TEMPERATURE IMPACT ON PAVEMENT STRUCTURES IN HOT ARID ENVIRONMENT

Hamad I. Al-abdul Wahhab*, Rezqallah H. Ramadhan**, and Ibrahim M. Asi*

* Civil Engineering Dept. ** Research Institute
King Fahd University of Petroleum and Minerals
Dhahran 31261, Saudi Arabia

ABSTRACT

Temperature is one of the most important factors affecting the design and performance of both flexible and rigid pavements. Temperature variations within pavement structure contribute in many different ways to distress and possible failure of that structure. Knowledge of temperature effects is essential for the determination of the design and maintenance requirements especially in the desert climates like most of Saudi environment.

This paper presents the results of different research studies that were carried out locally to explore the trends of temperature variation in both rigid and flexible pavement slabs in the arid Saudi environment and their implications on the design and material selection. Results indicated that temperature effects on both flexible and rigid pavements can not be ignored in design and analysis since high ranges were observed such as a maximum temperature differential of 15° C in rigid pavements whereas, flexible pavements are subjected to temperatures ranging between 3°C to 72°C. Maximum pavement temperature was recorded at a depth of 2 cm.

KEYWORDS: pavement, flexible, rigid, apron, curling stress, SHRP, ILLI-SLAB, temperature.

INTRODUCTION

The functional as well as the structural performance of flexible and rigid pavements is highly dependent on the temperature regime to which these pavements are exposed. Temperature variations within pavement structure contribute to distress and possible failure of that structure. Daily and seasonal variations of maximum, minimum, average and gradient across pavement depth must be considered in determining thermal stresses and calculating design parameters of rigid and flexible pavements.

Thermal condition, if not addressed, can lead to significant problems, including the following [Andersen, et al., 1992]:

1. Cracking caused by large temperature differentials between the interior of concrete and the external environment.

2. Strength loss caused by the freezing of concrete before it has reached sufficient strength, and

3. Strength loss caused by high internal temperatures within the concrete mass.

Temperature and moisture are fundamental variables in all problems of airport pavement construction, design, behavior, and performance [Dempsey, 1976]. They have a major influence on airport pavement surface deterioration, which has a great effect on the aircraft damage and runway closures for maintenance.

Stresses in rigid pavements result from a variety of causes [Yoder and Witczak, 1975], including wheel loads, cyclic changes in temperature (warping and shrinkage or expansion), changes in moisture, and volumetric changes in the subgrade or base course.

TEMPERATURE STUDIES

Extensive research on temperature distribution in asphalt pavements has been carried out in many different climatic areas of the world, such as the US, Australia, South Africa, Kuwait and Saudi Arabia (Kallas, 1966; Williamson, 1972; Bissada, 1972; Potocki (1973); Fatani et al., 1994; Al-Abdul Wahhab and Balghunaim, 1994). Several researchers have developed mathematical models to simulate pavement temperature with reasonable accuracy (Dempsy and Thompson, 1970; Venkataraman and Venkatasubramanian, 1977; Dickinson, 1978; Fatani et al., 1994; Ramadhan and Al-Abdul Wahhab, 1997).

In the Gulf region, Fatani et al. (1994), Al-Abdul Wahhab and Balghunaim (1994), Bissada (1972) and Potocki (1973) have carried out different research projects to quantify temperature regions in local pavements.

Fatani et al. (1994) in a national project entitled "Evaluation of Permanent Deformation of Asphalt Concrete Pavement in the Kingdom of Saudi Arabia (KSA)," have instrumented different pavement sections for temperature measurement in eastern, central, and western Saudi Arabia. Temperature was measured round-the-clock at the surface and at depths of 2 cm, 4 cm, 8 cm, 16 cm, and at the bottom of asphalt layers. They studied the effect on pavement temperature of factors such as cloud cover, air temperature, and solar radiation. The single most important factor that affects pavement temperature was found to be air temperature, which is directly affected by cloud cover and solar radiation. A database containing two years worth of pavement temperatures was developed. It was observed that the maximum recorded pavement temperature occurs at a depth of 2 cm from pavement surface, while the minimum pavement temperature is always recorded on the surface. A model has been developed and calibrated based on their study to predict maximum pavement temperature at a depth of 2 cm and minimum pavement temperature.

The model takes into account air temperature and solar radiation with a high degree of accuracy

Al-Abdul Wahhab and Balghunaim (1994) indicated that extreme pavement temperatures in the arid Saudi environment range between 3°C and 72°C for coastal areas and 4°C and 65°C for inland areas.

Bissada (1972) presented the results of a study on asphalt pavement temperatures relating to the Kuwait climate. He concluded that the asphalt surface course experienced substantial extremes in temperature. Within 9 hours on a summer day, the surface pavement temperatures fluctuate between 32 and 74°C. During the year, asphalt surface temperatures fluctuate between an average minimum of 5°C and an average maximum of 74°C.

Potocki (1973) carried out a more comprehensive study of pavement temperatures for different pavement cross-sections in Abu Dhabi and Al-Ain in the United Arab Emirates.

The asphalt binder specification AASHTO MP1 graded asphalt binder based on the prevailing upper and lower pavement temperatures. Asphalt binder is graded as:

$$\text{PG X-Y} \tag{1}$$

where

PG = stands for performance graded

X = designates the high pavement design temperature, and

Y = designates the low pavement design temperature.

The SHRP design temperatures and corresponding grades are given in Table 1. Therefore, asphalt binder PG 70-16 grade is suitable to be used in an environment to offer a protection for an average seven (consecutive) day maximum pavement temperature of <70°C (but greater than 64°C) and a minimum pavement design temperature of > −16°C (but less than −10°C) with 95% confidence.

Table 1. SHRP design temperatures and corresponding grades

igh-Temperature, °C (X)	PG Grade Designation	Low-Temperature, °C (Y)	PG Grade Designation
< 52	52	> −10	−10
< 58	58	> −16	−16
< 64	64	> −22	−22
< 70	70	> −28	−28
< 76	76	> −34	−34
< 82	82	> −40	−40
		> −46	−46

Ramadhan and Al-Abdul Wahhab (1997) reported their two field experiments carried out for the monitoring of temperature variations of asphalt concrete and Portland cement concrete pavements at King Fahd University of Petroleum and Minerals (KFUPM) in Dhahran, Eastern Province of Saudi Arabia. A temperature data base was developed and used to generate regression models for predicting temperatures in flexible pavement, and temperature differentials in rigid pavements, from measured air temperatures. For this study, recorded temperatures at depth of 2 cm in the flexible pavement (PAV) with the corresponding air temperature (AIR) has the following relationship:

$$PAV = 1.692 * (AIR) + 12.670 \qquad (2)$$

Similarly, the relationship between average temperature differentials (DIFF) versus corresponding air temperatures (AIR) is obtained and has the following form:

$$DIFF = 0.248 * (AIR) + 1.577 \qquad (3)$$

Arora et al. (1993) proposed a mechanistic approach for PCC apron pavement design for the Saudi-specific conditions using ILLI-SLAB finite element model. This approach was used to check the structural adequacy of PCC apron pavement system of the newly built King Fahd International Airport (KFIA) near Dammam, Saudi Arabia. In this approach, the combined effect of load and temperature, in terms of tensile stresses in the rigid pavements, was studied. Temperature data were obtained from the instrumented apron slabs in that airport as reported by Arora et al. (1994).

TEMPERATURE EFFECTS ON FLEXIBLE PAVEMENT

Temperature affects the pavement design in two ways; first it determines the temperature at which asphalt concrete mix should be designed and/or evaluated and second it indicates the asphalt grade that best work for a temperature zone and traffic load (Al-Abdul Wahhab et al. 1996)

In all of the above mentioned studies, it was observed that the minimum pavement temperature is always recorded on the surface of the pavement, which matches the lowest air temperature. The average maximum pavement design temperature over seven consecutive days is measured at a depth of 20 mm in pavement as recommended by the FHWA LTPP study (19[illegible]). Fig. 1 shows the relation between air temperature and recorded temperature at a depth of 20 mm in pavement for Saudi Arabia, Kuwait, and the UAE, as reported by the above studies. This relation has been utilized by Al-Abdul Wahhab et al. (1996) to predict the average seven day maximum pavement design temperature from the calculated average seven day maximum air temperature. The regression formula developed for Kuwait was used for Kuwait; the KSA formula was used for Saudi Arabia and Qatar; and the UAE formula was used for UAE and Oman.

Al-Abdul Wahhab et al. (1996) have carried a research project for the adaptation of SHRP performance based binder specifications in the Gulf countries. In their research, an extensive study of the temperature regimes within the Gulf countries has been executed. Twenty eight weather stations across the Kingdom and meteorological departments in the Gulf countries were contacted to collect available meteorological data. A huge amount of

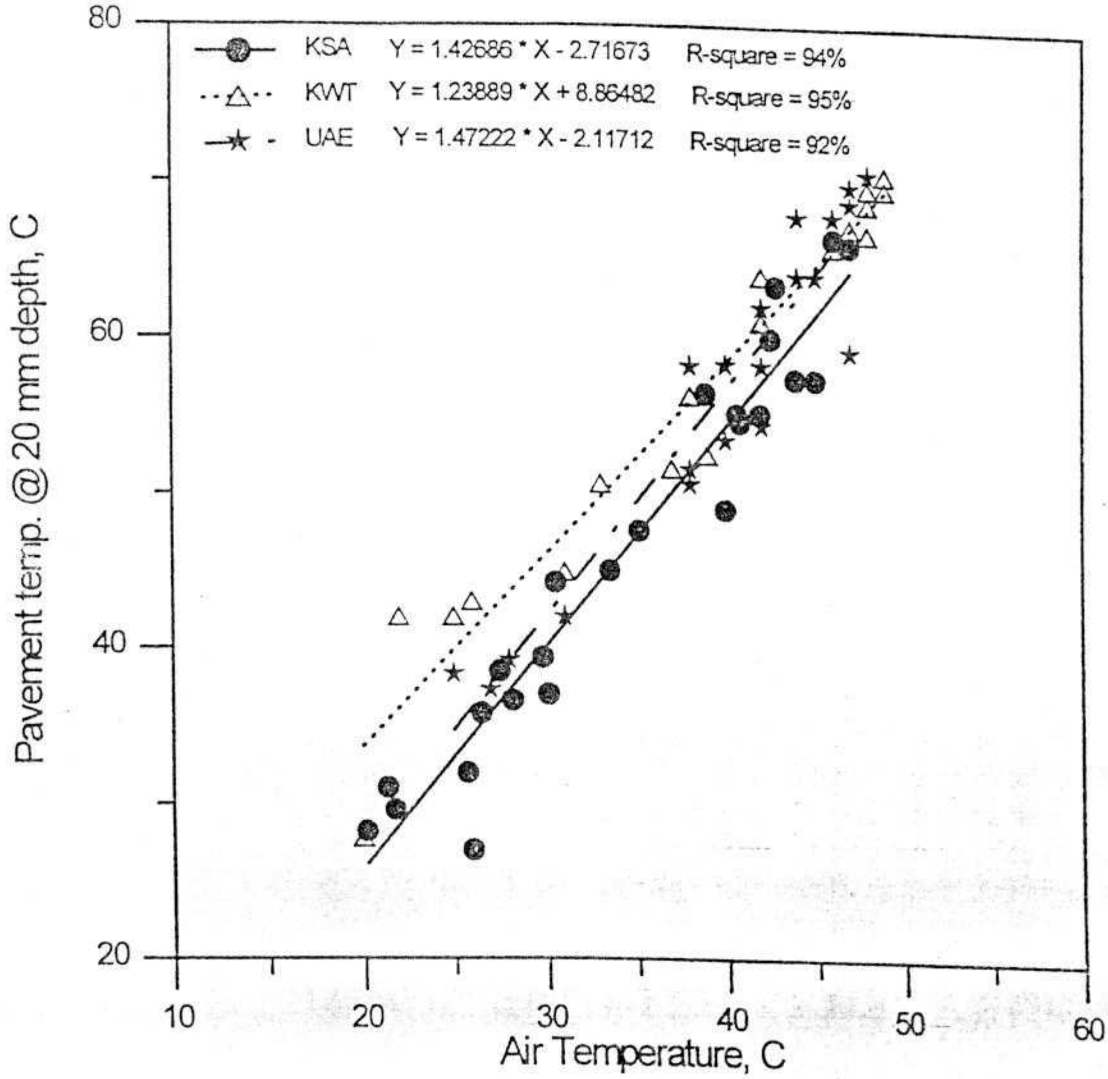

Fig. 1. Relation between air temperature and pavement temperature at a depth of 20 mm (Fatani et al., 1992; Bissada, 1972; Potocki, 1973)

weather data (covering 26 years) was received and analyzed to calculate the average seven day maximum air temperature and minimum air temperature.

The temperature zoning for the asphalt binder specification for the Gulf region is shown in Fig. 2. Four asphalt binder performance grades that satisfy the high and low temperature requirements are identified: PG 76-10, PG 70-10, PG 64-10, and PG 58-10. They have indicated that all neat asphalt cement, produced in the Gulf, had the same PG grade of PG 64-22 or PG 64-28. Polymer modification changed the grades of the samples into grades with higher upper limits. This limit reached as high as 82°C for some samples. Since pavement temperatures in most of the Gulf countries reach values higher than the 64°C, the suitability of neat asphalt is limited. This implies that polymer modification should be used in a large region of the Gulf countries. For the lower limit grades, polymer modification improved (lowered) the limit for some samples but had an adverse effect on other samples. Therefore, the suitability of any polymer for asphalt modification should be verified prior to use according to the temperature limits of the region.

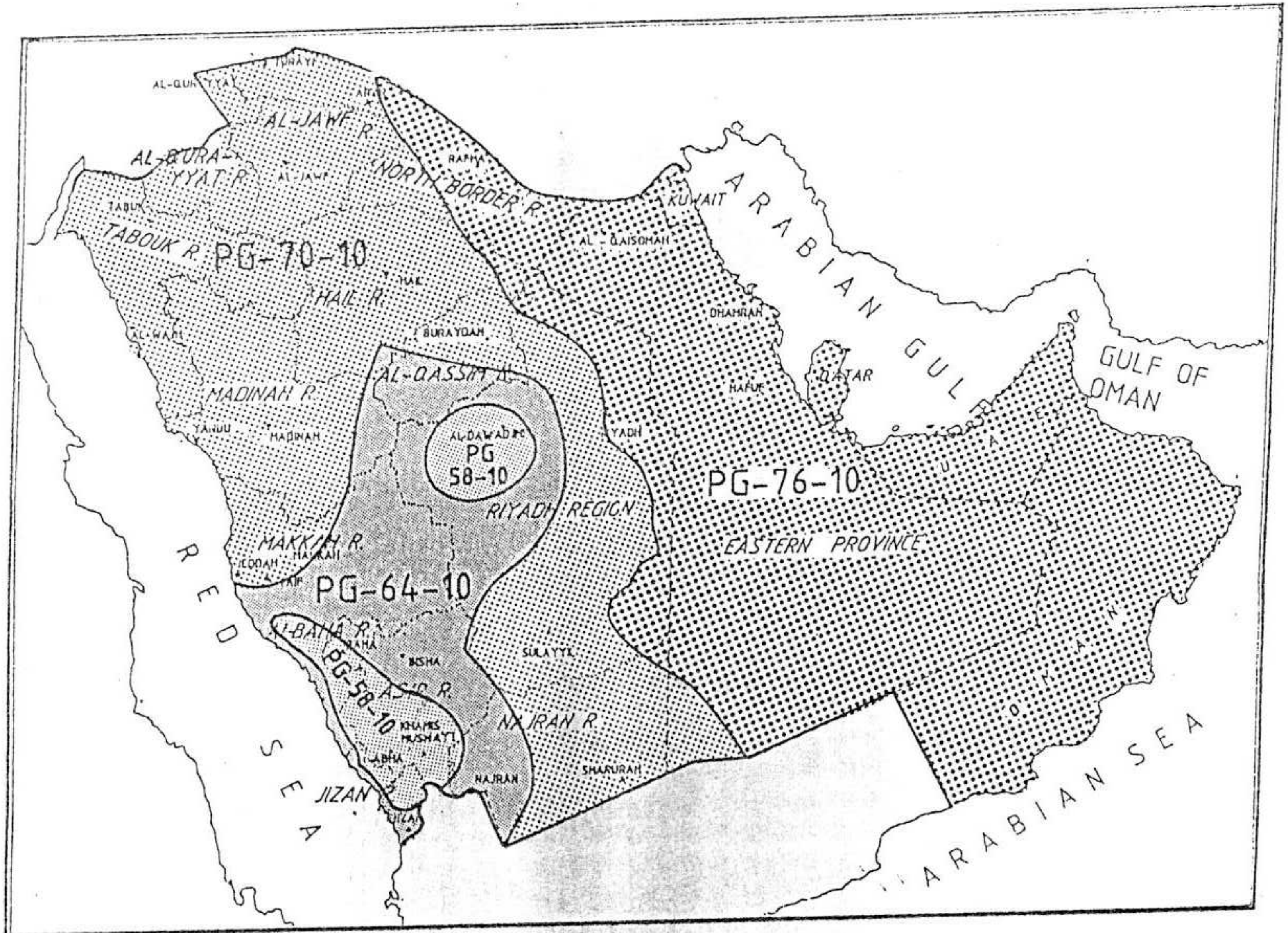

Fig. 2. Temperature zoning for asphalt binder specifications for the Gulf countries

Marshall mix design procedure (The Asphalt Institute 1984) is the only procedure used for local asphalt concrete mix design. This is an empirical design procedure which has no measure of shear strength. Asphalt mix is designed and evaluated at temperature of 50°C. These major deficiencies can be overcome by the use of SUPERPAVE mix design procedure (FHWA 1994).

TEMPERATURE EFFECTS ON RIGID PAVEMENT

The stresses generated by load are calculated using the Westergand closed-form known equations for edge, interior, and corner locations. Several design methods of rigid pavements were based on these equations such as Federal Aviation Administration (FAA) and Portland Cement Association (PCA). In these methods, the basic criteria is the limiting tensile stress in PCC slabs due to edge and interior loading. However, several limitations were observed by the users of these methods. For example, the closed-form solution assumed that the slab panel has infinite dimension, the amount of load transfer across joints has not been incorporated in the design, and the curling stresses due to temperature differential across the slab were not considered. These working stresses may add considerably to load stresses.

To overcome these limitations, the ILLI-SLAB design model was used for rigid pavement design and analysis, and to quantify the effect of temperature on this design and performance of PCC apron slab, using the conditions prevailing in the Kingdom. The ILLI-SLAB finite element model was developed at the University of Illinois, USA. This model was found to be an effective tool for analyzing the impact of number of design variables, such as joint spacing, temperature differentials, dowel bar diameter, and load transfer across joints on PCC pavement structural response. This model was thoroughly validated by other researchers, worldwide.

Daytime differentials (negative), which cause the slab to curl downward, induce tensile stresses (negative) at the bottom of the slab. Since these stresses are additive to the critical edge load stresses, the edge region also becomes the critical location for slab thickness design considering the combined effect of load and curling stresses. In the ILLI-SLAB model, the slab is initially assumed weightless, and the element deforms in a cylindrical shape as a result of non-uniform temperature strains through the slab. The weight of the slab is then superimposed on the deformed slab and the curling stresses are calculated. An iterative procedure is used to account for the effect of temperature curling and to accommodate regaining of subgrade support under load (Ioannides and Salsilli-Murua, 1989).

Table 2 shows the required data for a complete run of the ILLI-SLAB model. These data are the typical generated information for the King Fahd International Airport (KFIA), Dammam, as one of the Kingdom's international airports as reported by (Arora et al. 1993 and 1994).

The finite element mesh used for the analysis is shown in Fig. 3, where the design aircraft (L-1011-500) was placed so that the maximum (critical) edge loading stress can be determined. The ILLI-SLAB model calculates the stress, strain, and deformation for each node in the above mesh as well as the load transferred by the dowel bars between the

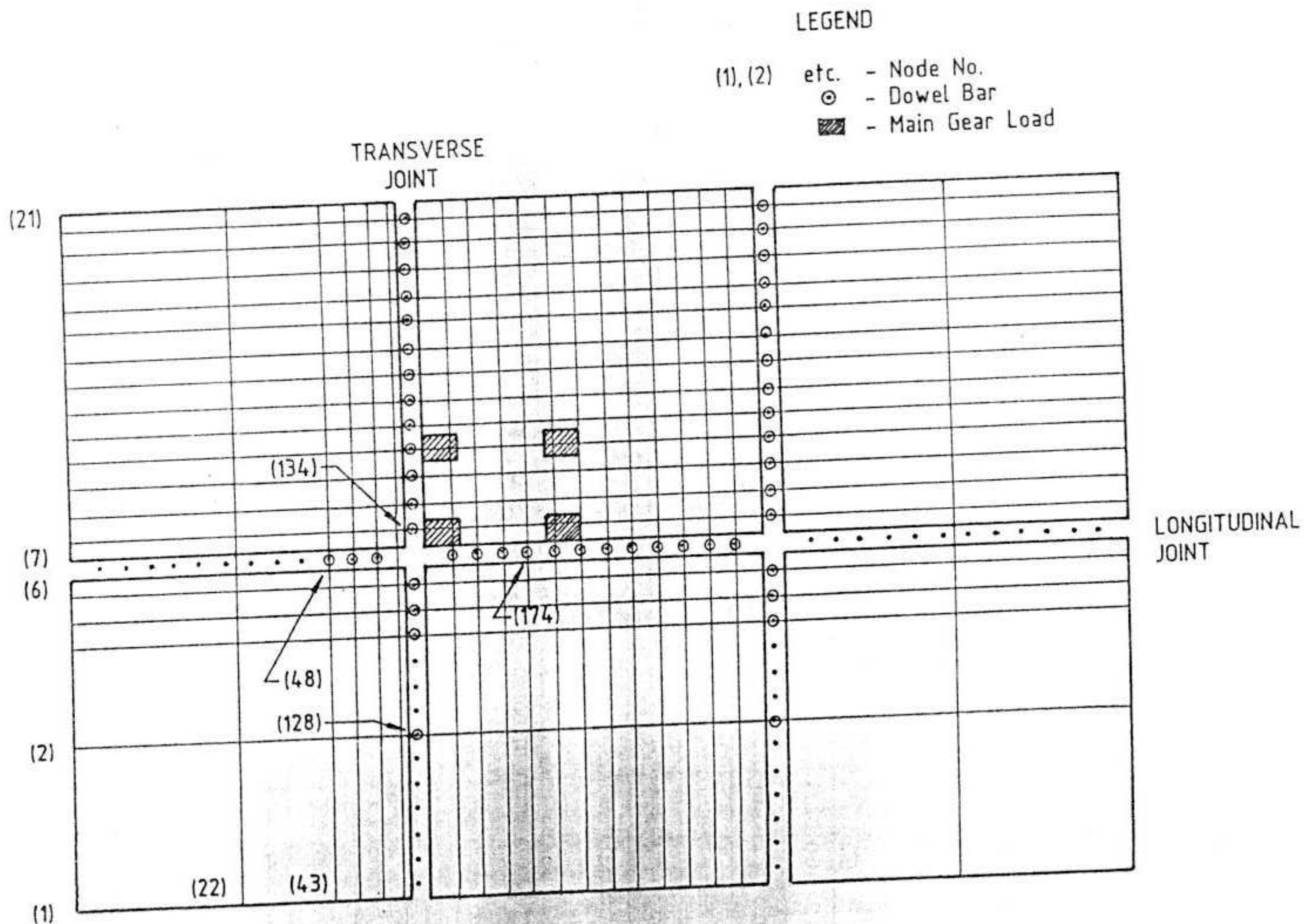

Fig. 3. Finite element mesh used for ILLI-SLAB model with L-1101-500 aircraft configuration

slabs. For thermal effect, one slab configuration was used with the temperature differential obtained for different time periods. Fig. 4 shows the day-time temperature curling stress contour for a typical summer day.

Table 2. Input data for complete ILLI-SLAB run

Property	Value and description
Number of slabs	6 slabs, divided into finite element mesh of suitable dimensions giving node numbers and coordinates
Number of structural layers	2, PCC and Asphalt concrete (AC)
Composite action	No bond between PCC and AC layers
Poisson's ratio of PCC layer	0.15
Thickness of PCC layer	16 in. (40 cm)
Modulus of elasticity of PCC layer	4.0×10^6 psi
Poisson's ratio of AC layer	0.35
Thickness of AC layer	6.3 in. (16 cm)
Modulus of elasticity of AC layer	5.0×10^5 psi
Modulus of subgrade reaction	250 pci
Inside and outside diameter of dowel bars	0.0 and 1.18 in.
Modulus of elasticity of dowel bars	29.0×10^6 psi
Spacing of dowel bars	14.96 in.
Poisson's ratio of dowel bars	0.29
Modulus of dowel/concrete interaction	1.86×10^6 pci
Joint width	0.118 in.
Design aircraft	L-1011-500
Main gear tire pressure	184 psi
Main gear wheel configuration	14.7 x 21.9 in.

Table 3 shows the results calculated using ILLI-SLAB model with the available information listed in Table 2. The temperature differentials were generated from temperature monitoring program (Arora et al. 1994). Two points for day-time curling (–14°C and –10°C) and another two points for night-time curling (+5.6°C and +7.5°C) were considered. At the no-curling conditions (zero temperature differential) the curling stress is equal to zero. Curling system, σ_c was generated from one-slab configuration with temperature differential effect only. The load stress σ_e was the critical edge stress

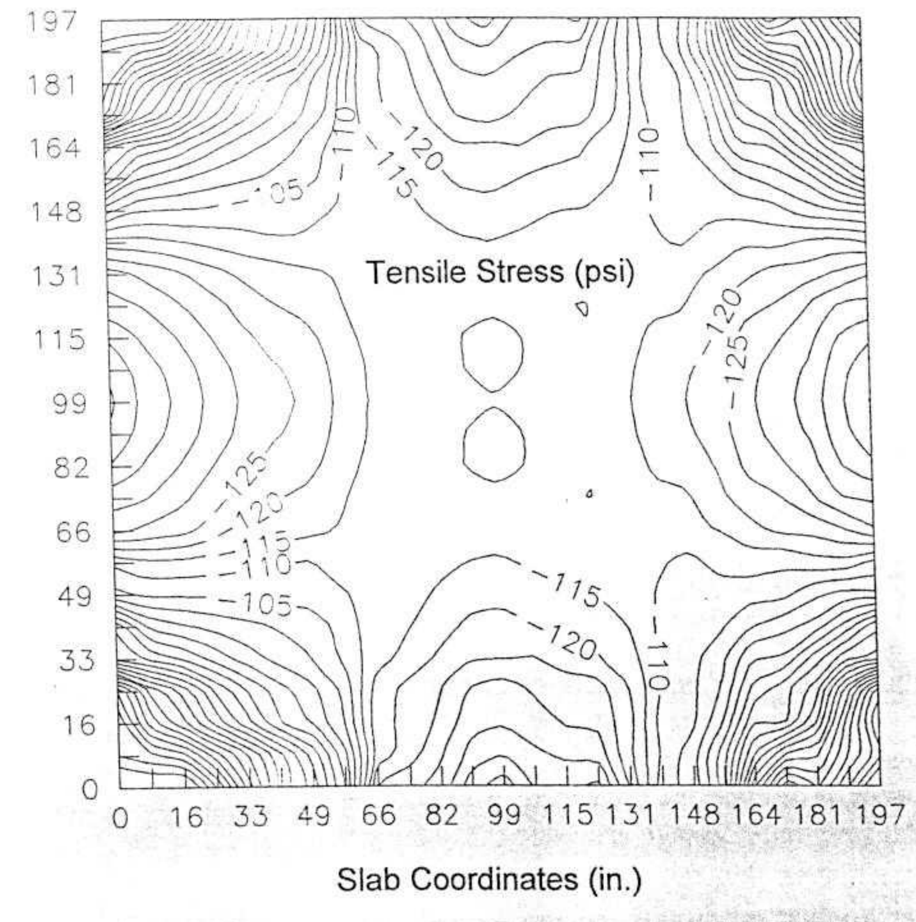

Fig. 4. Day-time curling stress contour for a temperature differential of 15°C

due to the aircraft load placed at the longitudinal edge of the PCC slabs as shown in Fig. 3. The combined stress, σ_{comb} (curling + load) at the bottom of the slabs was the one generated when considering the effects of both load and temperature differential simultaneously in Fig. 3.

Table 3. Load and curling stresses for rigid pavement

Curling period	Day-time 1	Day-time 2	Night-time 1	Night-time 2
Temperature Differential, C (bottom-top)	-14	-10	+5.6	+7.5
Curling stress, σ_c psi	-112	-94	+65 C	+69
Load stress, σ_e psi (Fig. 3)	-394	-394	-394	-394
Combined stress, σ_{comb}, psi (Fig3)	-625	-586	-433	-425

For design and evaluation purposes, the calculated load and combined stresses, σ_{comb}, are compared to the design flexural strength. However the curling stresses are not uniform over the months of the year, therefore, measuring the temperature differentials between top and bottom of the PCC slabs or predicting these differentials from the air temperature using the developed model (Eqn. 3) can be used to determine the curling stresses for each month. The combined stresses can also be determined, and then compared with the flexural strength. Fatigue models can also be utilized to calculate the cumulative damage over the design life of the rigid pavement. This process can be used in both the design phase of the pavement to determine the required thickness or the performance evaluation phase to check the remaining life of the pavement to determine the needed overlay thickness if required.

Other parameters of the rigid pavement can also be determined in the design phase or in the performance evaluations phase using the ILLI-SLAB finite element model. Knowing the input data to be used in certain rigid pavement, the required dowel-bar diameter, the adequate joint width, and the optimum slab dimension can be designed using similar procedure of superimposing the load and thermal effect on stress parameters. Arora et al. in their study about KFIA, have developed interactive programs to assist in carrying out the needed iterations to arrive to a suitable slab thickness and dowel diameter using the prevailing traffic and temperature conditions in Saudi Arabia. Using these programs, the change of slab size was investigated. It was concluded that increasing the slab size to 7.5 m as used by some airports in the Kingdom, increases the day-time curling stresses by an amount of 118% and the combined stresses by an amount of 18%. This shows that the cumulative fatigue damage exceeded the limiting value of 1.0 in the very first year during the hot summer, thus the fatigue cracking will develop in the 7.5 × 7.5 m slab dimension soon after opening to traffic.

CONCLUSIONS

Based on the extensive field and laboratory works conducted locally, the following can be stated:

1. Extreme asphalt pavement temperatures in the arid Saudi environment range between −10°C and 73°C.

2. Asphalt binder should be selected based on the prevailing temperature extremes.

3. For the rigid pavements, load stresses only - without considering the temperature curling effect - can not predict the actual behavior of PCC slabs. Results showed that the combined stresses are higher than those obtained from simple addition.

4. Increasing slab size from 5.0x5.0 m to 7.5x7.5 m will result in early fatigue failure due to the interaction between curling and load stresses.

ACKNOWLEDGMENTS

Authors wish to acknowledge the Ministry of Communication, King AbdulAziz City for Science and Technology, Civil Engineering Department, and the Research Institute of King Fahd University of Petroleum and Minerals, for valuable support.

REFERENCES

Al-Abdul Wahhab, H. (1993). "Effect of Truck Weight Enforcement in he Kingdom of Saudi Arabia", *Institute of Transportation Engineering Journal*, Vol. 63, No. 11, November 1993, pp. 38-44.

Al-Abdul Wahhab, H. and Balghonaim, F. (1994). Asphalt Pavement temperature related to arid Saudi environment. *ASCE Journal of Materials in Civil Engineering*, 6(1), pp. 1-14.

Al-Abdul Wahhab, H., Ali, M., Asi, I. and Al-Dhubeeb, I. (1996). *Adaptation of SHRP Performance Based Asphalt Specifications to the Gulf Countries*, Final Report submitted to KACST.

Al-Abdul Wahhab, H., Fatani, M., Noureldin, A., Bubshait, A. and Al-Dhubeeb, I. (1995), "National Study of Asphalt Pavement Rutting in Saudi Arabia", *TRR No. 1473*, Washington, D.C., pp. 35-42.

Al-Abdul Wahhab, M.F., Ali, I.M., Asi, A., And Al-Dhubeeb, I.A., *"Adaptation of SHRP Performance Based Asphalt Specification to The Gulf Countries,"* Progress Report No. 2, King Abdulaziz City for Science and Technology (KACST), December, 1994.

Andersen, P. J., Andersen, M. E., and Whiting, D. (1992), *"A Guide to Evaluating Thermal Effects in Concrete Pavements"* SHRP-C/FR-2-101, National Research Council, Washington, DC.

Arora, M.G., Al-Tayyib, A.J., Al-Mana, A.I., and Ramadhan, R. (1993). "Portland Cement Concrete Apron Pavement Design Study for King Fahd International Airport in Saudi Arabia," *Airfield Specialty Conference, Airport Pavement Innovations: Theory to Practice*, Vicksburg, MS, 216-231, 1993.

Arora, M.G., Al-Tayyib, A.J., Al-Mana, A.I., Ramadhan, R., and Uzri, T. (1994). "Field Instrumentation for Measuring Concrete Airport Pavement Response,", *Proc. of the Fourth International Conference on the bearing Capacity of Roads and Airfields*, University of Minnesota, USA.

Bisssada, F. (1972), "Asphalt Pavement Temperature Related to Kuwait Climate, "Highway Research Record 404, *Transportation Research Board*, Washington, D.C. 71-85.

Brule, B. (1988), "Paving Asphalt Polymer Blends: Relationships Between Composition, Structure and Properties", *AAPT, Vol. 57*, pp. 41-64.

Dempsey, B. J. (1976), *Climatic Effects on Airport Pavement System - State of The Art.* U.S. Army Engineers Waterways Experiment Station. Final Report, AD/A-029 422.

Dempsey, B. J. and Thompson, M. R. (1970), "A Heat transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered System." *Highway Research Record 342*, Transportation Research Record, Washington, DC, pp. 39-56.

Dickinson, E.J., 1978, "A Method of Calculating Temperature Gradients in Asphalt Concrete Pavement Structures Based on Climatic Data," *Australian Road Research*, Vol. 8, No. 4, 16-34.

Domenichinin, L., and Marchionna, A. (1981). "Influence of Stress Range on Plain Concrete Pavement Fatigue Design," *Proc. of the Second International Conference on Structural Design of Asphalt Pavements*, Purdue University, Indiana, USA.

Fatani, M., Al-Abdul Wahhab, H.I., Balghunaim, F.A., Bubshait, A., and Al-Dhubeeb, I. (1994). *Evaluation of Permanent Deformation of Asphalt Concrete Pavements in Saudi Arabia.* Final Report submitted to King Abdulaziz City for Science and Technology (KACST), Riyadh.

Ionnides, A. M. Salsilli-Murua, R. A. (1989), "Temperature Curling in Rigid Pavements, An Application of Dimensional Analysis." Transportation Research Board. 68th Annual Meeting, Washington, DC., USA.

FHWA (1994), *Specific Pavement Studies-Experiments Design and Research Plan for Experiment SPS-94 SUPERPAVE Asphalt Binder Study,* McLean, Virginia.

Kallas, B.F. (1966), "Asphalt Pavement Temperature," *Highway Research Record 150*, Transportation Research Board, Washington, D.C., pp. 1-11.

Potocki, F. P. (1973), *Road Temperature and Climatological Observations in The Emirate of Abu Dhabi.* Unpublished report.

Ramadhan, R. H. and Al-Abdul Wahhab (1997), "Temperature Variations of Flexible and Rigid Pavements in Eastern Saudi Arabia." *Building and Environment Journal,* Vol. 32, No. 2, pp. 1-7

The Asphalt Institute (1984). *Mix Design Methods for Asphalt Concrete and Other Hot Mix Types,* MS-2.

Venkataraman, T.S., and Venkatasubramanian, V. (1977). "Temperature Studies on Bituminous Pavements in Tropics," *Australian Road Research,* Vol. 7, No. 1, 32-37.

Wett, H. P. (1981), "Temperature Conditions in Bituminous Surfacing at Darwin during A Period of One Year." *Australian Road Research,* Vol. 11, No. 4, pp. 30-35.

Williamson, R.H. (1977), "Effect of Environment on Pavement Temperature," *Proc. of Third International Conference on Structural Design of Asphalt Pavements,* Vol. 1, 144-157, Michigan, USA.

Yoder, E. J. and Witczak, M. W. (1975), *Principle of Pavement Design.* 2nd Edition, John Wiley & Sons, Inc. USA.