

PERMANENT DEFORMATION OF BASE COURSE UNDER CONCRETE PAVEMENT AND ITS EFFECT TO FATIGUE FAILURE

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Yasushi Takeuchi

Assistant Professor, Tokyo University of Agriculture
1-1-1 Sakuragaoka, Setagaya-ku, Tokyo, 156-8502 JAPAN
TEL: +81-3-5477-2342, FAX: +81-3-5477-2620
E-mail: bamboo@nodai.ac.jp

Masashi Koyanagawa

Associate Professor, Tokyo University of Agriculture
1-1-1 Sakuragaoka, Setagaya-ku, Tokyo, 156-8502 JAPAN
TEL: +81-3-5477-2344, FAX: +81-3-5477-2620
E-mail: elric@nodai.ac.jp

Tatsuo Nishizawa

Associate Professor, Ishikawa National College of Technology
Tsubata, Ishikawa, 929-0392 JAPAN
TEL: +81-76-288-8167, FAX: +81-76-288-8171
E-mail: nishi@ishikawa-nct.ac.jp

Makoto Kimura

Researcher, Public Works Research Institute, Ministry of Construction
1 Asahi, Tsukuba, Ibaraki 305-0804 JAPAN
TEL: +81-298-64-4607, FAX: +81-298-64-0178
E-mail: kimurai@pwri.go.jp

ABSTRACT

In order to study the behavior of concrete pavement under cyclic loads, the static loading test and the cyclic loading test with the full scale concrete pavement were carried out at the Public Works Research Institute (PWRI) of the Ministry of Construction in 1997. In this study, the reduction of the base course reaction modulus (k value) with cyclic loads and its effect on the fatigue failure of a concrete slab were investigated. The plate FEM program was used for analysis of mechanical behaviors in the loading test, and two types of fatigue curve were utilized for the fatigue analysis of the concrete slab. The result showed that the reduction of k value with the permanent deformation of base course surface accelerated the fatigue failure of the concrete.

INTRODUCTION

In the concrete pavement, permanent deformation in the base course surface is made to lower the reaction modulus, and increases the bending stress of concrete slab. Also, the permanent deformation accelerates the fatigue failure of the concrete pavement. Therefore, it seems to be important to estimate the permanent deformation of base course surface in the concrete pavement design, when the long-term performance of the concrete pavement is predicted.

There are two major design methods for concrete pavements in Japan. One is the Japan Road Association (JRA) method (1), the other is the Japan Society of Civil Engineers (JSCE) method (2). However, it is assumed that the base course reaction modulus does not change in design service life in these design method. Authors examined permanent deformation of the base course surface and reduction of k value from the static and the cyclic loading test result using full-scale concrete pavement carried out in the PWRI of the Ministry of Construction (3). As the results, the permanent deformation and the reducing k values from the measurement data of cyclic loading test were confirmed. However, it was not possible to accurately grasp the variation of k value, since there was the effect of the temperature gradient in the concrete slab. Therefore, an objective of this study is to make clear the influence of the k value reduction on the bending stress and the fatigue damage of concrete pavement. For this purpose, the measurement strains were compared with the analytical results.

In the fatigue analysis, the difference of fatigue curve of concrete (S-N curve) gives a different fatigue damages. In this study, two types of S-N curves that were adopted in the JRA method and in the JSCE method were utilized to see the effect of the fatigue curves. And the plate FEM program developed by Nishizawa (4) was utilized for analysis of the loading tests.

EXPERIMENTAL METHOD

Outline

Figure 1 shows the concrete pavement used for the static and the cyclic loading test. And each concrete slab has been coupled in dowel bars. The loading machine consists of an actuator (diameter of loading plate =300mm) under an oil pressure control unit and a rigid beam. The actuator has ability to apply 0-98kN in static, 0-49kN and 0.5-5Hz in cyclic loads. And the actuator is movable by two rails that equipped on the sidewall.

As shown in Figure 1, the loading position was a free transverse edge of Slab1. In the static loading test, the range of the load was 0-49kN and the step of the load was 9.8kN. The stress

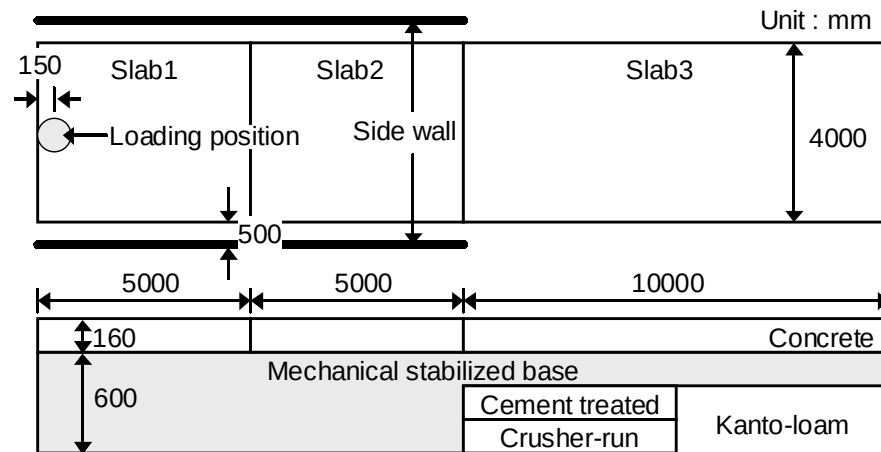


FIGURE 1 Outline of concrete pavement used for loading test

TABLE 1 Mechanical properties of base course and concrete

Base course		Concrete	
Dry density	2.255 (g/cm ³)	Density	2.4 (g/cm ³)
Modified CBR	105 (%)	Bending strength	6.1 (MPa)
Degree of compaction	95.7 (%)	Young's modulus	31392.0 (MPa)
K ₇₅	83.4 (MN/m ³)	Poisson's ratio	0.2 (-)
		Coeff. of thermal expansion	0.00001 (°C)

waveform of the cyclic load was taken to be a sinusoidal curve variation of frequency of 2Hz, and about 800000 times loading were applied. The maximum value of the cyclic load was 49kN and the minimum load was 2kN. And the static loading test was carried out at the night in order to remove the influence of the thermal stress of slab. And the cyclic loading test was started after static loading test was finished.

Materials

Table 1 shows the mechanical properties of the base course and the concrete. The base course material is the crush stone for mechanical stabilization (M-30) which is the common material used for base course in Japan. And the mechanical properties of concrete were measured using test pieces cured in the same condition as the slab.

Measurement Method

In the loading test, the following were measured : Load, deflection of concrete slab and strain distribution in the slab with the loading, temperature distribution in the slab, base course surface

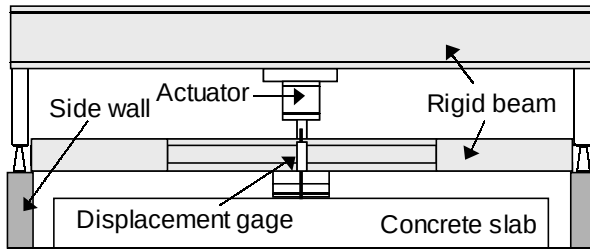


FIGURE2 Displacement gage for deflection measurement

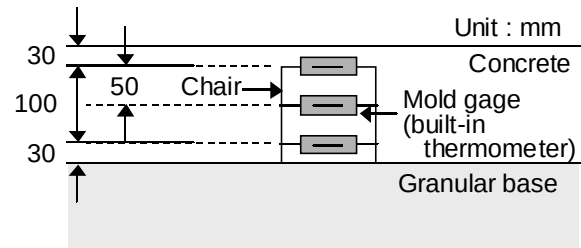


FIGURE3 Embedding gages for strain measurement

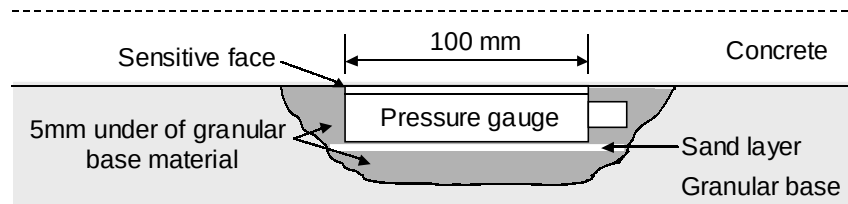


FIGURE 4 Earth pressure gauge for base course surface pressure measurement

pressure.

As shown in Figure 2, the deflection at the loading position (transverse edge) of the slab was measured using the supersensitive displacement gage that was installed by the magnet stand at the central of the steel rigidity beam between sidewalls. The temperature distribution and the strain distribution in the slab were measured using the embedding gages with built-in thermometer. And as shown in Figure 3, each gage was installed at regular intervals. And the base course surface pressure at the loading position was measured using the earth pressure gauge installed in the base course surface as shown in Figure4. Here, we paid much attention to make sure that the sensitive face of the earth pressure gauge and the base course surface became same level.

The temperature distribution was measured using data logger in hourly interval. And the load, the deflection and the pressure were also hourly measured using personal computer through the dynamic strain gauges. In order to analyze the cyclic loading test, it is necessary to know the temperature differential between the top and the bottom of slab. In this study, the temperature differential was estimated from the quadric curve approximation of measurement data. If the temperature at the slab surface is higher than the one at the bottom side, temperature differential is defined to be positive.

BACK-CALCULATION OF K-VALUE

The k-values were back-calculated based on the Winkler's formula of Eq.(1) and the

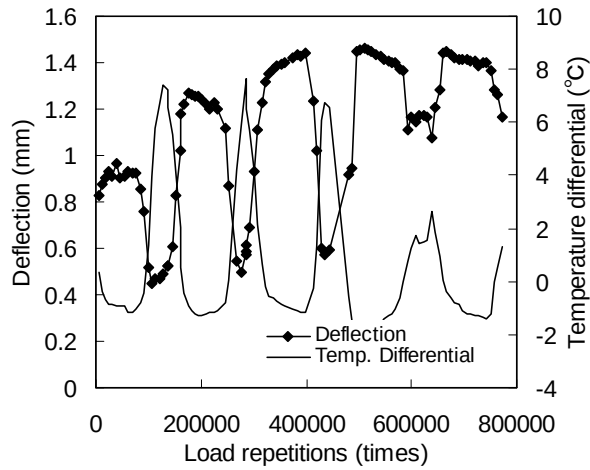


FIGURE5 Relationship between deflection and temperature differential

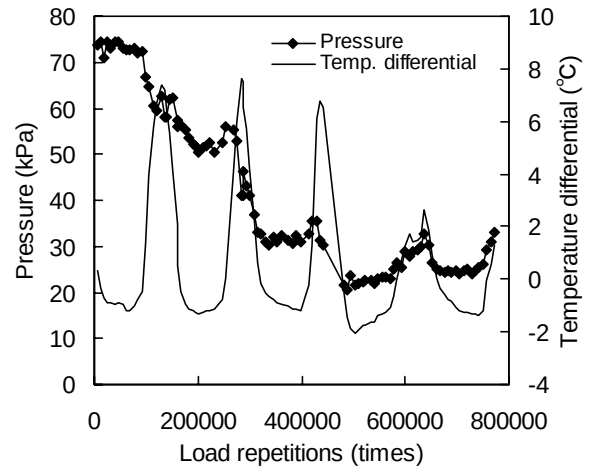


FIGURE6 Relationship between pressure and temperature differential

Westergaard's deflection formula of Eq.(2) (5).

$$P = K \cdot \Delta_e \quad (1)$$

$$\Delta_e = \frac{0.441F}{K \cdot l^2} \left[1 - 0.84 \left(\frac{a}{l} \right) \right] \quad (2)$$

where, Δ_e : Deflection of slab (m), k : k-value (N/m^3), P : Pressure (Pa)
 F : Load (N), a : Radius of contact area (m), h : Thickness of slab (m)
 l : Radius of relative stiffness (m) and $l = \sqrt{E_c \cdot h^3 / 12(1 - \nu_c^2)k}$
 E_c : Modulus of elasticity (Pa), ν_c : Poisson's ratio (0.2)

Figure 5 shows the relationship between the deflection and the temperature differential, and the Figure 6 shows the relationship between the base course surface pressure and the temperature differential. From these figures, it can be seen that the deflection increased and the pressure decreased with the load repetitions. From these results, it is found that the permanent deformation has been generated by the cyclic-load in the base course surface.

Figure 7 shows the relationship between the back-calculated k vales and the temperature differential. In this figure, $K_{75}^{(LD)}$ indicates the k value back-calculated from the load and the deflection and $K_{75}^{(LP)}$ indicates back-calculated from the load and the pressure. And each k value was calculated using Eq.(1) and Eq.(2). Also $K_{75}^{(DP)}$ indicates the k value calculated from the deflection and the pressure using Eq.(1). From this figure, it is found that the k values varied

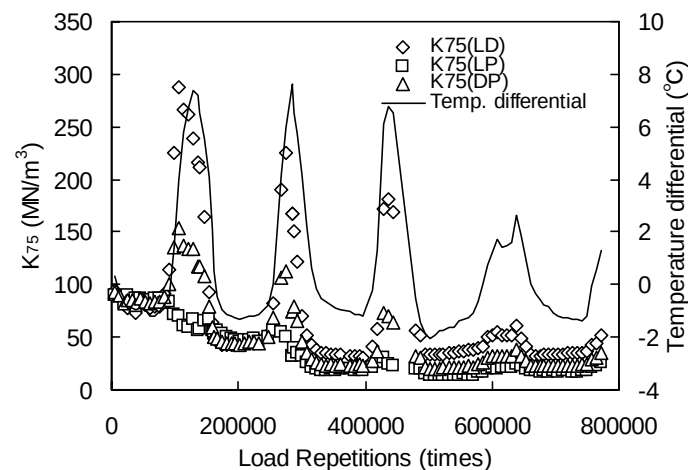


FIGURE 7 Relationship between back-calculated K-values and temperature differential

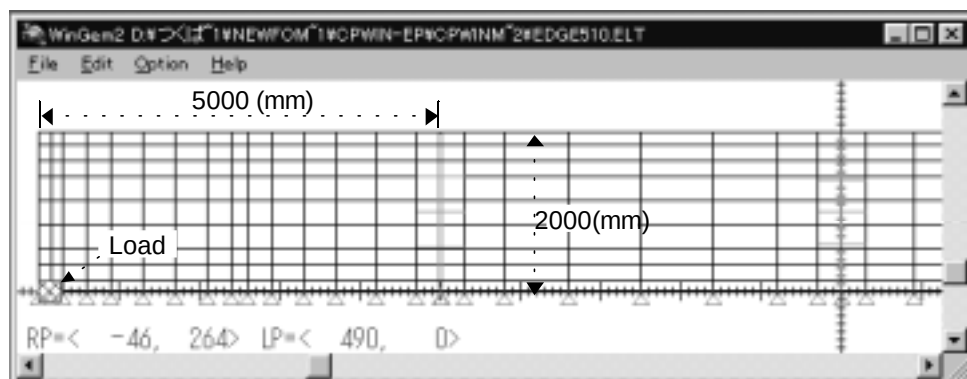


FIGURE 8 Territory for FEM analysis

widely when the temperature differential was large in positive. However the variation decreased and finally reached 1/3 - 1/4 of the initial value (3).

METHOD OF ANALYSIS

In the FEM analysis, considering the symmetrical shape of the concrete pavement, half area of the pavement was meshed as shown in Figure 8. And the input parameters on the concrete necessary for the analysis utilized the value in Table 1. The FEM analysis was carried out for both the static and the cyclic loading tests. The k value used in the static loading analysis was the measurement data of Table 1. And the k value mainly used in the cyclic loading analysis was the back-calculated k value from the measurement data.

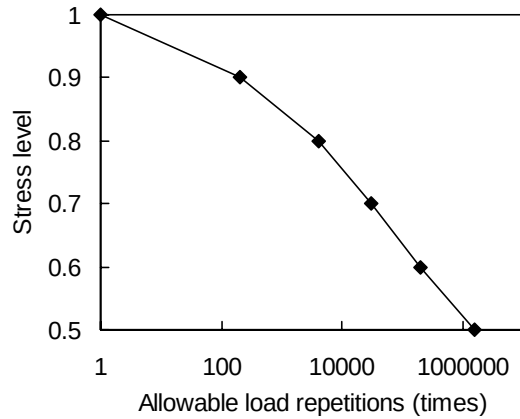


FIGURE 9 S-N curve of JRA method

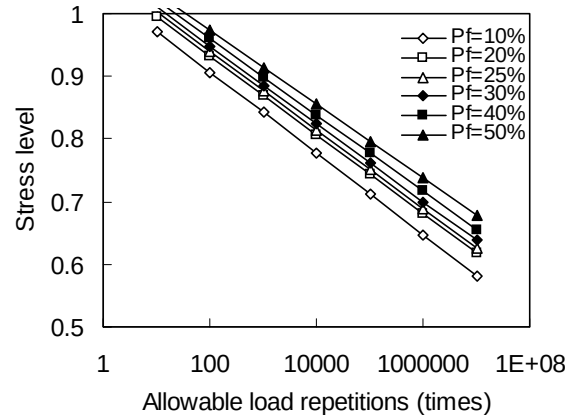


FIGURE 10 S-N curve of JSCE method

TABLE 2 Constants of two S-N curves

Range of S	JRA		Probability P_f	JSCE	
	a	b		a	b
$S > 0.9$	1.0	0.0435	10%	1.037	0.065
			20%	1.058	0.063
$0.8 < S \leq 0.9$	1.0769	0.0769	25%	1.066	0.063
			30%	1.072	0.062
$S \leq 0.8$	1.2240	0.1177	40%	1.082	0.061
			50%	1.091	0.059

Fatigue Damage

The fatigue analysis was conducted using two types of fatigue curves, and the accumulated fatigue damage was calculated by the Miner's rule shown in Eq.(3). And the fatigue crack occurs when the accumulated fatigue damage is over 1.0.

$$FD = \sum_{i=1}^m \frac{n_i}{N_i} \quad (3)$$

where, FD : Accumulated fatigue damage, n_i : Number of repetitions of stress level I
 N_i : Arrowable number of repetitions of stress level i , m : Number of stress level

In order to calculate the fatigue damage, two types of S-N curves were utilized. One is adopted in the JRA method shown in Figure 9, the other is adopted in the JSCE method shown in Figure10. Later curve was established based on the Koyanagawa's experimental results (6), and the curve varies by the probability of failure of concrete (P_f). In these figures, S is a stress level defined in Eq.(4). And Eq.(5) and Table2 shows the properties of two S-N curves. In this study, the probability of failure was selected to fit for the cyclic loading test result.

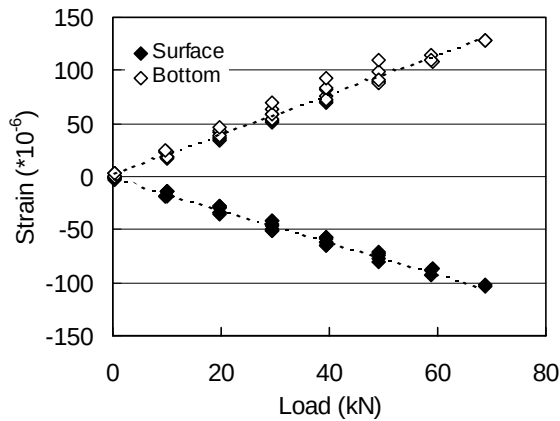


FIGURE 11 Relationship between loads and strains in static loading test

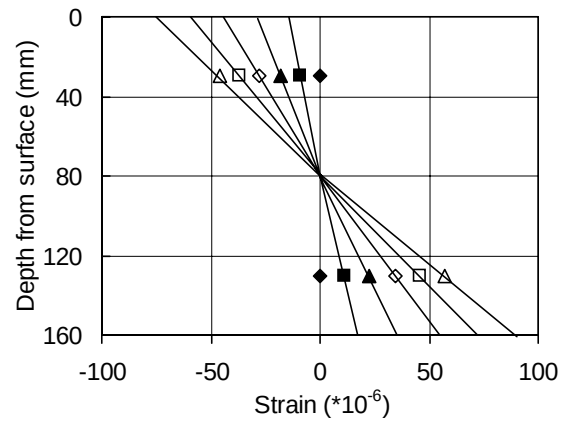


FIGURE 12 Calculation method of surface and bottom strains

$$S = \frac{\sigma_b}{f_b} \quad (4)$$

$$S = a - b \cdot \log_{10} N \quad (5)$$

where, σ_b : Calculated bending stress, f_b : Average bending strength of test-piece
 a, b : Constants shown at Table2, N : Allowable load repetitions

ANALYSIS OF STATIC LOADING TEST

Since the static loading test was conducted in the night, the temperature differential of slab in the static loading test was about 0.2 °C. Accordingly, it can be said that the influence of the temperature differential was negligible.

Figure 11 shows the relationship between the loads and the strains in the static loading test. As shown in Figure 3, the measured value of embedded gage installed at upper and lower sides of the slab is not the strain in surface and bottom of slab. Therefore, as shown in Figure 12, the surface and the bottom strains of slab were estimated using the regression line. As the results, the strain at the surface and the bottom varied linearly with the increase of the load. The strain calculated according to the above-mentioned method shall be called "measurement" result in order to distinguish from the FEM analytical result.

Figure 13 and Figure 14 show the relationship between the measurement strain and the FEM strain. Figure 13 shows the result at the compression (surface) side, and Figure 14 shows the

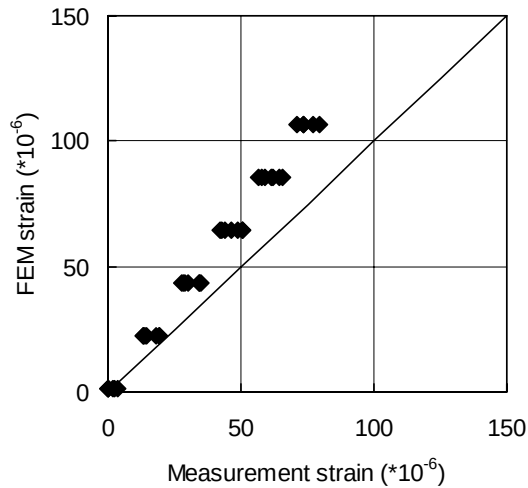


FIGURE 13 Comparison between measurement strain and FEM strain (surface)

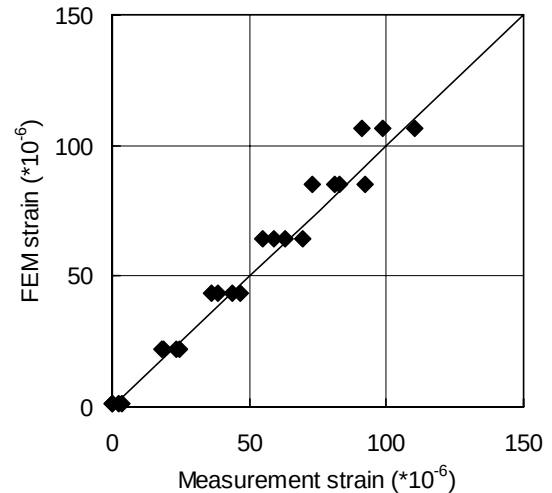


FIGURE 14 Comparison between measurement strain and FEM strain (bottom)

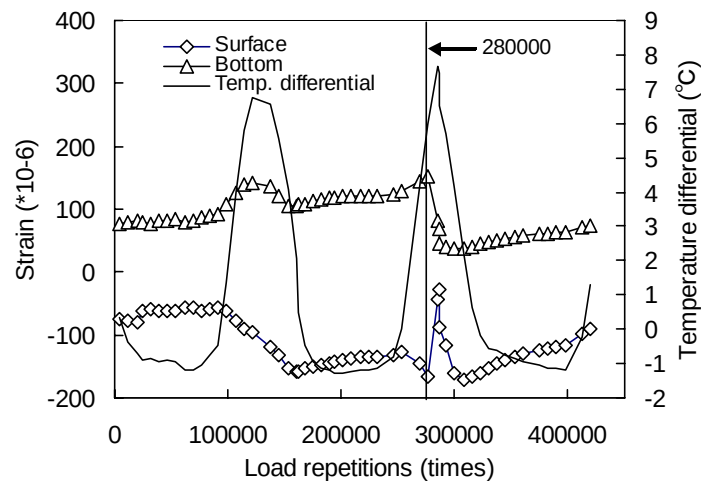


FIGURE 15 Change of measurement strain within cyclic loading test period

result at the tensile (bottom) side. It is found that the measurement data agrees well with the FEM data in the tensile side. But in the compression side, the measurement data has a tendency to leave from the FEM data. For this reason, it is thought that the embedded gage at the compression side might have been installed slightly lower than the intended position.

ANALYSIS OF CYCLIC LOADING TEST

Experimental Results

There was no rainfall in the cyclic loading test period. And the temperature of pavement surface

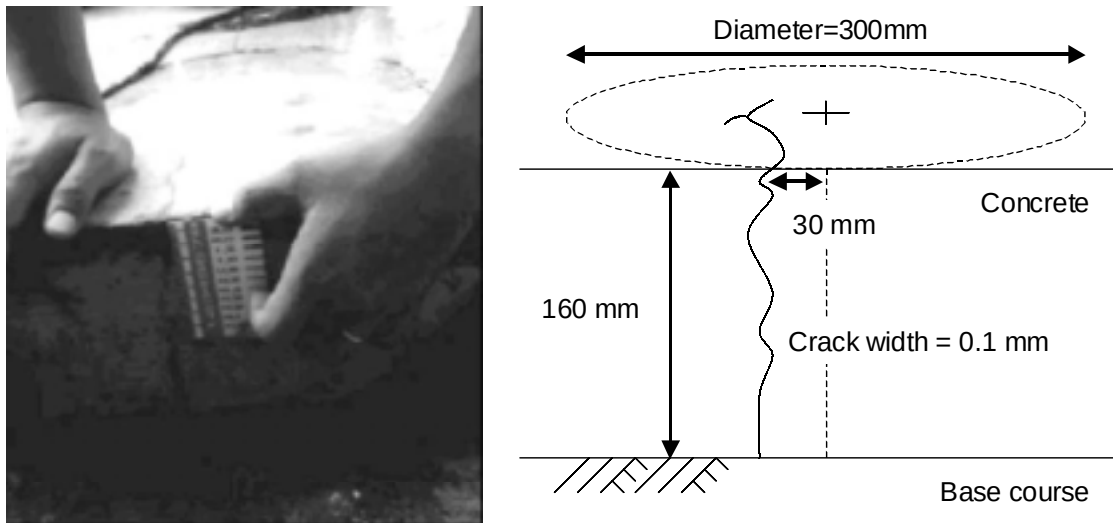


FIGURE 16 Crack at loading position and its details

in the daytime was 40-46 °C. In the test period, when the cyclic loading was about 430000th repetition, a crack from surface to bottom at the loading position was observed. Therefore, as shown in Figure 15, measurement data until 430000th repetition were selected.

Figure 16 shows a close up shot of the crack at the loading position and its detailed sketch. This crack occurred across the installed position of the embedded gages, therefore it seems that this crack affected the measurement strains. And as shown in Figure 15, the measurement strains varied widely at around 280000th repetition. This fact indicates that the crack occurred at around 280000th repetition actually. From the measured bending strength and the elastic modulus of concrete, the strain to failure of the concrete is about 200×10^{-6} . But the measured strains at the cracking were less than this value. Therefore, it seems that the crack was caused by fatigue of the concrete. Further, it was found that the influence of the thermal stress was large because the slab was in failure just after the 2nd peak of the temperature differential.

FEM Analysis

With the above-mentioned result, the FEM analysis until the about 280000th repetition was conducted. And in the FEM analysis, three types of the back-calculated k value were used. However these k values were varied widely when the temperature differential was large in positive. Therefore, as shown in Figure 17, the measurement data at the 1st peak of the temperature differential was compared with the FEM results calculated from $K_{75}^{(LD)}$, $K_{75}^{(LP)}$ and $K_{75}^{(DP)}$. From this figure, it was found that the FEM result calculated from $K_{75}^{(LP)}$ was most close to the measurement data. And the reason that the FEM results calculated from $K_{75}^{(LD)}$ and $K_{75}^{(DP)}$

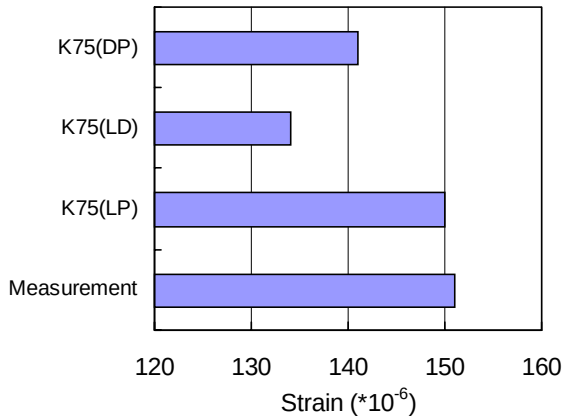


FIGURE 17 Comparison among measurement strain at 1st peak of temperature differential and FEM strains

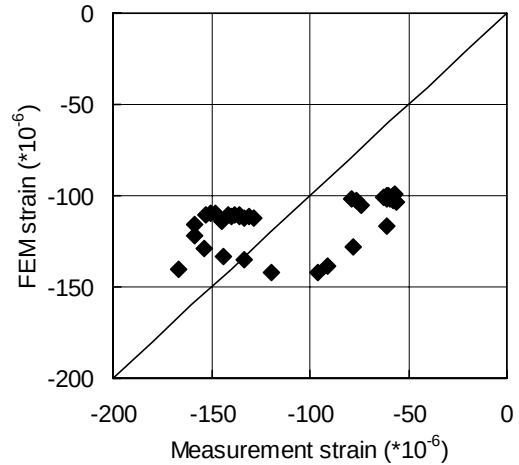


FIGURE 18 Comparison between measurement strain and FEM strain (surface)

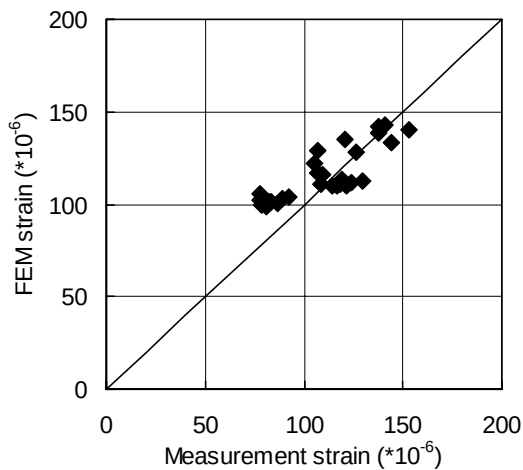


FIGURE 19 Comparison between measurement strain and FEM strain (bottom)

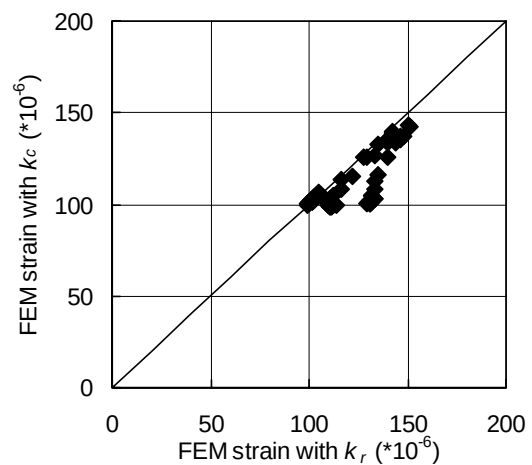


FIGURE 20 Comparison between two FEM results (k_c and k_r)

didn't agree with the measurement data was the decrease of the bending stress owing to the increase of the k value. Therefore, in the FEM analysis, the back-calculated k value, $K_{75}^{(LP)}$, was used.

The relationship between FEM results and measurement data is shown in Figure 18, 19. Figure 18 shows the result in the compression side, and Figure 19 shows the result in the tensile side. Figure 20 shows the relationship between the results with the constant k value and the results with the reducing k value. The constant k value is equal to the measurement k value, and the reducing k value equals $K_{75}^{(LP)}$. And following, the constant k value and the reducing k value shall be respectively called k_c and k_r .

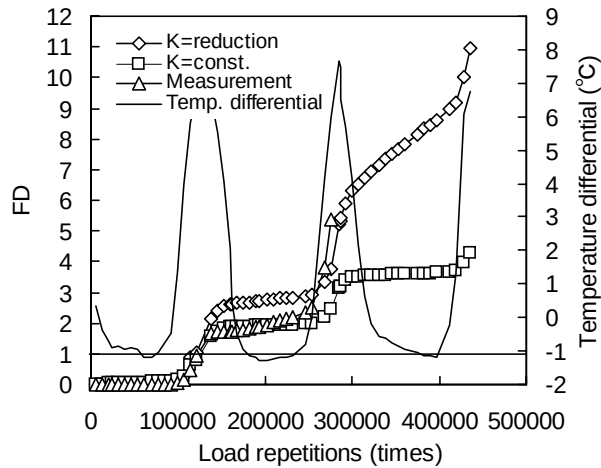


FIGURE 21 Results of fatigue damage analysis (JRA method)

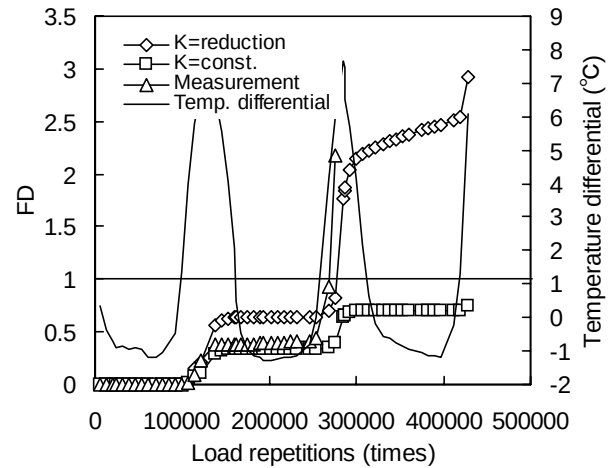


FIGURE 22 Results of fatigue damage analysis (JSCE method)

TABLE 2 Results of fatigue damage analysis

	JRA method		JSCE method (Pf=10%)	
	Load repetitions	FD	Load repetitions	FD
K=decline	119516	1.00	277933	1.00
	280000	5.23	280000	1.77
K=const.	126193	1.00	-	1.00
	280000	3.14	280000	0.64
Measurement	122838	1.00	269180	1.00
	280000	5.38	280000	2.17

In Figure 18, the FEM results at the compression side didn't agree with the measurement data. The reason of this disagreement was that the embedded gage was not able to follow the behavior of the concrete with the cyclic loads. However, as shown in Figure 19, it was found that the FEM results in the tensile side agrees well with the measurement data. From this result, the reduction of k value by the cyclic loads was confirmed. And from Figure 20, it was found that the FEM results with the constant k value had a tendency to be larger than those with the data used the reducing k value (bottom). However, the difference between these results was slight.

Fatigue Damage Analysis

Figures 21, 22 and Table 3 shows the results of the fatigue analysis. The result shown in Figure 21 was obtained using the JRA S-N curve, and the result in Figure 22 was obtained using the JSCE S-N curve with the probability of failure of 10%. In each result, the measurement data and the FEM data with k_c and k_r were used. And the data when $FD=1.0$ and 280000th repetition

were indicated in Table 2.

In Figures 21 and 22, FD increased widely when the temperature differential was large in positive. And it can be seen in each figure that the differential between the k_c condition and the k_r condition occurred by the reducing of k value.

From Table 2, it was found that all FD results using the JRA's S-N curve has already reached 1.0 in the about 120000th repetition. Therefore, it seems that the use of the S-N curve of the JRA method gives the over design of concrete pavements. And in the results using the JSCE's S-N curve, FD calculated from the FEM results with $K_{reduction}$ and from the measurement data reached 1.0 in the about 270000th to 280000th repetition. But, in the result as k value is fixed ($K_{const.}$), FD did not reach 1.0 even in the 400000 repetitions. From these results, it can be said that the reducing effect of k value on the fatigue failure of concrete slab was big.

CONCLUSIONS

In this study, the reduction of the base course k value by cyclic loads and its effect on the fatigue damage of the concrete slab were investigated from the static and the cyclic loading tests of the concrete pavement at the Public Works Research Institute. As a result, the following conclusions were obtained:

- (1) From the results of the loading test and its analysis, the reduction of k value with the cyclic loads was confirmed.
- (2) The accumulated fatigue damage was increased with the increase of the temperature differential and the reduction of k value.
- (3) It was found that in the fatigue analysis the result using the S-N curve of the Japan Road Association (JRA) method overestimates the accumulated fatigue damage. This result indicates that the use of the S-N curve of the JRA method gives the over design of concrete pavements.
- (4) The influence of the reduction of k value on the strain of the concrete slab was slight. However, it was confirmed that the reduction of k value with the permanent deformation of base course surface accelerated the fatigue failure of concrete slab.

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