TEMPERATURE EFFECTS ON FWD MEASUREMENTS OF CONCRETE PAVEMENT

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It is well known that the temperature gradient through the concrete pavement slab has a significant influence on the degree of support offered by the foundation. Hence, the FWD deflection measurements of concrete pavement are dependent on temperature gradient to some extent, which makes it difficult to reasonably evaluate pavement structural conditions. On the basis of a recent experimental study, a temperature gradient prediction model for jointed concrete pavement is developed in this paper. Next, by analyzing the influence of temperature gradient on FWD measurements, the temperature gradient-deflection correction charts are proposed. These procedures will make it easier to adjust pavement deflection data and backcalculated moduli to standard temperature gradient conditions.

INTRODUCTION

FWD deflection testing is now widely recognized as an important tool for pavement structural evaluation. The amount of deflection for a given load is influenced by the pavement structural conditions and environmental factors, in which the pavement structural conditions consist of slab size, joint, and support of foundation etc., whereas the environmental factors include moisture, temperature and temperature gradient. As for temperature gradient, a positive gradient with the temperature higher at the surface will tend to lift the pavement slab off the subgrade in its central portion. On the contrary, a negative gradient will result in the pavement slab curing upward along joints and edges. It has been observed that temperature gradient can vary considerably during the day and can result in significant changes of FWD deflection (*1,2*). Therefore, proper structural evaluation requires consideration of the effect of temperature gradient.

Determining the temperature effects on deflection of asphalt pavement is currently accomplished in many ways(*3~5*). However, few reports concerned about the temperature gradient estimate and its effects on jointed concrete pavement. In this paper, a recent experimental study of temperature gradient effects on FWD measurements of jointed concrete pavement is presented firstly. For a period of one year, temperatures throughout the concrete slab were recorded from a test pavement. The FWD testing was conducted at two hour intervals over an entire day during each season of the year. Based on these measurements, together with other available field data (*6,7*), an effective temperature-gradient (TG) prediction model is developed, which uses testing time (time of day, in 24-hour system), pavement surface temperature (it can be measured automatically at time of FWD test), one-day's average air temperature, and slab thickness as input data. The verification demonstrates that the prediction model is simple and accurate, and all its necessary input data can be obtained conveniently, together with the FWD test. Secondly, the influence of TG on pavement deflections is analyzed. It is found that the TG has a pronounced effect on FWD deflections, especially for the slab corner load case. For example, the deflection measured during early morning (negative gradient) on warm days may be twice as much as that of measured in the afternoon (positive gradient). Finally, the correction charts of TG on FWD deflection measurements are proposed so as to improve the adequacy of backcalculation and structural evaluation for jointed concrete pavement.

INVESTIGATION

Test Pavement at Kurihashi

As one of the research subjects undertaken by Japan FWD Research Association, a concrete test pavement was constructed in 1993 at Kurihashi (*8*). The concrete slab is 8.0m in length, 5.4m in width, and the cross-section is shown in Fig.1. To obtain the temperature data in the pavement, at the slab interior, five thermocouples were embedded at 0.5, 8, 16, 24 and 32cm below the slab surface (see Fig.1). Together with FWD tests, the air temperature and the temperature at each

thermocouple's position were measured at 2-hour intervals over an entire day during different seasons of the year. A KUAB FWD was used for measuring deflections at slab center and corner locations. With a 30cm diameter loading plate and 100kN peak load, the FWD deflection basins were measured at load center, 20, 30, 45, 60, 75, 90, 120, 150, and 200cm from the load center. The slab surface temperature was simultaneously measured by a thermometer that was installed on the trailer of the FWD.

FWD Common Test at Haneda Airfield Pavement

In order to calibrate FWD's as well as collection deflection data, the common testing (13 FWD's) was held at the concrete apron of Haneda airport on June 18-19, 1996. The apron pavement consists of 36cm cement concrete slab over 25cm crushed stone base course, with the slab dimension of 5m×5m and aggregate interlock joints. On slab center and corner load case, the FWD deflections were tested. Meanwhile, the temperatures within the slab were measured by means of thermocouples grouted into small holes drilled at the slab interior. More detailed description of the test and measurements are available elsewhere(*9*).

Collection of Other Available Temperature Data

To enlarge the data range, for example, climatic and pavement structural conditions, some useful data from other test pavements were collected for the prediction analysis in this paper.

Arlington Experiment----In the Arlington road test (in 1930s), the effects of temperature condition on load bearing capacity of pavement slabs were one of the main subjects. The temperature measurements were made on two small slabs, both were 1.2m square, one being 15cm and the other 23cm in thickness. From the original figures of reference (*6*), 88 temperature data sets were collected which covered periods of two years.

Dr. Iwama's Test----Under the program of "Experimental Studies on the Structural Design of Concrete Pavement ", full scale concrete slabs with thickness of 15, 20 and 25cm were paved at Tokyo & Chiba in 1960s. The temperatures at various positions in these slabs were measured for about 3 years (1957~1960). From reference (*7*) 105 data sets were gathered.

PREDICTION OF SLAB TEMPERATURE GRADIENT

Recorded Temperature Distribution

The temperature difference between the surface and the bottom of the slab is responsible for the magnitude and direction of slab curling. For all practical purposes, the TG computed from temperature differential divided by slab thickness is popularly used to evaluate the temperature conditions of concrete pavement. The typical temperature distribution characteristics from Kurihashi test slab are shown in Fig.2. It can be observed that: (1) Zero TG occurs at approximately 6:00~9:00 a.m. and 18:00~20:00 p.m.. Maximum positive and negative TG occur at 12:00~14:00 p.m. and 4:00~6:00 a.m., respectively. (2) Variation in TG follows a pattern that is similar to that of pavement surface temperature, maximum and minimum TG occur normally at the same time as surface temperatures reached their maximum and minimum. (3) Throughout the day and night, the changing of TG is similar to the curves of sine wave function, which is also obvious in Fig.3, the collected data from Arlington experiment and Dr. Iwama's test.

Development of Prediction Equation

Considering the above test data and investigations, the independent variables were studied in various ways in an attempt to determine the best form of a prediction model. It was found that pavement surface temperature and one-day's average air temperature were two significant variables. By multiple regression analysis, the following empirical equation has been developed which can be used to predict TG of concrete slabs conveniently. It can be seen that both the correlation coefficient and standard error of the estimate are quite good, and the comparison of measured and predicted TG for the above 439 data is shown in Fig.4.

$$TG=(0.062\times TS-0.0727\times Y)/H^{0.165} -\sin((X-15)/12\times\pi)\times(1.167+0.236\times(TS-Y))/H \quad (1)$$

(n=439, R^2=0.967, SEE=0.048)

TG: temperature gradient (°C/cm)
TS: pavement surface temperature (°C)
Y: average air temperature (one day)
X: testing time (in 24 hour system)
H: slab thickness (cm)

Verification of Prediction Equation

To further verify the validity of above prediction model, the measurements from reference (*2*) were used to check the estimate accuracy. These data were measured from a specially prepared jointed concrete test pavement at Balcones Research Center (BRC) of The University of Texas at Austin in 1986. The test pavement consisted of 25.4cm of cement concrete slab placed on a 7.6cm asphalt concrete base on a 15cm crushed stone subbase course, and temperature data were measured by thermocouples installed within the slab. It is demonstrated from Table 1 that there is an excellent agreement between estimated TG and measured values, which indicates that the proposed prediction equation is also suitable for other climate regions with satisfied estimate accuracy.

TEMPERATURE GRADIENT CORRECT-ION OF FWD DEFLECTION

It has been widely recognized that asphalt is a viscous material, its properties are highly dependent on temperature. So that, when use of deflection measurements in asphalt pavement structural evaluation and overlay design require the adjustment of deflections to a reference temperature, e.g., a temperature correction procedure for FWD deflections and backcalculated asphalt concrete moduli has been introduced in 1986 AASHTO Guide (*3*).

As indicated earlier, temperature within the concrete slab has a strong influence on slab curl and surface deflection measurements. For similar reason, the temperature gradient-deflection correction is also necessary when FWD deflections are used to evaluate the in situ structural capacity of rigid pavement.

TG Correction of Slab Interior FWD Deflection

Fig.5 is the typical FWD measurements from Kurihashi test pavement. As shown, the temperature gradient has an effect on interior deflections at each of the FWD sensors. Although in winter days there was little TG in the slab, the deflection variation with TG was still observed. When TG increasing, the slab interior FWD deflection also increased. Fig.5 appear to indicate that the relationship between TG and FWD deflections could be approximated by a linear function with the following form:

$$D_i=a+b\times TG \quad (2)$$

Where D_i is the deflection at sensor i, coefficient a is the deflection corresponding to a TG=0 condition, and b is the slope of the straight line. In this study, the deflection for TG=0 is selected as the standardized deflection, so temperature correction factors for FWD deflections can be developed by calculating the ratios between the deflection at the condition of zero TG and the measured deflection value at a specific TG value. By comprehensive statistical analysis of the FWD measurements from Kurihashi test slab and Haneda apron pavement, the correction factors for slab center FWD deflection basins are summarized in Table 2.

As can be seen in Table 2, the correction factors for each of the FWD sensors show no obvious difference. For practical purposes, a common correction equation is recommended for slab interior load case. The measured deflections at each of the FWD sensors can be corrected to the zero TG condition using the following relationship:

$$D_{TG=0}= D_i\times e^{-0.38TG} \quad (3)$$

TG Correction of Slab Corner FWD Deflection

For jointed concrete pavement, the most critical deflection occurs at the slab corner. The plots of deflection-TG relationships in Fig.6 appear to indicate that the corner maximum deflection values varied significantly as the TG varying. When the TG increasing, the corner deflection decreased, opposite to the slab center load case. Although the measurements shown in Fig.6 were measured from different test pavements by different FWD devices, the linear relationship between corner deflections and TG clearly existed for each test section. Similar to that of the slab interior load case, the following correction equation is obtained for slab corner maximum deflection (D_0):

$$D_{0(TG=0)}=D_0 \times e^{1.174TG} \quad (4)$$

($n=200$, $R^2=0.80$, SEE=0.14)

Discussion of The Results

By using the above regression relationship, the TG correction charts for maximum deflection (D0) were calculated as shown in Fig.7. It can be seen that the slab center deflection correction factor is fairly near 1 until the TG exceeded 0.2C°/cm. But with the increasing of TG, the correction factor increases gradually. When FWD test is done in winter, or at other times there is little or no temperature gradient in the slab, center deflection can be used directly without correction. However, if FWD testing is conducted in summer, especially at midday, for the TG being normally greater than 0.4C°/cm (see Fig.2), the correction of center deflection should be necessary. On the other hand, the slab corner deflections measured at different time of one day, should not be used directly without TG correction.

In order to verify the correction procedure, the TG correction charts were used to recalculate the corrected deflections as shown in Fig.8. The result reveals that the corrected deflections are relatively constant, regardless of the TG values. This means that the accuracy of the correction procedure is acceptable. However, as emphasized earlier, the range of slab sizes and joint restraint conditions are other main factors that affect the TG-deflection characteristics of in-service concrete pavements. So, the correction equations of this paper may not necessarily be satisfied with other different concrete pavement conditions. For this correction procedure to be of ultimate utility to the engineering community, additional research is needed to refine the procedure and account for those factors. Currently, three-dimensional finite element analysis seems to be the most promising method to examine above mentioned complex effects.

CONCLUSIONS

(1) In order to apply TG correction to FWD deflections, a temperature gradient prediction model for jointed concrete pavements was developed. The verification demonstrated that the prediction model is fairly simple and sufficiently accurate. Together with the FWD test, all the necessary input data could be obtained conveniently.

(2) The temperature gradient within the slab showed significant influence on FWD deflection. Using TG=0 as the standard condition, the TG correction factors for slab corner & center FWD deflections were recommended.

(3) The deflection data collected in this study were obtained from a limited number of test pavements, further research efforts should be concentrated on calibrating and improving the accuracy of the proposed correction procedure.

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Fig.3. Temperature gradient versus time of day

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Fig.7. Temperature gradient correction factors for FWD deflection

Fig.8. Validation of temperature gradient correction procedure

TABLE 1. Verification of Temperature Gradient Prediction Model
(data were measured from BRC test pavement in April 23 & July 19,1986)

Date	Hour X	Average Temp Y(°C)	Surface Temp TS(°C)	Slab H (cm)	Measured TG(°C/cm)	Predicted TG(°C/cm)	Absolute error(°C/cm)
4/23	0:00	20.8	21.6	25.4	-0.16	-0.14	0.02
4/23	1:00	20.8	20.8	25.4	-0.17	-0.15	0.02
4/23	2:00	20.8	20.1	25.4	-0.18	-0.17	0.01
4/23	3:00	20.8	19.5	25.4	-0.18	-0.18	0.00
4/23	4:00	20.8	18.9	25.4	-0.19	-0.19	0.00
4/23	5:00	20.8	18.5	25.4	-0.19	-0.20	0.01
4/23	6:00	20.8	18.1	25.4	-0.19	-0.21	0.02
4/23	7:00	20.8	18.5	25.4	-0.16	-0.19	0.03
4/23	8:00	20.8	20.8	25.4	-0.04	-0.08	0.04
4/23	9:00	20.8	23.7	25.4	0.08	0.05	0.03
4/23	10:00	20.8	27.0	25.4	0.21	0.19	0.01
4/23	11:00	20.8	30.3	25.4	0.33	0.33	0.00
4/23	12:00	20.8	33.2	25.4	0.42	0.43	0.01
4/23	13:00	20.8	35.5	25.4	0.48	0.49	0.01
4/23	14:00	20.8	36.8	25.4	0.49	0.50	0.01
4/23	15:00	20.8	37.0	25.4	0.46	0.46	0.00
4/23	16:00	20.8	35.9	25.4	0.38	0.37	0.01
4/23	17:00	20.8	33.7	25.4	0.26	0.26	0.00
4/23	18:00	20.8	30.7	25.4	0.12	0.13	0.01
4/23	19:00	20.8	28.3	25.4	0.01	0.04	0.03
4/23	20:00	20.8	26.4	25.4	-0.05	-0.02	0.03
4/23	21:00	20.8	25.1	25.4	-0.09	-0.06	0.03
4/23	22:00	20.8	23.8	25.4	-0.12	-0.09	0.03
4/23	23:00	20.8	22.7	25.4	-0.15	-0.12	0.03
7/19	0:00	29.1	32.3	25.4	-0.13	-0.12	0.01
7/19	1:00	29.1	31.3	25.4	-0.15	-0.14	0.01
7/19	2:00	29.1	30.4	25.4	-0.16	-0.15	0.01
7/19	3:00	29.1	29.6	25.4	-0.17	-0.17	0.01
7/19	4:00	29.1	29.0	25.4	-0.18	-0.18	0.00
7/19	5:00	29.1	28.4	25.4	-0.19	-0.19	0.00
7/19	6:00	29.1	27.7	25.4	-0.19	-0.21	0.02
7/19	7:00	29.1	27.2	25.4	-0.19	-0.23	0.04
7/19	8:00	29.1	28.0	25.4	-0.14	-0.19	0.05
7/19	9:00	29.1	30.0	25.4	-0.04	-0.09	0.05
7/19	10:00	29.1	33.1	25.4	0.09	0.04	0.05
7/19	11:00	29.1	36.6	25.4	0.23	0.19	0.04
7/19	12:00	29.1	40.1	25.4	0.36	0.32	0.04
7/19	13:00	29.1	42.6	25.4	0.42	0.39	0.03
7/19	14:00	29.1	44.9	25.4	0.49	0.44	0.05
7/19	15:00	29.1	46.2	25.4	0.50	0.44	0.06
7/19	16:00	29.1	47.1	25.4	0.50	0.42	0.08
7/19	17:00	29.1	46.5	25.4	0.43	0.35	0.08
7/19	18:00	29.1	44.8	25.4	0.33	0.25	0.08
7/19	19:00	29.1	42.4	25.4	0.21	0.15	0.06
7/19	20:00	29.1	39.6	25.4	0.08	0.06	0.02
7/19	21:00	29.1	37.2	25.4	-0.01	-0.01	0.00
7/19	22:00	29.1	35.7	25.4	-0.05	-0.05	0.00
7/19	23:00	29.1	34.4	25.4	-0.09	-0.07	0.02

TABLE 2. Slab Center Deflection Correction Factors

Deflection	Correction Factors	n	R^2	SEE
D0	$F0=e^{-0.364TG}$	88	0.73	0.039
D30	$F30=e^{-0.403TG}$	88	0.88	0.027
D60	$F60=e^{-0.405TG}$	88	0.86	0.030
D90	$F90=e^{-0.380TG}$	88	0.79	0.036
D150	$F150=e^{-0.356TG}$	88	0.79	0.039

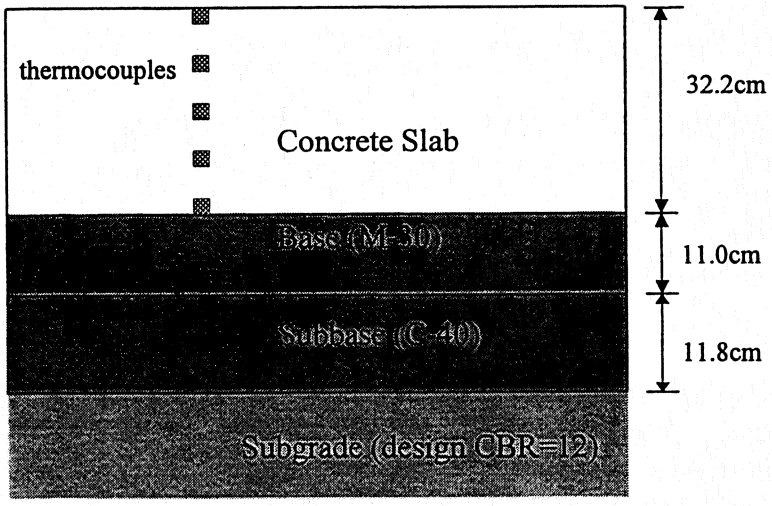


Fig.1. Kurihashi concrete test pavement cross-section

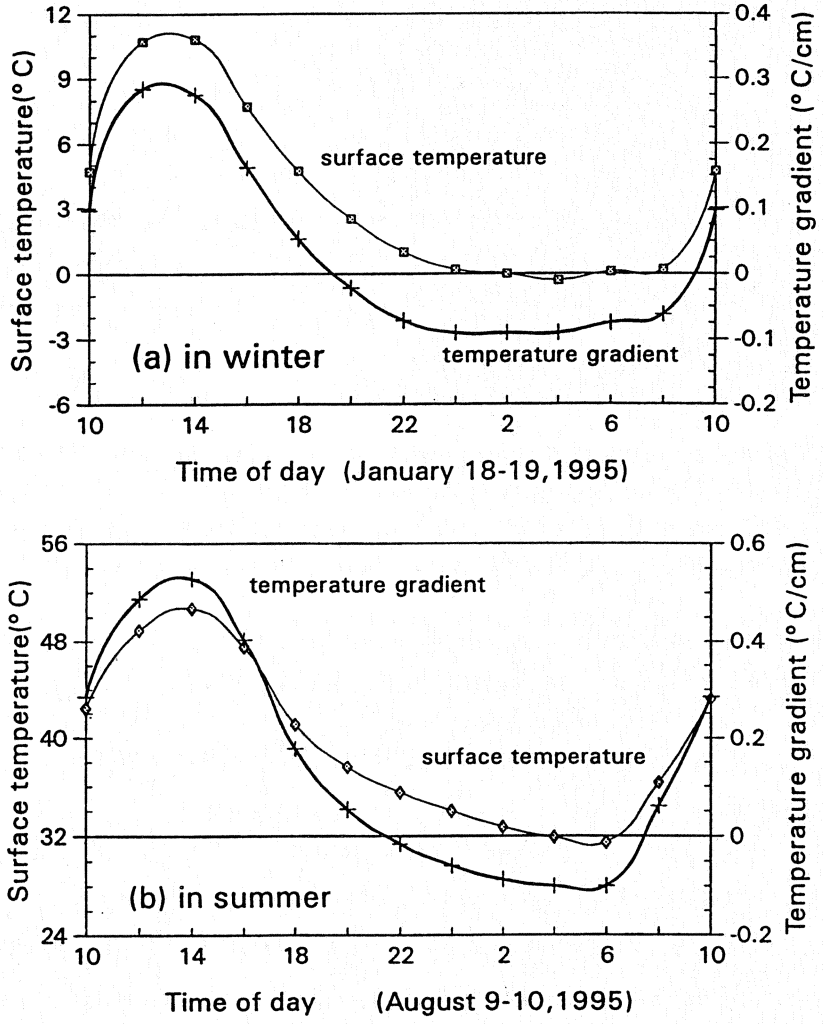
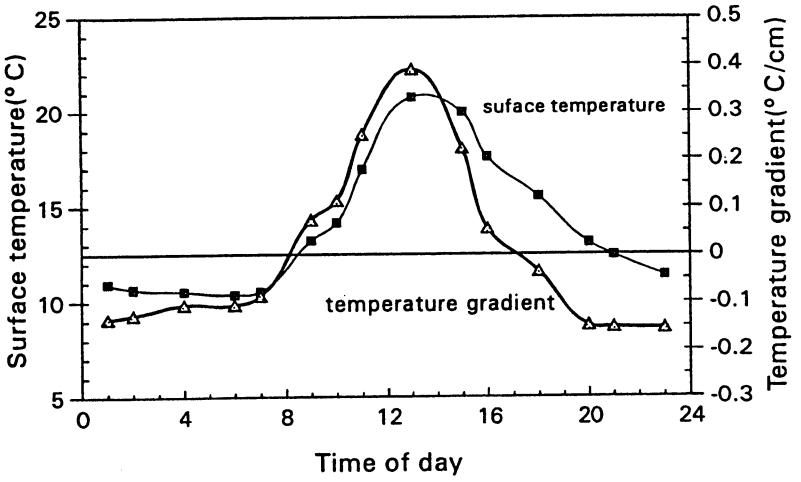
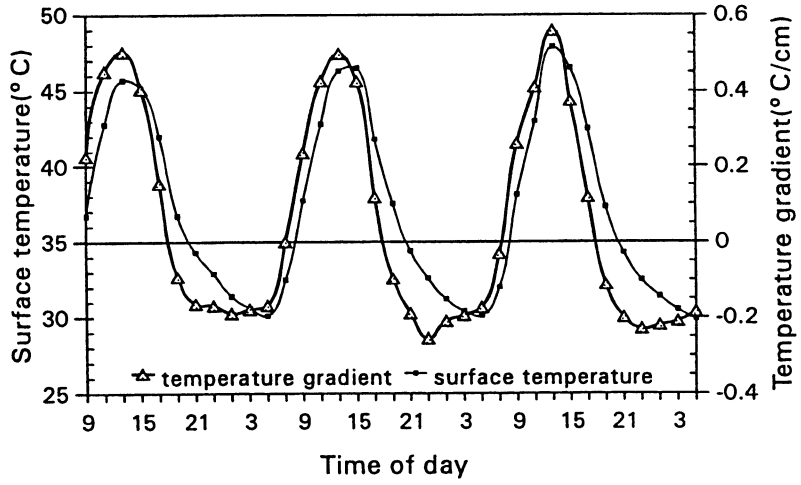


Fig.2. Temperature gradient within the slab at Kurihashi test pavement



(a) Arlington experiment measured in November 24,1933



(b) Dr.Iwama measured in August 4-7,1960

Fig.3. Temperature gradient versus time of day

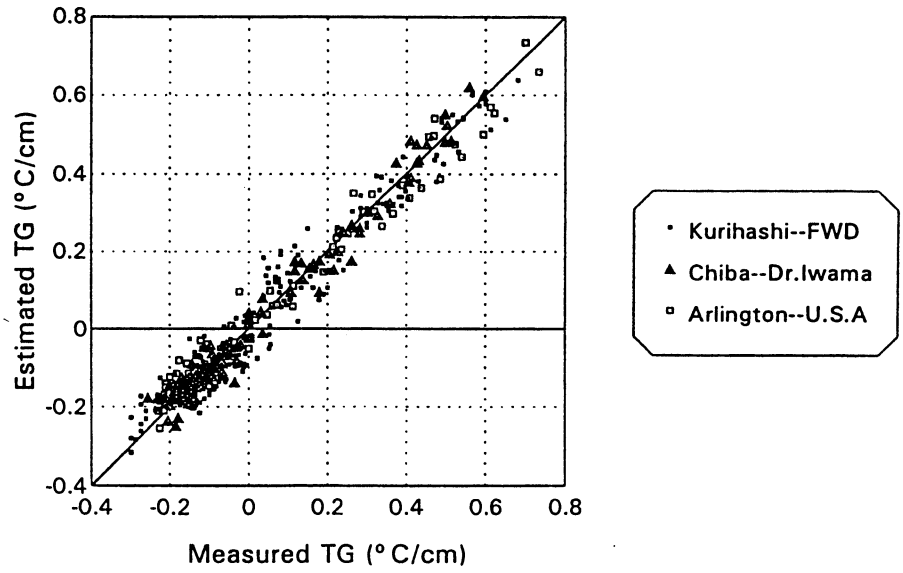


Fig.4. Comparison of measured and predicted temperature gradient

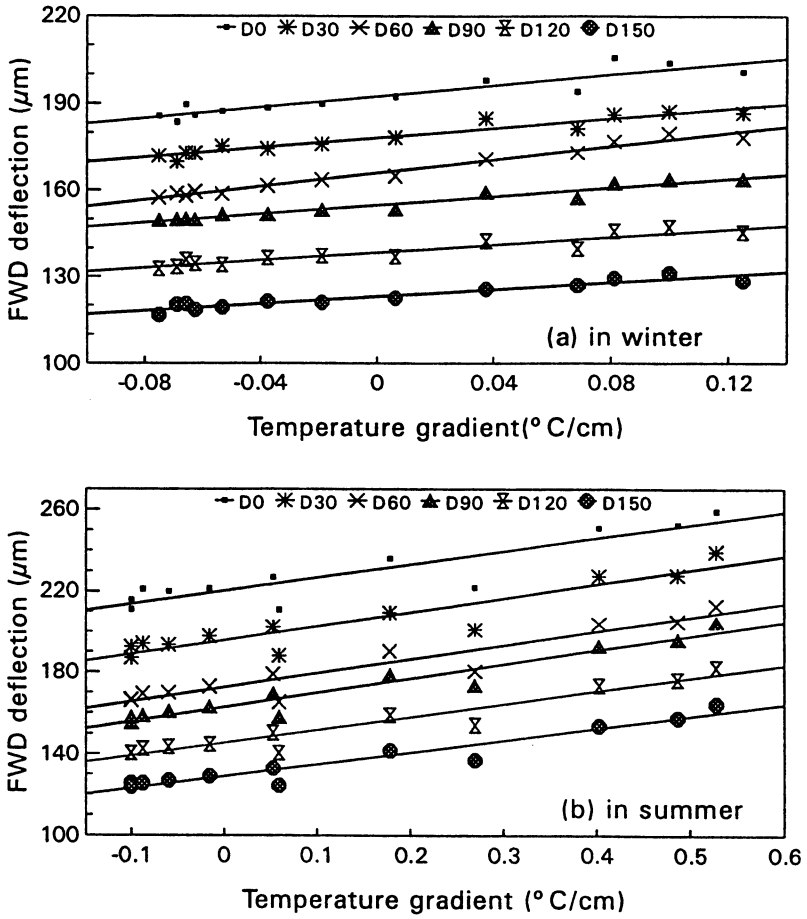


Fig.5. Temperature gradient versus slab center deflection at Kurihashi test pavement

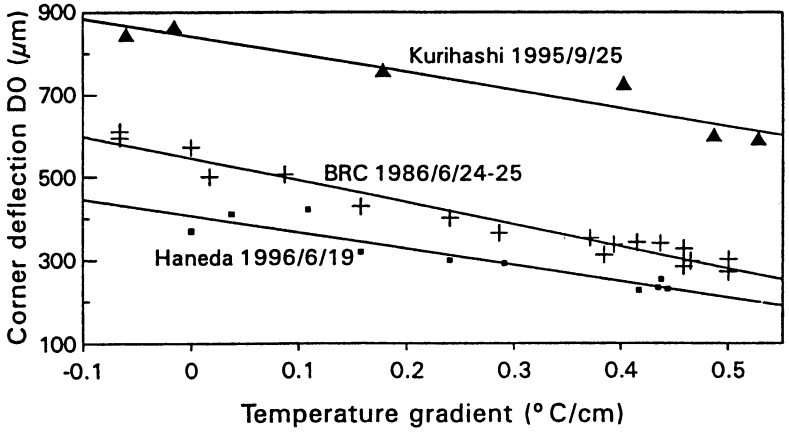


Fig.6. Slab corner deflection versus temperature gradient

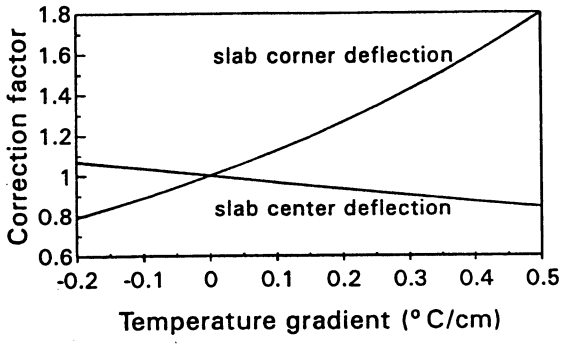


Fig.7. Temperature gradient correction factors for FWD deflection

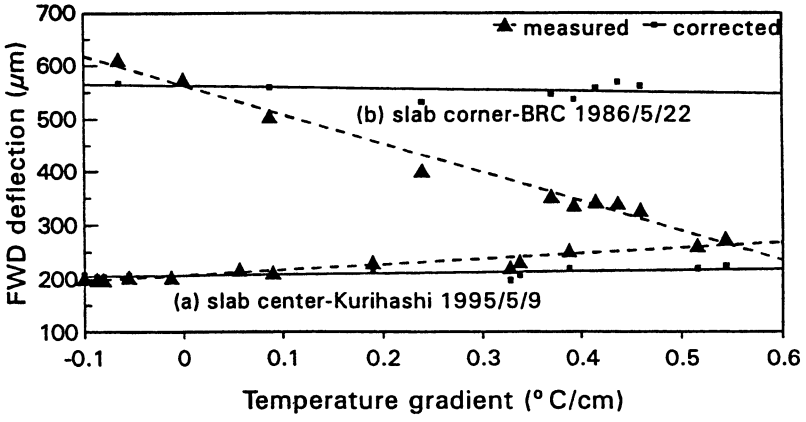


Fig.8. Validation of temperature gradient correction procedure

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ACKNOWLEDGMENTS

The temperature and deflection data used in this research were collected as part of study sponsored by Japan FWD Research Association (JFRA). The writers are grateful for the availability of these valuable data. The technical advice and helpful comments by Dr. Tatsuo Nishizawa of Ishikawa National College of Technology & Dr. Jianjun Yin of PHRI are highly appreciated.