in Michigan[11] are shown in Table 5. The minimum values shown are the lowest temperatures observed during the designated winters. In all but one case, the difference between the observed minimum pavement temperature and that estimated using equation 2 is less than two times the standard error of the predicted value. This indicates that the measurements at these locations belong to the same population as those used to develop the relationship between minimum pavement and air temperatures.

For the locations in Table 5, the observed minimum pavement temperature is on average 1°C warmer than that predicted by equation 2. Therefore, equation 2 appears to be slightly conservative for estimating minimum pavement temperatures for design purposes.

Table 5

Comparison of Observed and Estimated Minimum Pavement Temperatures

Winter	Location	Minimum Air Temp., °C	Minimum Pavement Temp., °C		Difference Obs. - Est.
			Measured	Equation 2	
1968-69	Ste Anne, MB - TR1	-40.6	-31.4	-30.4	-1.0
	Ste Anne, MB - TR2	-39.4	-29.4	-29.5	0.1
	Ste Anne, MB - TR3	-40.3	-29.4	-30.2	0.7
1974-75	McLean, SK - 9	-33.9	-23.3	-25.4	2.1
	McLean, SK - 11	-33.9	-23.3	-25.4	2.1
1995-96	Brighton, MI	-23.7	-19.8	-17.8	-2.0
	New Buffalo, MI	-23.3	-17.5	-17.5	0.0
	Port Sanilac, MI	-23.6	-15.8	-17.7	1.9
	Traverse City, MI	-31.8	-20.6	-23.8	3.2
	Jonesville, MI	-26.1	-18.0	-19.5	1.5
	Farwell, MI	-37.2	-24.9	-27.8	2.9
	Alpena, MI	-23.4	-15.9	-17.5	1.6
	Brevort, MI	-30.3	-24.1	-22.7	-1.4
	Deerton, MI	-33.3	-23.8	-24.9	1.1
	Carney, MI	-36.8	-24.7	-27.6	2.9
	Iron River, MI	-36.9	-27.1	-27.6	0.5

6. WINTER DESIGN TEMPERATURE ALGORITHM

The winter design temperature is the lowest expected pavement temperature, which is the lowest expected surface temperature. The winter design temperature is given by equation 1, with coefficients A = 0.749, B = 0, and $\sigma_{surface}$ = 1.5°C. This gives:

$$T_{design} = 0.749(T_{air} - n\sigma_{air}) - 1.5n \quad \text{...} \quad (3)$$

where T_{design} = winter design temperature, °C;
T_{air} = mean of minimum air temperatures at the pavement site, °C;
σ_{air} = Standard Deviation of the minimum air temperature, °C;
n = multiplier associated with the desired reliability for the design temperature.

The value of the reliability factor, *n* is related to the probability that the pavement surface temperature will fall below the value estimated using equation 2. It is determined from the standard normal distribution curve as follows:

The risk that the air temperature will fall at least one standard deviation below the mean minimum air temperature is 15.87%. The risk that the pavement temperature will fall at least one standard error below the value estimated from the correlation between minimum pavement and air temperatures is also 15.87%. The probability of both these events happening is $0.1587 \times 0.1587 = 0.0252$, or 2.5%. This corresponds to 97.5% reliability for a design temperature determined using these probability levels. Therefore, for 97.5% reliability, $n = 1.0$ in equation 3. Factors for use when other degrees of reliability are desired are given in Table 6.

Table 6

Reliability Factors for Winter Design Temperature

Reliability	Reliability Factor, n
90%	0.48
95%	0.76
97.5%	1.00
99%	1.28

Considering the high cost of effectively repairing thermal cracking damage, there seems to be no good reason to design for less than 95% reliability. A reliability of 90% implies that some cracking will occur during the first 10 years of the pavement's service life. At 95% reliability, some cracking can be expected during the first 20 years of service. Designing for 97.5% reliability will probably result in no thermal cracking during the usual design life of 20 years. This seems to be the optimum reliability level. A reliability of 99%, which virtually ensures no thermal cracking during the life of the pavement, appears to be unnecessarily high.

7. PROCEDURE FOR DETERMINING THE WINTER DESIGN TEMPERATURE

The only input data required for determining the winter design temperature are the long term mean and standard deviation of the annual minimum air temperatures at the site. The procedure is:

1. Determine the long term mean of the minimum air temperatures at the pavement site and its standard deviation. Usually this data will not be available for the exact pavement location, so the data for the nearest weather station having long term records should be used. Long term minimum temperature data are published in the “Weather Database for the SUPERPAVE Mix Design System”,[4] and in the computer program “SHRPBIND”.[12] (Note that the winter design temperatures or binder winter grades in these publications should NOT be used.) Canadian weather information is also available in “SHRPBIND Weather Database: Canadian Weather Station Data”.[13]

2. If there is no nearby weather station, data for two or three more distant locations will have to be used. These should be selected to have winter climate similar to that at the pavement site. This can be checked by comparing the measured minimum air temperature at the pavement site with those at the weather stations being considered during the winter prior to construction of the pavement.

3. Calculate the winter design temperature using equation 3. The reliability for the winter design temperature is at the discretion of the designer. The reliability factor corresponding to the desired reliability is given in Table 6.

4. If data for more than one weather station is being used, calculate the winter design temperature for each station and average the results.

5. The binder winter grade is the grade whose minimum service temperature is equal to or lower than the winter design temperature.

8. WINTER DESIGN TEMPERATURES FOR CANADIAN LOCATIONS

Winter design temperatures for representative Canadian locations were determined using equation 3, and are shown in Table 7. A reliability of 97.5% was used for the design temperature. The binder winter grade shown for each location is the SUPERPAVE grade whose minimum service temperature is equal to or lower than the winter design temperature for the pavement site.

The Canadian prairies, northern Ontario and northern Quebec have very low winter temperatures requiring PG xx-40 binder at most locations. PG xx-46 binder is needed to avoid thermal cracking at Peace River in northern Alberta. Southern Ontario, the St Lawrence valley and Atlantic Canada locations usually need PG xx-22 or PG xx-28 binder. The west coast has warmer winters than the east coast. The winter binder grade for Vancouver is PG xx-16, compared to PG xx-22 for Halifax and St. John's.

8.1 Low Temperature Performance vs Winter Grade

No studies specifically designed to verify equation 3 have been done. However, thermal cracking performance data for five test road locations shown in Table 8 support the validity of this winter design equation. This table shows the thermal cracking performance of SUPERPAVE binder grades compared to the recommended winter grade determined using equation 3. No significance should be attached to the cracking frequencies in Table 8; only the presence or absence of thermal cracking is important in this analysis.

The binder winter grade for Lamont, AB[14] determined using equation 3 is PG xx-40. This is based on winter climate data for Fort Saskatchewan, AB, the nearest weather station. None of the binders used in the Lamont pavements meet the winter design requirement, and all except one have cracked. The uncracked section 5 was paved using the softer of the two PG xx-34 binders. Cracking is just beginning in the other PG xx-34 pavement after five winters. It appears that the design winter grade, PG xx-40, would perform satisfactorily at this location.

Table 7

Binder Winter Grades for Canadian Locations

Location	Minimum Air Temperature, °C[1]		Winter Design Temp., °C[2]	Recommended Winter Grade[2]	SUPERPAVE Algorithm Winter Grade[3]	FHWA Interim Guideline Winter Grade[4]
	Mean	SD				
Vancouver, BC	-11	3.5	-12.4	PG xx-16	PG xx-22	PG xx-22
Kamloops, BC	-26	6.2	-25.6	PG xx-28	PG xx-40	PG xx-40
Prince George, BC	-38	5.5	-34.1	PG xx-40	PG xx-52	PG xx-40
Whitehorse, YT	-44	3.6	-37.2	PG xx-40	PG xx-52	PG xx-46
Hay River, NT	-47	3.0	-39.0	PG xx-40	(PG xx-58)	PG xx-52
Edmonton, AB	-41	4.2	-35.4	PG xx-40	PG xx-52	PG xx-46
Calgary, AB	-35	2.9	-29.9	PG xx-34	PG xx-46	PG xx-40
Lethbridge, AB	-36	4.2	-31.6	PG xx-34	PG xx-46	PG xx-40
Peace River, AB	-46	6.2	-40.6	PG xx-46	(PG xx-64)	PG xx-46
Saskatoon, SK	-40	6.0	-36.0	PG xx-40	PG xx-52	PG xx-40
Prince Albert, SK	-44	4.2	-37.6	PG xx-40	(PG xx-58)	PG xx-46
Regina, SK	-39	4.5	-34.1	PG xx-40	PG xx-52	PG xx-40
Winnipeg, MB	-40	3.5	-34.1	PG xx-40	PG xx-52	PG xx-40
Thompson, MB	-45	2.2	-36.9	PG xx-40	PG xx-52	PG xx-46
Brandon, MB	-37	4.1	-32.3	PG xx-34	PG xx-46	PG xx-40
Windsor, ON	-22	5.0	-21.7	PG xx-22	PG xx-34	PG xx-34
Toronto, ON	-25	2.8	-22.3	PG xx-28	PG xx-34	PG xx-34
North Bay, ON	-35	3.7	-30.5	PG xx-34	PG xx-46	PG xx-40
Ottawa, ON	-31	3.4	-27.3	PG xx-28	PG xx-40	PG xx-34
Kapuskasing, ON	-41	2.8	-34.3	PG xx-40	PG xx-52	PG xx-46
Dryden, ON	-40	2.7	-33.5	PG xx-34	PG xx-46	PG xx-40
Thunder Bay, ON	-35	3.2	-30.1	PG xx-34	PG xx-46	PG xx-40
Montreal, QC	-29	3.0	-25.5	PG xx-28	PG xx-40	PG xx-34
Quebec, QC	-31	2.6	-26.7	PG xx-28	PG xx-40	PG xx-34
Amos, QC	-42	4.1	-36.0	PG xx-40	PG xx-52	PG xx-46
Chibougamau, QC	-42	2.5	-34.8	PG xx-40	PG xx-52	PG xx-46
Arvida, QC	-35	2.9	-29.9	PG xx-34	PG xx-46	PG xx-40
Sherbrooke, QC	-35	2.7	-29.7	PG xx-34	PG xx-46	PG xx-40
Gaspé, QC	-29	4.0	-26.2	PG xx-28	PG xx-40	PG xx-34
Fredericton, NB	-32	3.0	-27.7	PG xx-28	PG xx-40	PG xx-34
Saint John, NB	-28	3.6	-25.2	PG xx-28	PG xx-40	PG xx-28
Moncton, NB	-27	2.8	-23.8	PG xx-28	PG xx-34	PG xx-34
Halifax, NS	-22	2.6	-19.9	PG xx-22	PG xx-28	PG xx-28
Antigonish, NS	-26	5.7	-25.2	PG xx-28	PG xx-40	PG xx-40
Truro, NS	-29	3.4	-25.8	PG xx-28	PG xx-40	PG xx-34
Charlottetown, PE	-25	3.0	-22.5	PG xx-28	PG xx-34	PG xx-34
St John's, NF	-20	3.9	-19.4	PG xx-22	PG xx-28	PG xx-28
Grand Falls, NF	-26	3.9	-23.9	PG xx-28	PG xx-34	PG xx-34

1. Long term minimum air temperature. Data from Reference 4.
2. Winter Design Temperature from equation 3 (97.5% reliability).
3. Winter Design Temperature = Mean Minimum Air Temperature - 2 × SD (97.5% reliability).
4. If the Mean Minimum Air Temperature ≤-28°C, Winter Design Temperature = Mean Minimum Air Temperature.

Table 8

Thermal Cracking Performance of SUPERPAVE Graded Binders

Location	Winter Design Temp., °C[1]	Recommended Winter Grade[1]	Test Section	Grade Used	Cracks/km
Lamont, AB	-34.2	PG xx-40	1	PG 58-22	83
			2	PG 52-28	144
			3	PG 46-34	0
			4	PG 58-22	137
			5	PG 64-28	33
			6	PG 52-28	10
			7	PG 52-34	<1
Hearst, ON	-34.3	PG xx-40	AA	PG 46-34	4
			A	PG 52-28	2
			B	PG 52-28	2
			BB	PG 52-28	0
Sherbrooke, QC	-29.7	PG xx-34	A	PG 52-34	0
			B	PG58-22	36
			C	PG64-28	17
			D	PG52-28	0
Sturgeon Falls, ON	-30.5	PG xx-34	North	PG 52-28	>90
			Centre	PG 52-34	0
			South	PG 52-28	15
Wilcox, PA	-25.0	PG xx-28	T-1	PG 64-16	604
			T-2	PG 64-16	171
			T-3	PG 64-22	0
			T-4	PG 64-22	197
			T-5	PG 58-22	420
			T-6	PG 64-28	72

1. Equation 3 (97.5% Reliability)

The winter design temperature for Hearst, ON[14] is based on data from the weather station at Kapuskasing, ON. There are only three binders at this site; sections B and BB contain the same binder. None of the binders used at Hearst satisfy the recommended winter grade requirement, and pavements made with all of them have cracked during the first five years of service. The uncracked section is 100 mm thick, compared to only 50 mm for the others. However, this pavement has started to crack outside the designated test section boundary. Use of the recommended winter grade of binder (PG xx-40) at this location would probably prevent thermal cracking.

At Sherbrooke, QC,[14] one of the pavement sections was paved with the recommended winter grade of binder (PG xx-34), and it has not cracked after four winters. One section made with PG 52-28 binder is also uncracked, but the other section paved with this winter grade is cracked. The section paved with PG 58-22 binder is also cracked. Therefore, the thermal cracking performance of the binders at this site is consistent with the winter design grade determined using equation 3.

The recommended winter grade for Sturgeon Falls, ON,[15] determined from climatic data at North Bay, ON, is PG xx-34. Two sections at this site were paved with the same PG 52-28 binder, which does not meet the winter design requirement, and both are cracked. The other section, paved with the recommended winter grade, is not cracked after three winters. Therefore, it appears that using the winter grade of binder determined using equation 3 will provide resistance to thermal cracking at this location.

The winter design temperature for the Pennsylvania test road near Wilcox, PA[16] was determined from air temperature data at Ridgway, PA. The winter design grade determined using equation 3 is PG xx-28. After seven winters, all but one section of the test pavement had cracked. The binder in the uncracked section did not meet the winter design requirement. One section made with the recommended winter design grade did crack. However, the critical temperature of this binder is at the boundary between the PG xx-22 and the PG xx-28 grades. Since there may be a 15% probability that a binder graded according to the SUPERPAVE criteria may crack above its critical temperature,[3] the behaviour of the binders at this location is not inconsistent with expectations.

All the performance data in Table 8 are for the early part of the service lives of the pavements. For this reason, it is not conclusive. However, in all but one questionable case, binders selected using the recommended winter design equation have resisted thermal cracking. Therefore, the validity of equation 3 for determining the winter design temperature of asphalt pavements is strongly supported. Additional studies should be carried out to confirm this conclusion. These can be simple experiments in which sections of pavement at the same location are constructed using two or three different binders, one of which is the grade determined by equation 3.

8.2 Comparison with the SUPERPAVE Algorithm

The binder winter grade selected for most locations using equation 3 is one or two grades less restrictive than is required by the original SUPERPAVE algorithm, or the FHWA interim design guideline. The exception is locations with very mild winter climate, where the difference between minimum pavement and minimum air temperatures is small.

The SUPERPAVE winter design temperature is the lowest expected air temperature at the design reliability. For 97.5% reliability, the design temperature is two times the standard deviation of the minimum air temperature below the mean. This algorithm assumes that the minimum pavement temperature in winter is equal to the minimum air temperature. This is not a bad assumption if the temperature in winter rarely falls below freezing. However, as has been shown in this study, minimum pavement temperatures are significantly warmer than the minimum air temperature at locations where the winters are very cold. This is due to heat transfer from the warmer subgrade to the surface. The difference between pavement and air temperatures is larger when the air temperature is lower, because the heat flux is greater in this situation. This accounts for the higher minimum service temperature of winter grades selected for cold locations using equation 3, compared to the SUPERPAVE algorithm.

The FHWA interim guideline for determining the winter design temperature was introduced because the SUPERPAVE recommendation was found to be unrealistic for very cold locations. Some examples are shown in Table 7. If the mean minimum air temperature is -28°C or lower, the winter design temperature is the mean minimum air temperature, instead of the lowest expected temperature at the design reliability. This is equivalent to using a design reliability of 50% for cold locations. The interim guideline is not based on analysis of air and pavement temperatures, or pavement performance observations. However it does give more realistic design temperatures for cold locations than the original SUPERPAVE algorithm.

Winter design temperatures given by equation 3 are preferred over the FHWA recommendations, because this algorithm is based on an analysis of observed pavement and air temperatures, while the SUPERPAVE algorithm and FHWA interim guideline are not. In addition, equation 3 has been shown to select binder winter grades that resist thermal cracking in service.

9. SUMMARY AND RECOMMENDATIONS

1. The lowest expected pavement surface temperature should be used as the winter design temperature, because this is the lowest temperature which the pavement will experience.

2. Analysis of air and pavement temperature data for seven Canadian locations gave a linear relationship between the minimum pavement temperature and the minimum air temperature. A single equation represents the relationship between minimum pavement and air temperatures for all these locations, and accounts for 95% of the observed variance. This equation gave good estimates of measured minimum pavement temperatures at 13 other locations.

3. An equation for estimating the winter design temperature for a pavement site from the local winter temperature history has been developed. This equation includes a factor for the desired reliability of the design temperature, and can be used with the SUPERPAVE paving mix design system.

4. The range of historical minimum temperatures at the sites used to define the parameters in the winter design temperature equation is -36° to -48°C. Therefore, the design equation should be suitable for use in any of the populated regions of Canada, where winter temperatures rarely fall below -54°C.

5. Additional air and pavement temperature data should be collected for validation of the winter design temperature equation. The data should consist of periodic measurements of the air temperature, and at three or more depths in the pavement structure. The temperature probes should be at locations where the pavement thickness is at least 100 mm.

6. Experience at a small number of locations indicates that a binder selected using the winter design equation developed in this study will resist thermal cracking. Additional studies are required to confirm this conclusion.

7. The winter design equation developed in this study gives a winter grade requirement that is one or two grades less restrictive for most locations than those obtained using the SUPERPAVE algorithm, or the FHWA interim winter design guideline. This design equation is preferred over the FHWA recommendations because it is based on analysis of observed air and pavement temperatures during winter, and has been shown to select binder winter grades that resist thermal cracking.

8. Design for thermal cracking resistance should preferably be at the 97.5% or higher reliability level, because the cost of effectively repairing damage from thermal cracking is high.

10. REFERENCES

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APPENDIX

Appendix A

SUPERPAVE Performance Graded Asphalt Binder Specification[1]

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-						PG 70-						PG 76-					PG 82-				
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40	10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
ORIGINAL BINDER																																					
Flash Point, °C, Minimum	230																																				
Maximum Temperature for Viscosity < 3000 mPas (ASTM D 4402), °C	135																																				
Dynamic Shear at 10 rad/s: Minimum Temperature for G*/sin δ > 1.00 kPa, °C	46			52							58					64						70						76					82				
ROLLING THIN FILM OVEN RESIDUE																																					
Mass Loss, %, Maximum	1.00																																				
Dynamic Shear at 10 rad/s: Minimum Temperature for G*/sin δ > 2.20 kPa, °C	46			52							58					64						70						76					82				
PRESSURE AGING VESSEL RESIDUE																																					
PAV Aging Temperature, °C	90			90							100					100						100 (110)[2]						100 (110)[2]					100 (110)[2]				
Dynamic Shear at 10 rad/s: Minimum Temperature for G*/sin δ < 5.00 MPa, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Flexural Creep Stiffness: Maximum Temperature for S(60) < 300 MPa, and m(60) > 0.300, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
Direct Tension at 1 mm/min:[3] Maximum Temperature for Failure Strain > 1%, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

1. Material property requirements from AASHTO Specification MP1, Edition 1A, September, 1993.
2. PAV conditioning temperature of 110°C to be used if the binder will be used in a desert climate.
3. If the creep stiffness is <300 MPa, the Direct Tension test is not required. If the creep stiffness is between 300 and 600 MPa, and m>0.300, the failure strain requirement may be used in lieu of the maximum stiffness requirement.

Appendix B

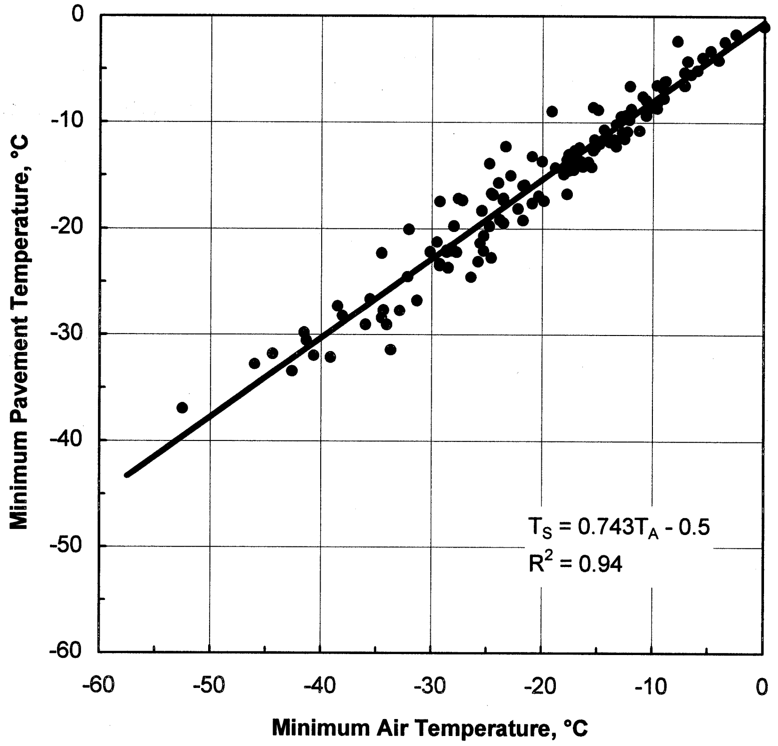
Air and Pavement Temperature Database

Location	Pavement Thickness mm	Minimum Air Temp. °C[1]	Probe Depths, mm	Data Periods
Lamont, AB	100	-48	12,33,66,100	1991-92, 1992-93, 1993-94
Ste Anne, MB	102	-47	0,102,457,1067,1676,2286,2896,3505,3810	1968,1968-69
Ste Anne, MB	254	-47	0,102,178,254,610,1219,1829,2438,3048,3658	1968,1968-69
Ste Anne, MB	102	-47	0,51,102,495,1092,1676,2286,2934,3543,3658	1968,1968-69
Hearst, ON	100	-47	10,35,70,100,175	1991-92, 1992-93, 1993-94
Invermere, BC	130	-47	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Westbridge, BC	90	-45	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Riondel, BC	130	-45	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Princeton, BC	203	-45	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Golden, BC	100	-44	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Golden, BC	140	-44	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Kelowna, BC	203	-44	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Merritt, BC	100	-42	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Kimberley, BC	80	-42	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Sherbrooke, QC	120	-40	13,50,100,163,300,420,540,845,1150,1455,1760	1992-93, 1993-94, 1994-95
Cache Creek, BC	140	-40	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Grand Forks, BC	100	-39	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Kamloops, BC	244	-38	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Farmington, ME	137	-37	25,69,112	1993-94, 1994-95
Revelstoke, BC	60	-36	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Lumby, BC	150	-36	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Kelowna, BC	102	-35	20,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Lillooet, BC	102	-32	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Rossland, BC	140	-31	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Creston, BC	190	-31	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Kingsgate, BC	230	-31	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Oliver, BC	150	-30	20,100,250,400,600,800,1000,1200,1400,1600,2000	1992-93, 1993-94, 1994-95
Winlaw, BC	220	-28	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Salmo, BC	250	-28	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95
Groton, CT	183	-27	25,92,158	1993-94, 1994-95
Castlegar, BC	90	-27	10,100,250,400,600,800,1000,1200,1400,1600,2000	1994-95

1. Long term minimum air temperature (97.5% Probability). Data from Huber, G.A., “Weather Database for the SUPERPAVE Mix Design System”, SHRP-A-648A, February, 1994.

Appendix C1

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Highway 637, Lamont, AB



Regression Statistics	
Multiple R	0.969
R^2	0.938
Adjusted R^2	0.938
Standard Error	1.97
Observations	131

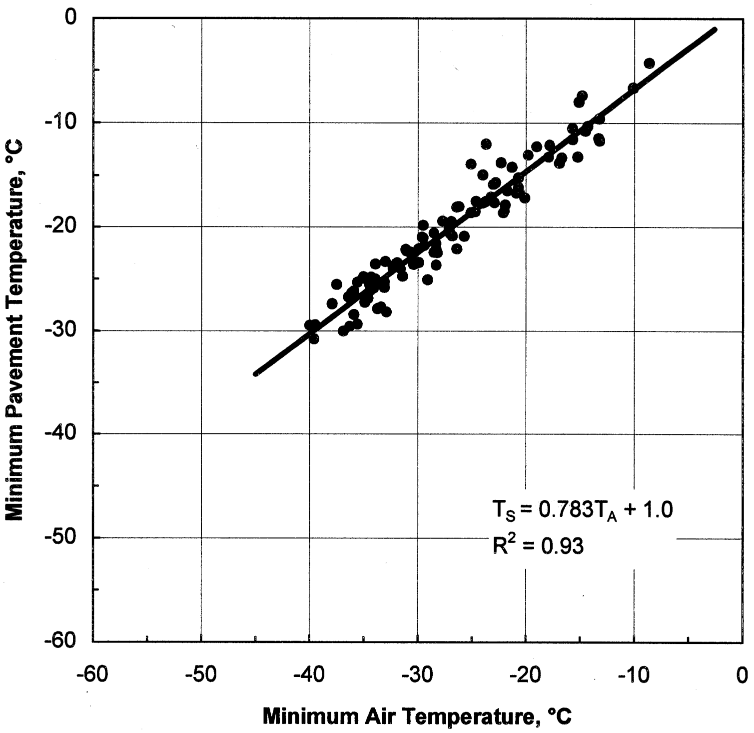
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	7666.0	7666.0	1966.6	5.86E-80
Residual	129	502.9	3.9		
Total	130	8168.8			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.539	0.386	-1.40	0.165	-1.303	0.225
Minimum Air Temp.	0.743	0.017	44.35	5.86E-80	0.710	0.777

Appendix C2

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Highway 631, Hearst, ON



Regression Statistics	
Multiple R	0.964
R^2	0.929
Adjusted R^2	0.928
Standard Error	1.62
Observations	105

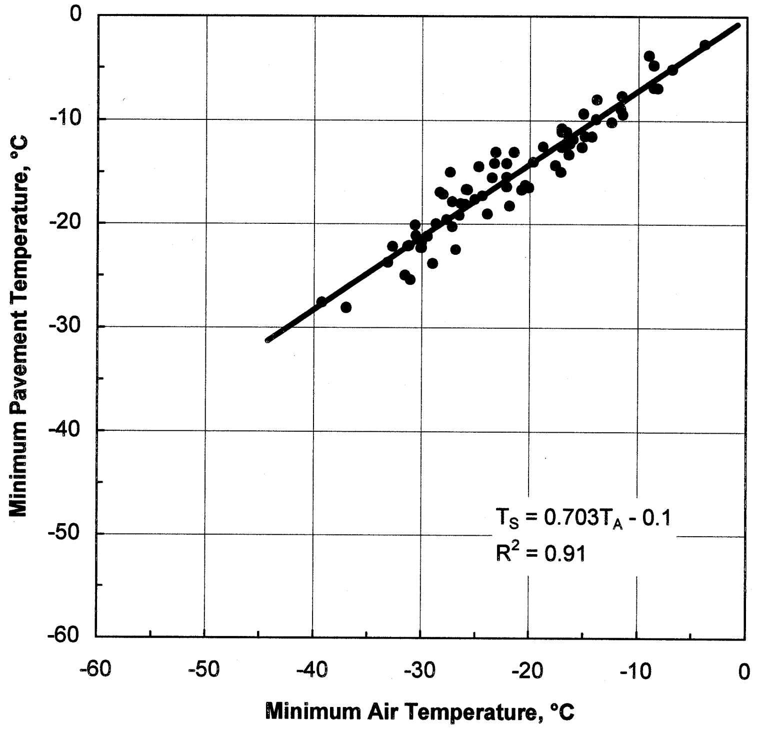
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1.0	3509.2	3509.2	1337.7	8.03E-61
Residual	103.0	270.2	2.6		
Total	104.0	3779.4			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.033	0.603	1.71	0.090	-0.162	2.227
Minimum Air Temp.	0.783	0.021	36.57	8.03E-61	0.741	0.826

Appendix C3

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Autoroute 10, Sherbrooke, QC



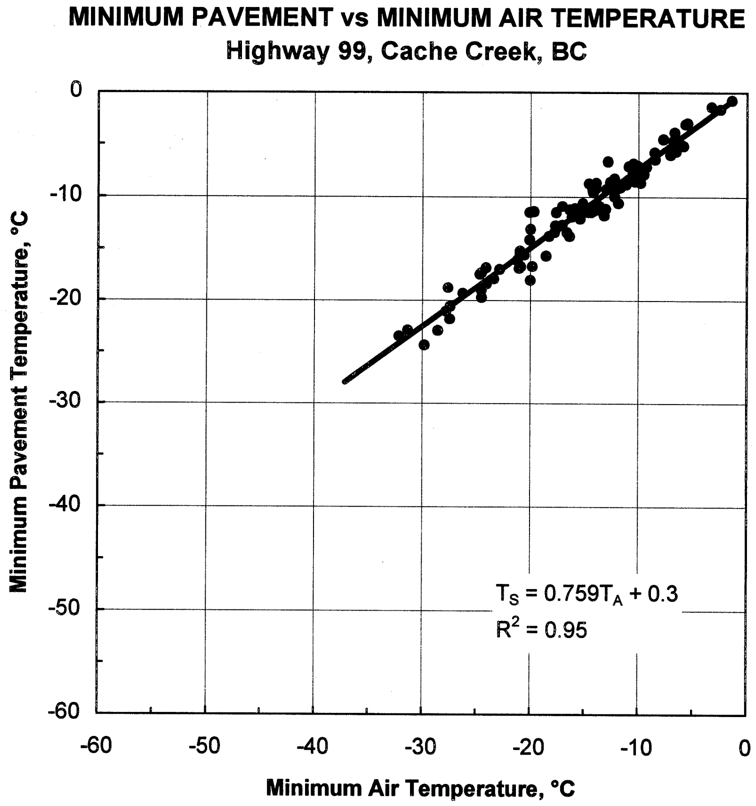
Regression Statistics	
Multiple R	0.956
R^2	0.913
Adjusted R^2	0.912
Standard Error	1.71
Observations	71

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2113.1	2113.1	726.7	2.31E-38
Residual	69	200.6	2.9		
Total	70	2313.8			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-0.137	0.606	-0.23	0.822	-1.346	1.072
Minimum Air Temp.	0.703	0.026	26.96	2.31E-38	0.651	0.755

Appendix C4



Regression Statistics	
Multiple R	0.976
R^2	0.952
Adjusted R^2	0.951
Standard Error	1.17
Observations	96

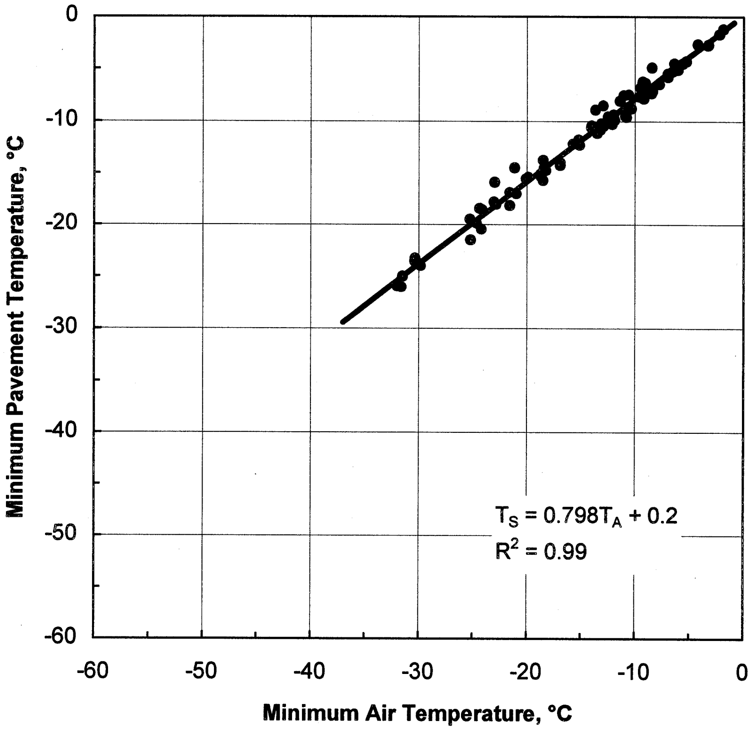
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2534.1	2534.1	1861.3	9.44E-64
Residual	94	128.0	1.4		
Total	95	2662.1			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.266	0.299	0.89	0.377	-0.328	0.860
Minimum Air Temp.	0.759	0.018	43.14	9.44E-64	0.724	0.794

Appendix C5

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Highway 3, Princeton, BC



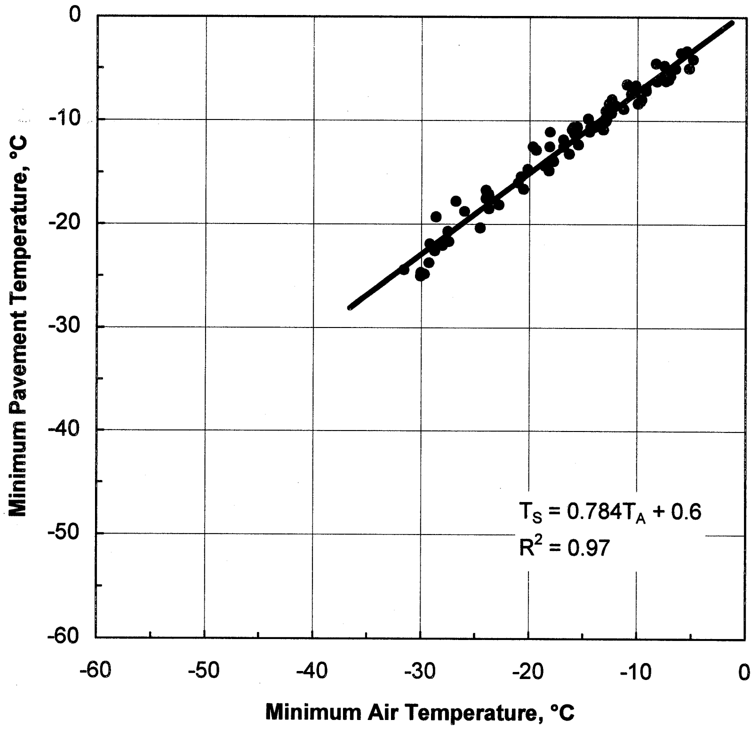
Regression Statistics	
Multiple R	0.993
R^2	0.986
Adjusted R^2	0.986
Standard Error	0.75
Observations	84

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3221.1	3221.1	5694.7	1.53E-77
Residual	82	46.4	0.6		
Total	83	3267.5			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.150	0.179	0.84	0.406	-0.207	0.506
Minimum Air Temp.	0.798	0.011	75.46	1.53E-77	0.777	0.820

Appendix C6



MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Highway 5, Merritt, BC

Regression Statistics	
Multiple R	0.984
R^2	0.968
Adjusted R^2	0.968
Standard Error	1.09
Observations	80

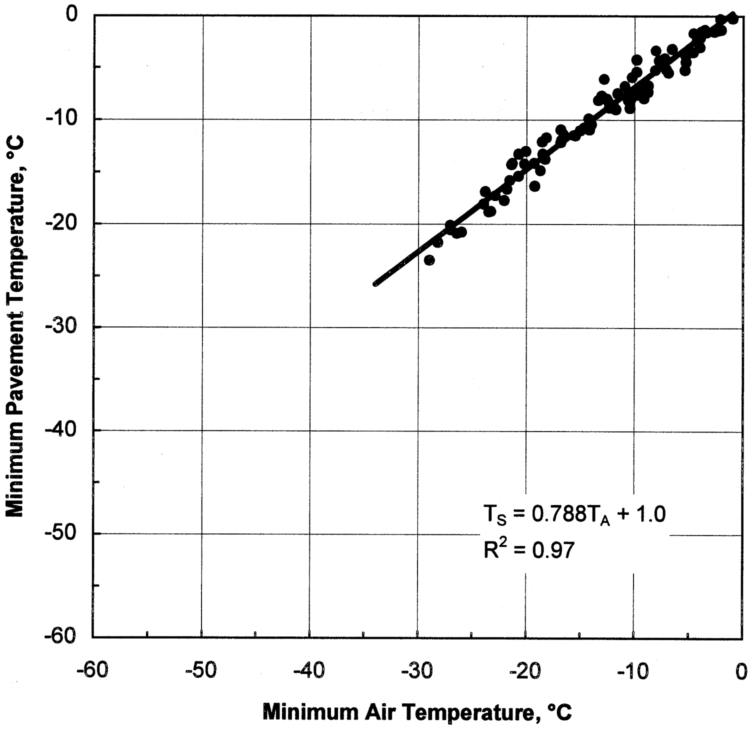
ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	2843.3	2843.3	2380.6	3.28E-60
Residual	78	93.2	1.2		
Total	79	2936.5			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.614	0.297	2.06	0.042	0.022	1.206
Minimum Air Temp.	0.784	0.016	48.79	3.28E-60	0.752	0.816

Appendix C7

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Mabel Lake Road, Lumby, BC



Regression Statistics	
Multiple R	0.984
R^2	0.968
Adjusted R^2	0.967
Standard Error	1.07
Observations	86

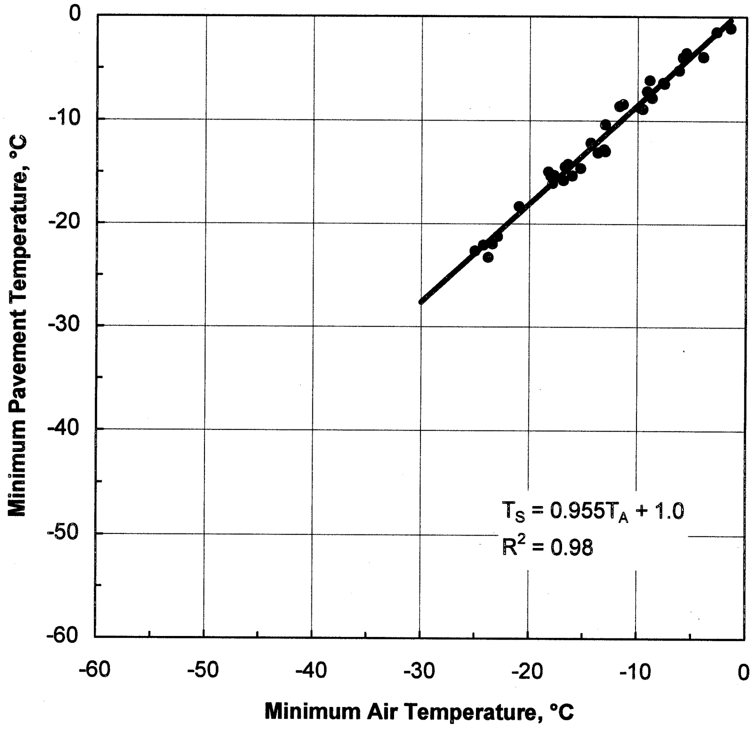
ANOVA

	df	***SS***	***MS***	***F***	***Significance F***
Regression	1	2877.5	2877.5	2528.7	1.77E-64
Residual	84	95.6	1.1		
Total	85	2973.1			

Variable	***Coefficient***	***Standard Error***	***t Stat***	***P-value***	***Lower 95%***	***Upper 95%***
Intercept	1.008	0.238	4.24	5.67E-05	0.535	1.480
Minimum Air Temp.	0.788	0.016	50.29	1.77E-64	0.757	0.819

Appendix C8

MINIMUM PAVEMENT vs MINIMUM AIR TEMPERATURE
Highway 99, Lillooet, BC



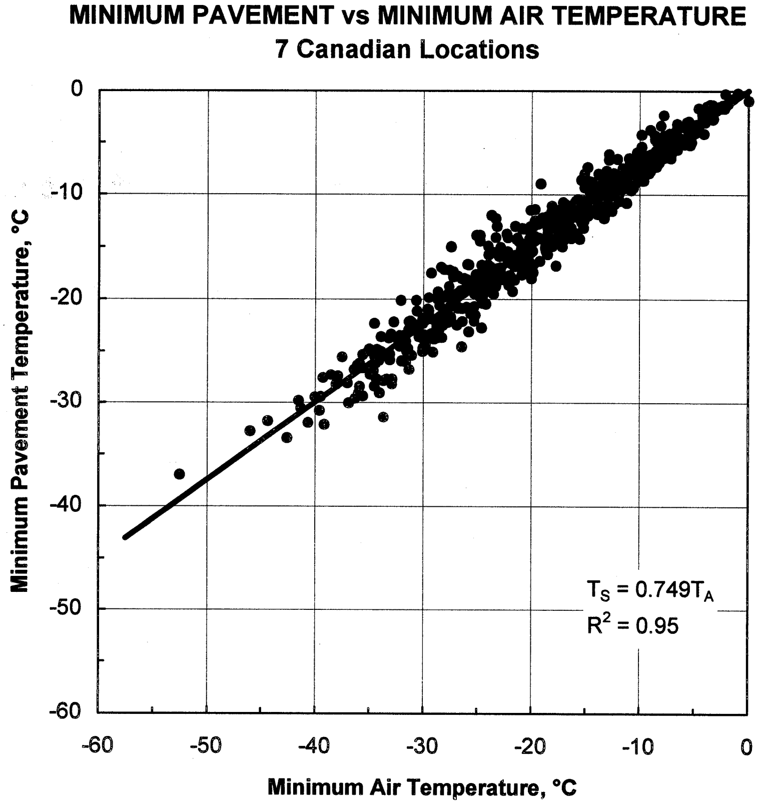
Regression Statistics	
Multiple R	0.990
R^2	0.980
Adjusted R^2	0.979
Standard Error	0.89
Observations	36

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	1307.2	1307.2	1652.4	2.06E-30
Residual	34	26.9	0.8		
Total	35	1334.1			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	1.032	0.352	2.935	0.006	0.317	1.747
Minimum Air Temp.	0.955	0.023	40.649	2.06E-30	0.907	1.002

Appendix C9



Regression Statistics	
Multiple R	0.977
R^2	0.955
Adjusted R^2	0.954
Standard Error	1.52
Observations	653

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	32166.7	32166.7	13912.0	0.0
Residual	652	1507.5	2.3		
Total	653	33674.2			

Variable	*Coefficient*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.000					
Minimum Air Temp.	0.749	0.003	265.3	0.0	0.744	0.755