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Thermal Fatigue Considerations in Asphalt Pavement Design

Pabitra Rajbongshi[1] and Animesh Das[2+]

Abstract: Thermal fatigue cracking of asphalt pavements is one of the distress phenomena in colder climates. It occurs due to repetitive application of thermal stress generated due to temperature variations. This paper attempts to develop a phenomenological thermal fatigue model which can be used for pavement design purpose. The reliability of a pavement section from thermal fatigue considerations has been estimated by performing simulation study. The proposed approach is illustrated through a numerical example.

***Key words**: Asphalt pavement; Reliability; Thermal fatigue; Thermal stress.*

Introduction

Thermal cracking of asphalt pavement is one of the primary modes of pavement failure in colder regions. These cracks are of two types, namely, low-temperature cracking and thermal fatigue cracking. A low-temperature cracking may happen at a single cooling event when thermal stress developed exceeds the tensile strength of the asphalt mix. This occurs when temperature is low and/or, the rate of fall of temperature is high. However, if thermal stress developed does not exceed the strength of asphalt mix, failure of pavement may still occur due to thermal fatigue caused by repetitive application of thermal load (i.e. temperature variation). The number of thermal cycles to cause a specific level of thermal cracking as failure may be termed as thermal fatigue life. The present paper attempts to develop a phenomenological thermal fatigue model which can be used while designing an asphalt pavement structure. Also, an approach for estimation of reliability of thermal fatigue failure has been proposed. This approach may be used during the pavement design process to check whether the thermal fatigue reliability is within the acceptable design limit.

Background

In general, thermal cracks occur in transverse direction of the pavements due to more restraint along the longitudinal direction. Cracks are approximately distributed at an equal spacing and the average crack spacing may range from 3 to 30m [1-8]. Primarily, thermal cracking models can be categorized as empirical [9-11] and mechanistic-empirical [4, 7, 12-14] models. Recent National Cooperative Highway Research Program (NCHRP) guidelines [14] adopted the mechanistic-empirical approach proposed by Hiltunen and Roque [12].

Generally, the thermal fatigue failure is measured by certain length of transverse cracks [13-14]. Similar to load fatigue (due to vehicular loading), a simple form of thermal fatigue equation may be expressed as [8, 13, 15],

$$N = d_1 \times \left(\frac{1}{\varepsilon}\right)^{d_2} \tag{1}$$

where, N is thermal fatigue life for certain level of thermal fatigue cracking at failure; ε is the thermal strain; and, d_1 and d_2 are regression constants. In Eq. (1), the thermal strain (ε) is related to the thermal fatigue life (N). Thermal strain is independent of relaxation modulus/stiffness of the asphalt mix, whereas the estimation of thermal stress includes relaxation modulus of the asphalt mix and stress dissipation phenomenon due to viscoelastic effect. Therefore, an attempt can be made to relate the thermal fatigue life with the thermal stress.

Proposed Methodology

Thermal fatigue failure of asphalt pavements is caused due to repetitive application of thermal cycles. It is important to know the thermal stress for a given temperature variation. In this section, first the estimation of thermal stress has been presented. Next, a thermal fatigue cracking model is proposed. The Long Term Pavement Performance (LTPP) [16] database is used in the present study. In the last section the developed equation is validated through another set of data.

Estimation of Thermal Stress

The thermal strain function ($\varepsilon(t)$) caused due to any temperature function ($T(t)$) may be expressed as,

$$\varepsilon(t) = \alpha \times [T_0 - T(t)] \tag{2}$$

where, α is the linear coefficient of thermal contraction (or expansion); T_0 is the reference temperature at which strain is zero; and t represents the time. The thermal stress is developed when this strain is restrained. Using Boltzman superposition theorem for linear viscoelastic material, the stress function ($\sigma(t)$) can be expressed as [13, 17],

$$\sigma(t) = \int_0^t E_r(t-t') \times \dot{\varepsilon}(t')\,dt' \tag{3}$$

where, $E_r(t)$ represents the relaxation modulus at time t; and t' is a

[1] Ph.D. Student, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.

[2] Associate Professor, Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208016, India.

[+] Corresponding Author: E-mail adas@iitk.ac.in

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variable of integration. The strain rate $\dot{\varepsilon}(t) = d\varepsilon(t)/dt = \alpha \times \dot{T}(t)$ (refer to Eq. (2)).

Considering (i) the relaxation modulus of asphalt mix can be modeled by a generalized Maxwell model [4, 12, 14], and (ii) the asphalt mix follows WLF (Williams-Landel-Ferry) equation of time-temperature superposition for thermo-rheologically simple material [17-22], the $\sigma(t)$ can be expressed as [23],

$$\sigma(t) = -\alpha \times \left[\int_0^t \left\{ \sum_{i=1}^{q+1} E_i e^{-\frac{1}{\rho_i}\int_0^{t-t'} 10^{\frac{C_1 \times (T(\tau)-T_r)}{C_2 + (T(\tau)-T_r)}} d\tau} \right\} \times \dot{T}(t')dt' \right] \quad (4)$$

where, E_i and ρ_i are the parameters of Maxwell model; and $q + 1$ is the number of Maxwell arms of the model; and, C_1 and C_2 are the regression constants of WLF equation. C_1 and C_2 can be obtained for known time-temperature shift factors [17-18]. The relaxation parameters E_i and ρ_i can also be determined using creep compliance data through Laplace transformation [14, 17].

To estimate the $\sigma(t)$ values, the temperature $T(t)$ is to be known. The daily temperature variation of pavement surface may be approximated as sinusoidal [24-26] and may be expressed as,

$$T(t) = T_{av} + T_f \sin(wt) \quad (5)$$

where, T_{av} is the daily average temperature; T_f is the temperature fluctuation around T_{av}; and ω is the angular frequency = $2\pi/24$ in radian per hour. Differentiating Eq. (5) and putting in Eq. (4), the final expression for $\sigma(t)$ can be obtained. Thus, the values of $\sigma(t)$ for given input parameters can be obtained numerically.

Development of Thermal Fatigue Equation

The basic task of the development of thermal fatigue equation is to correlate the number of thermal cycles with certain mechanistic parameters of the pavement which can be related to thermal fatigue failure. As an attempt to perform this, certain Strategic Highway Research Program (SHRP) sections have been selected from LTPP database [16] based on availability of various relevant data. Table 1 shows the LTPP data used in the present analysis. In Table 1, L represents the transverse crack length for 150m length of pavement section (one lane). Number of days is counted as equal to the number of thermal cycles (n). The following points are kept in mind while selecting the pavement sections:

- Material properties namely creep compliance data and time-temperature shift factors of the asphalt mix are available.
- Excessive cracks are not observed within single winter period which may be considered as low-temperature thermal cracking.

For each section, the material properties namely, creep compliance parameters and time-temperature shift factors, corresponding reference temperature T_r = -20^{0}C are used as provided in the NCHRP guidelines [14]. Accordingly, the parameters C_1 and C_2 for given shift factors, and the relaxation modulus parameters for given creep data are calculated. The value of α is taken as $2.5\times10^{-5}/^0$C [27]. Thus, the thermal stress (σ) can be estimated using Eq. (4). Table 2 shows the maximum stress (σ_m) value

Table 1. Data Used for Thermal Fatigue Cracking Analysis.

SHRP Sections	Asphalt Layer Thickness h_1(m)	T_{av} (^{0}C)*	T_f (^{0}C)*	Crack Length L(m)	Number of Thermal Cycles n (days)**
16-1001	0.09	- 2.5	4	09.6	2220
				13.5	3285
				14.8	3700
24-1634	0.09	0	5	16.2	1795
				54.3	3000
				68.7	3770
16-1010	0.27	- 2.5	5	67.4	1120
				70.0	2000
				74.0	2300
				75.3	2500
				76.5	3150
40-4086	0.11	1	6	34.5	8200
				37.6	8910
				43.2	9915
				43.8	10500
				45.2	11500
31-1030	0.18	- 2	7	45.5	1000
				47.1	1675
				51.7	2615
29-1010	0.35	- 3	5	89	2250
08-1047	0.09	- 8	7	51.0	1125
42-1597	0.16	- 2	6	26.2	4260
				67.7	5020
				91.7	5475
18-1028	0.29	0	4	34.7	6050
				37.5	6350
				42.1	6700
				42.8	7000
				54.8	7420

* Data based on winter period.
** Number of days from opening the pavement to the date of crack survey.

along with the number of thermal cycles (n) and length to asphalt layer thickness ratio (L/h_1) values for the data considered.

As seen from Table 2, the n value is affected by σ_m as well as L/h_1. In this study, it is decided to perform a regression analysis considering n as dependent variable and, σ_m and L/h_1 as independent variables. Thus, it is proposed to develop a thermal fatigue equation of the following form,

$$n = a_1 \times \left(\frac{1}{\sigma_m}\right)^{a_2} \left(\frac{L}{h_1}\right)^{a_3} \quad (6)$$

where, a_1, a_2, and a_3 are regression constants.

The data presented in Table 2 have been divided into two parts. The first part containing 19 out of 29 data points have been used for development of the thermal fatigue equation. Rest 10 data points are used for validation purpose.

Using the method of least square error, the values of a_1, a_2, and a_3 are obtained as 3.899, 0.2693, and 0.8956 respectively, where σ_m is in MPa. Fig. 1 shows the comparison of observed and estimated n values for the data considered. The value of the correlation coefficient (R^2) is obtained as 0.85.

Validation of Thermal Fatigue Equation

For validation of the proposed thermal fatigue equation (i.e. Eq. (6)),

Table 2. Various Parameters for the Chosen Pavement Sections.

Number of Thermal Cycles n(days)	Maximum Stress σ_m(MPa)	L/h_1 Value	SHRP Sections
2220	0.0002	106.67	16-1001
3285		150.00	
3700		164.44	
1795	0.0062	180.00	24-1634
3000		603.33	
3770		763.33	
1120	0.00009	249.63	16-1010
2000		259.26	
2300		274.07	
2500		278.89	
3150		283.33	
8200	0.00000152	313.64	40-4086
8910		341.82	
9915		392.73	
10500		398.18	
11500		410.91	
1000	0.0011	247.22	31-1030
1675		261.67	
2615		287.22	
2250	0.00088	254.29	29-1010
1125	0.2133	566.67	08-1047
4260	0.00041	163.75	42-1597
5020		423.13	
5475		573.13	
6050	0.000022	119.66	18-1028
6350		129.31	
6700		145.17	
7000		147.59	
7420		188.97	

10 data points have been considered which are not used for the development of the equation. Fig. 2 shows the scatter plot of observed versus predicted n values. The value of the correlation coefficient (R^2) is obtained as 0.50. It is observed that the predicted n value shows a reasonably good agreement with the observed n value for the data considered.

The n used in Eq. (6) represents the number of thermal cycles which depends on crack length (L). The specific value of n corresponding to the crack length at failure is the thermal fatigue life (N). In this work, a 60m crack length per 150m length of pavement section (≈ 200ft/500ft) is considered as thermal cracking failure criteria [14]. Therefore, putting L = 60m in Eq. (6), the thermal fatigue life (N) in days can be estimated from the following equation,

$$N = 152.569 \times \left(\frac{1}{\sigma_m}\right)^{0.2693} \left(\frac{1}{h_1}\right)^{0.8956} \quad (7)$$

where, maximum thermal stress σ_m is in MPa and asphalt layer thickness h_1 is in m. It may be noted that the equation for thermal fatigue life (i.e. Eq. (7)) has been developed based on limited data whatever could be extracted from the LTPP database and NCHRP guidelines relevant to the present study. Use of additional data, if available, can further improve the robustness of the developed equation.

Table 3. Distribution Parameters Used for Simulation Study.

Parameter	Distribution	Expected Value	Coefficient of Variation	Standard Deviation
T_{av}	Normal	- 8 ^{0}C	15%	1.2 ^{0}C
T_f	Normal	7 ^{0}C	10%	0.7 ^{0}C
h_1	Normal	0.09m	10%	0.009m
α	Normal	2.5×10^{-5}/^{0}C	5%	0.125×10^{-5}/^{0}C

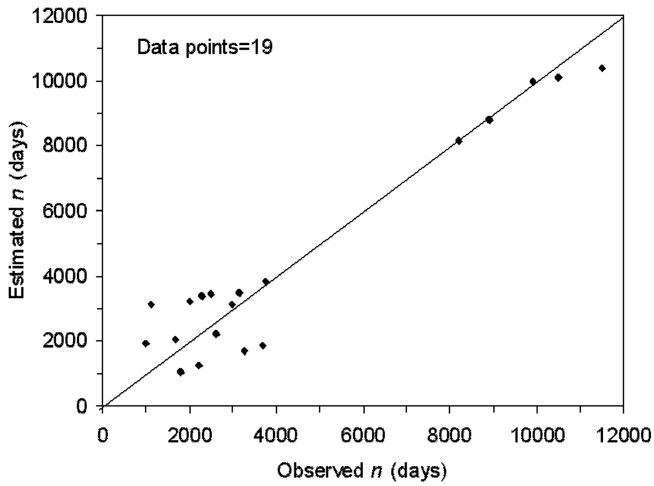

Fig. 1. Comparison of Observed versus Estimated Thermal Cycles for the Data Used for Development.

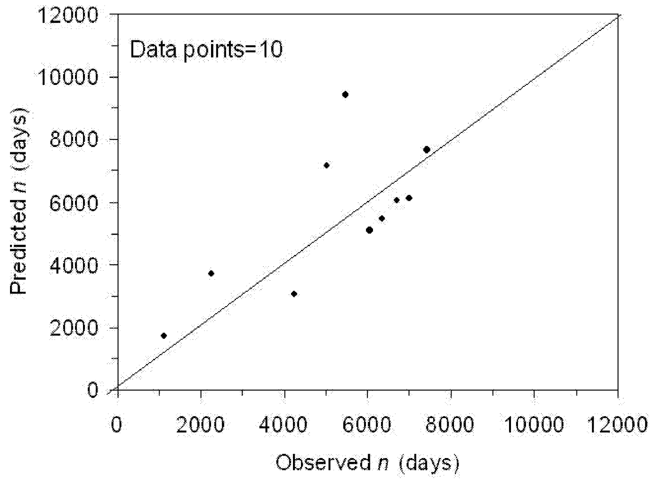

Fig. 2. Scatter Plot of Observed verses Predicted Thermal Cycles for the Data Used for Validation.

Reliability Analysis

Various researchers [15, 28-30] studied the reliability of thermal cracking failure under certain laboratory conditions. The reliability (R) of thermal fatigue failure of any pavement section may be defined as the probability that the thermal fatigue life (N) is greater than the design life of the same pavement section. To estimate R, the probability density function (pdf) of N is to be known. Let the pdf of N is designated as $f_N(n)$. Thus, the value of R can be estimated as,

$$R = \int_{365\times yr}^{\infty} f_N(n)\, dn \quad (8)$$

where, yr is the design period in years. The $f_N(n)$ can be obtained for

Table 4. Creep Compliance (C_r) Data at T_r = -20^{0}C.

$D_0 = 3.41\times10^{\ 5}$ MPa^{-1}	$\eta_0 = 1.44\times10^{10}$ MPa-sec
$D_1 = 7.76\times10^{\ 6}$ MPa^{-1}	$\lambda_1 = 14.125$ sec
$D_2 = 3.47\times10^{\ 6}$ MPa^{-1}	$\lambda_2 = 199.5$ sec
$D_3 = 1.39\times10^{\ 5}$ MPa^{-1}	$\lambda_3 = 2818$ sec
$D_4 = 2.83\times10^{\ 5}$ MPa^{-1}	$\lambda_4 = 39810$ sec

Table 5. Relaxation Modulus (E_r) and WLF Parameters at T_r = -20^{0}C.

$E_1 = 5513$ MPa	$\rho_1 = 11.49$ sec
$E_2 = 1862$ MPa	$\rho_2 = 184.13$ sec
$E_3 = 5391$ MPa	$\rho_3 = 2146$ sec
$E_4 = 5386$ MPa	$\rho_4 = 26954$ sec
$E_5 = 11187$ MPa	$\rho_5 = 1273723$ sec
C_1 =7	C_2 =17.8

known distributions of input variables. To obtain the $f_N(n)$, a Monte Carlo simulation study has been performed. The synthetic data used for the simulation study is presented in Table 3.

For estimation of temperature stress, the creep compliance (C_r) model parameters for SHRP section 08-1047 has been used as provided in the NCHRP guidelines [14]. Under creep condition, this model (a generalized Burger model) is represented as,

$$C_r(\xi) = D_0 + \frac{\xi}{\eta_0} + \sum_{i=1}^{q} D_i \times \left(1 - e^{-\xi/\lambda_i}\right) \tag{9}$$

where, D_0, η_0, D_i, and λ_i are model parameters; q is the number of Kelvin arms of the model; and ξ represents the time. The value of the model parameters are presented in Table 4 [14]. The computed parameters of relaxation modulus for the given creep compliance data are presented in Table 5.

The time-temperature shift factor ($\log(1/a_T)$) values for SHRP section 08-1047 are 3.75 and 2.55 at 0^{0}C and –10^{0}C respectively with respect to T_r = -20^{0}C [14]. Accordingly, the WLF parameters C_1 and C_2 values are obtained and are presented in Table 5. Thus, the stress $\sigma(t)$ can be obtained using Eq. (4) for known $T(t)$.

For each random variable (as given in Table 3), 10,000 data points are considered for simulation study. For each data set, N value is calculated using Eq. (7). Fig. 3 shows the frequency distribution and the deviation of observed probability from normal probability for random variable ln$N$.

It is observed that ln$N$ closely follows a normal distribution (i.e. N follows a lognormal distribution) for the data considered. The probability deviation of ln$N$ from the normal distribution is less than ±0.02. The Chi-square test also ensured that ln$N$ is normally distributed with more than 97% confidence level. Thus, $f_N(n)$ may be taken as lognormal pdf. In the present case, the expected value (E[ln$N$]) and standard deviation ($sd_{\ln N}$) of ln$N$ are obtained as 7.3 and 0.2844 respectively, i.e. the coefficient of variation of ln$N$, $COV_{\ln N}$ = 0.2844/7.3 = 3.89%. Thus, the value of R can be estimated using Eq. (8) for known yr value. For lognormal $f_N(n)$ (as in the present case), Eq. (8) can be re-written as,

$$R = \mathrm{N}\left(\frac{E[\ln N] - \ln(365 \times yr)}{sd_{\ln N}}\right) \tag{10}$$

where, N(Z) represents the probability for standard normal deviate Z, for example N(0) = 0.5. The E[ln$N$] is equal to ln$N$; where, N can be determined from Eq. (7) using the expected values of various input parameters. The expected value of σ_m in the present case (for SHRP section 08-1047) is obtained as 0.2133MPa (refer to Table 2).

Numerical Analysis

In this section, first, an example problem on the thermal fatigue consideration in asphalt pavement is framed and next, its solution is presented. Realistic data is taken from the literature [14, 27].

Example Problem

The daily average temperature (T_{av}) and temperature fluctuation (T_f) for the winter period of a colder region is given as 0^{0}C and 4^{0}C respectively. Estimate thermal fatigue life and the reliability of thermal fatigue failure of an asphalt pavement from the following data.

The relaxation modulus parameters and, C_1 and C_2 values (for SHRP section 08-1047) can be taken from Table 5. The α value for the asphalt mix is taken as 2.5×10^{-5}/^{0}C [27]. The asphalt layer

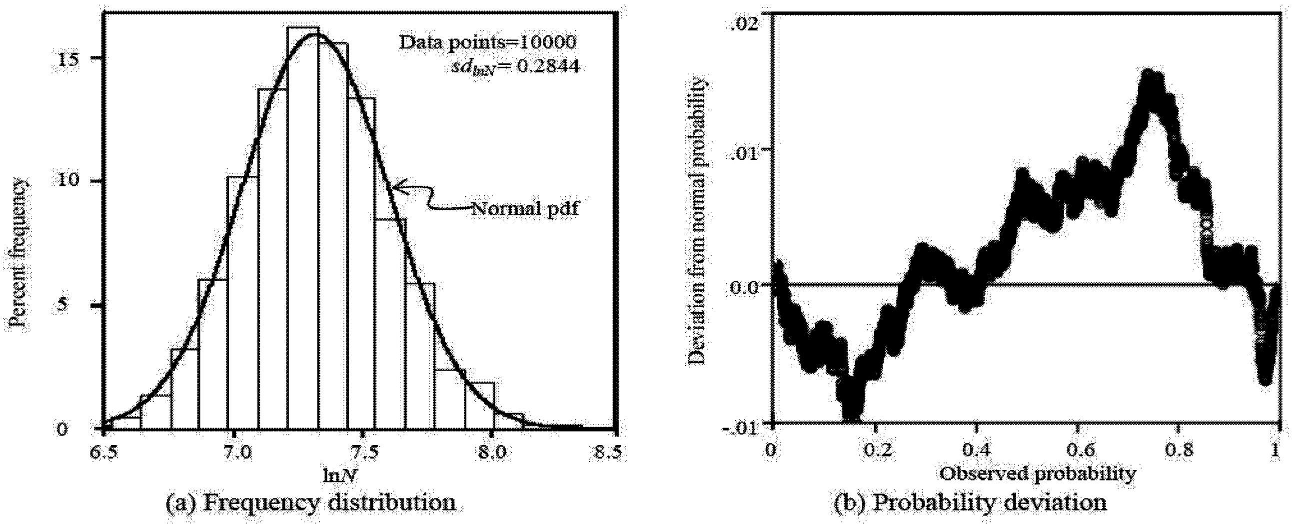

Fig. 3. Frequency Distribution and the Probability Deviation of Random Variable ln$N$.

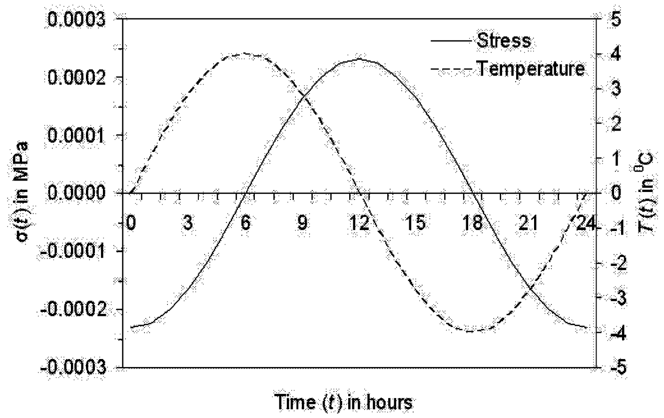

Fig. 4. Variation of Temperature and Thermal Stress (Positive Tensile) with Time (Sixth Cycle).

thickness (h_1) of the pavement section is given as 200mm. The thermal fatigue life (N) is lognormally distributed with coefficient of variation, $COV_N = 30\%$. Consider the design period (yr) as 15 years.

Solution

Using Eq. (4), the values of $\sigma(t)$ can be obtained for given $T(t)$. Fig. 4 shows the variation of $\sigma(t)$ along with $T(t)$. It may be mentioned that $\sigma(t = 0)$ is taken as 0 for numerical calculation. To take into account of the past stress history, the $\sigma(t)$ values computed after five cycles has been presented in Fig. 4. This is because after five cycles, the maximum stress (σ_m) value of any thermal cycle is observed to be stabilized. The value of σ_m is obtained as 0.00023MPa (refer to Fig. 4) for the example problem. Thus, using Eq. (7) the thermal fatigue life (N) can be estimated as 6,155 days, i.e. $E[\ln N] = \ln(6{,}155) = 8.73$.

The standard deviation of $\ln N$ can be calculated as, $sd_{\ln N} = \{\ln[1+(COV_N)^2]\}^{1/2} = \{\ln(1+0.30^2)\}^{1/2} = 0.2935$. Thus, using Eq. (10) the reliability of thermal fatigue failure of the pavement structure can be estimated as $R = \mathrm{N}(0.4158) = 0.66$.

Conclusions

This paper develops a phenomenological model for prediction of thermal fatigue life based on field observations. This can be used as a design equation to estimate the thermal fatigue life of a given asphalt pavement. The reliability of a given pavement from thermal fatigue consideration has also been estimated. Thus, the estimated thermal fatigue reliability can be compared with the acceptable design reliability limit, while performing the pavement design.

References

1. Kandhal, P.S., Dongre, R., and Malone, M.S., (1996). Prediction of Low-Temperature Cracking of Pennsylvania Project Using Superpave Binder Specification, *J. of the Association of Asphalt Paving Technologists*, Baltimore, MD, USA, Vol. 65, pp. 491-518.
2. Kanerva, H.K., Vinson, T.S., and Zeng, H., (1994). Low-temperature Cracking: Field Validation of the Thermal Stress Restrained Specimen Test, *SHRP-A-401*, Strategic Highway Research Program, Dept. of Civil Engineering, Oregon State University, OR., USA.
3. Kliewer, J.E., Zeng, H., and Vinson, T.S., (1996). Aging and Low-Temperature Cracking of Asphalt Concrete Mixtures, *J. of Cold Regions Engineering*, 10(3), pp. 134-148.
4. Marasteanu, M.O., Li, X., Clyne, T.R., Voller, V.R., Timm, D.H., and Newcomb, D.E., (2004). Low Temperature Cracking of Asphalt Concrete Pavements, *Report No. MN/RC – 2004-23*, Dept. of Civil Engineering, University of Minnesota, Minneapolis, MN, USA.
5. MnRoad, (2007). *Minnesota Road Research Section*, MnRoad Database, <http://mnroad.dot.state.mn.us/research/cell_info/trackml_lv.asp> (accessed December, 2007).
6. Shen, W. and Kirkner, D.J., (1999). Distributed Thermal Cracking of AC Pavement with Frictional Constraint, *J. of Engineering Mechanics*, ASCE, 125(5), pp. 554-560.
7. Timm, D.H., Guzina, B.B., and Voller, V.R., (2003). Prediction of Thermal Crack Spacing, *International J. of Solids and Structures*, 40(1), pp. 125-142.
8. Vinson, T.S., Janoo, V.C., and Haas, R.C.G., (1989). Low Temperature and Thermal Fatigue Cracking, *Summary Report SR-OSU-A-003A-89-1*, Strategic Highway Research Program, National Research Council, Washington, D.C., USA.
9. Chang, H.S., Lytton, R.L., and Carpenter, H.S., (1976). Prediction of Thermal Reflection Cracks in West Texas, *Report No. TTI-2-8-73-18-3*, Texas Transportation Institute, College Station, TX, USA.
10. Fromm, H.F. and Phang, W.A., (1972). A Study of Transverse Cracking of Bituminous Pavements, *Proceedings of the Association of Asphalt Paving Technologists*, Baltimore, MD, USA, Vol. 41, pp. 383-423.
11. Haas, R., Meyer, F., Assaf, G., and Lee, H., (1987). A Comprehensive Study of Cold Climate Airport Pavement Cracking, *Proceedings of the Association of Asphalt Paving Technologists*, St. Louis, MO, USA, Vol. 56, pp. 198-245.
12. Hiltunen, D.R. and Roque, R., (1994). A Mechanics-Based Prediction Model for Thermal Cracking of Asphaltic Concrete Pavements, *J. of the Association of Asphalt Paving Technologies*, St. Louis, MO, USA, Vol. 63, pp. 81-108.
13. Huang, Y.H., (2004). *Pavement Analysis and Design*, Person Prentice Hall, NJ, USA.
14. National Cooperative Highway Research Program (NCHRP), (2004). Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, *NCHRP Design Guide*, Project 1-37A, Washington, D.C., USA, <http://www.trb.org/mepdg/guide.htm> (Accessed December, 2006).
15. Easa, S.M., Shalably, A., and Halim, A.O., (1996). Reliability-Based Model for Predicting Pavement Thermal Cracking, *J. of Transportation Engineering*, ASCE, 122(5), pp. 374-380.
16. Long Term Pavement Performance (LTPP), (2007). *LTPP DataPave Online*, Release 21, <http://ltpp-products.com/DataPave/index.asp> (Accessed November, 2007).

17. Robert, L., (2002). Rheological and Fatigue Characterization of Asphalt Concrete Mixtures Using Uniaxial Testing, *Licentiate thesis, Research Report TRITA-VT FR 02:02*, Kungl Tekniska Högskolan, Sweden.
18. Findley, W.N., Lai, J.S., and Onaran, K., (1976). *Creep and Relaxation of Non-linear Viscoelastic Materials: with an Introduction to Linear Viscoelasticity*, North-Holland Publishing Company, NY, USA.
19. Shields, D.H., Zeng, M., and Kwok, R., (1998). Nonlinear Viscoelastic Behavior of Asphalt Concrete in Stress Relaxation, *J. of the Association of Asphalt Paving Technologists*, Boston, MA, USA, Vol. 67, pp. 358-385.
20. Williams, M.L., Landel, R.F., and Ferry, J.D., (1955). The Temperature Dependence of Relaxation Mechanisms in Amorphous Polymers and Other Glass-Forming Liquids, *J. of the American Chemical Society*, 77(14), pp. 3701-3707.
21. Zhao, Y. and Kim, Y.R., (2003). Time-Temperature Superposition for Asphalt Mixtures with Growing Damage and Permanent Deformation in Compression, *Transportation Research Records*, No. 1832, pp. 161-172.
22. Zhai, H. and Salomon, D., (2005). Evaluation of Low-Temperature Properties and the Fragility of Asphalt Binders with Non-Arrhenius Viscosity-Temperature Dependence, *Transportation Research Records*, No. 1901, pp. 44-51.
23. Rajbongshi, P. and Das, A., (2008). Temperature Stress in Asphalt Pavements Considering Nonlinear Temperature Profile, communicated to *J. of Transportation Engineering*, ASCE, May 2008.
24. Barber, E.S., (1957). Calculation of Maximum Pavement Temperatures from Weather Reports, *Highway Research Board Bulletin 168*, National Research Council, Washington, D.C., USA, pp. 1-8.
25. Celauro, C., (2004). Influence of the Hourly Variation of Temperature on the Estimation of Fatigue Damage and Rutting in Flexible Pavement Design, *The International J. of Pavement Engineering*, 5(4), pp. 221-231.
26. Hulsey, J.L. and Powell, D., (1993). Rational Weather Model for Highway Structures, *Transportation Research Records*, No. 1393, pp. 54-64.
27. Stoffels, S. and Kwanda, F.D., (1996). Determination of the Coefficient of Thermal Contraction of Asphalt Concrete Using the Resistant Strain Gage Technique, *Proceedings of the Association of Asphalt Paving Technologists*, Baltimore, MD, USA, Vol. 65, pp. 73-90.
28. Epps, A., (1998). A Comparison of Measured and Predicted Low-Temperature Cracking Conditions, *J. of the Association of Asphalt Paving Technologists*, Boston, MA, USA, Vol. 67, pp. 277-310.
29. Epps, A., (2000). Design and Analysis System for Thermal Cracking in Asphalt Concrete, *J. of Transportation Engineering*, ASCE, 126(4), pp. 300-307.
30. Zubeck, H.K. and Vinson, T.S., (1996). Prediction of Low-Temperature Cracking of Asphalt Concrete Mixtures with Thermal Stress Restrained Specimen Test Results, *Transportation Research Records*, No. 1545, pp. 50-58.