# A STUDY ON THE EFFECT OF FAILURE PROBABILITY OF DESIGN FATIGUE CURVE ON THE RELIABILITY OF CONCRETE PAVEMENT

M. Koyanagawa, Y. Takeuchi & T. Maki
*Department of Bioproduction and Environment Engineering, Tokyo University of Agriculture, Tokyo, Japan*

M. Ito
*Road Technology Group, Public Works Research Institute, Tsukuba, Japan*

E. Noda
*Technical Laboratory, the NIPPON Road Co. LTD, Tokyo, Japan*

T. Nishizawa
*Ishikawa National College of Technology, Tsubata, Japan*

ABSTRACT: The design fatigue curve for concrete pavement must be considered the probability of failure because the fatigue lives of concrete show a large scatter, and the probability of design fatigue curve has a great influence on the reliability of concrete pavement. But the relationship between the failure probability of design fatigue curve and the reliability of concrete pavement was not cleared therefore there were no realistic guide for the choice of the failure probability of design fatigue curve. In this paper, this relationship was studied by the result of performance survey about the concrete pavement under service period of 25 years.
According to the survey result, the rate of cracked slabs of this concrete pavement was about 30%. On the other hand, the calculation result of fatigue damage of this concrete pavement using the failure probability of 30% fatigue curve was 1.0 for the calculation period of 20 years. This means that this concrete pavement cause the fatigue crack after 20 years service. Consequently, it is appeared that the reliability of concrete pavement can predict by the failure probability of design fatigue curve.
And more, from the flexural fatigue test results of specimens obtained from the survey area, the validity of the Miner's rule for cumulative fatigue damage of concrete was verified.

KEY WORDS: Reliability, probability of fatigue failure, concrete pavement

## 1 INTRODUCTION

The failure of concrete pavement slab is caused by the repetition of the wheel loads and thermal deference in the slab. These two actions cause the flexural stress in the concrete slab. Consequently, on the mechanical design method for concrete pavement, the flexural fatigue curve has great influence when analyzing the fatigue life of concrete pavement slab. But the fatigue lives of concrete show a large scatter, so the design fatigue curve must be considered the probabilistic properties of fatigue failure. In Japan, the fatigue curve under consideration of probabilistic properties was used for new design method. This fatigue curve was obtained by the accelerated tests of concrete specimens, so the relationship between the probability of fatigue curve and the reliability of concrete slab was not cleared. In this study, the validity of the design fatigue curve was verified by the survey results of concrete pavement under service load of over 20 years.

In the design methods based on the fatigue failure, the Miner’s rule was applied to examine the influence of variable magnitude repeated stresses on the fatigue life of concrete. The validity of the Miner’s rule for fatigue life of the metal materials has been already confirmed. But for concrete, there were recognized the influence of the order of the stress magnitude and the rest period of load repetition on the fatigue lives[1], so the validity of application of Miner’s rule to concrete was not examined enough. If the Miner’s rule is able to explain the fatigue phenomenon of concrete, the fatigue lives of concrete under service load should be short compared to the virgin concrete, and the residual lives of loaded concrete will be able to predict under the Miner’s rule. In this study, the validity of application of Miner’s rule was examined by the fatigue tests using the specimens which cut off from the concrete pavement slab mentioned above.

## 2 PERFORMANCE SURVEY OF CONCRETE PAVEMENT

The concrete pavement investigated in this study was depth of 30cm jointed concrete pavement which was paved in 1975. The concrete slab of this pavement had length of 10m and width of 3.5m, and the dowel bars were used at the joints. The survey was operated in 2000, so the age of this pavement is 25years in that time.

### 2.1 Items of the Survey

The items of the performance survey were as follows.
(1) The cracks survey by sketch.
(2) The flexural strength and flexural fatigue tests by cut-off specimens.
(3) The plate loading tests of the base course.
(4) The survey of wheel passing positions
In this study, the validity of design fatigue curve was examined by using the results of (1), (3), (4), and the validity of Miner’s rule was examined by the results of (2) mainly.

### 2.2 Cut-off specimens

The several slabs of this pavement already showed the cracks, and the cut-off specimens were obtained from both of the cracked slab and the non-cracked slab which selected randomly. On the cutting, it was considered that the specimens were obtained from the wheel pass areas. At first the slab were divided into 6 blocks shown as fig.1, and the 6 specimens for test of flexural strength were cut from each of 5 blocks. The specimen had dimension of 15x15x53cm. Consequently, the numbers of testing specimens were 30 from cracked slab and 30 from non-cracked slab.

### 2.3 flexural fatigue test

The test method was third point loading of span 45cm for both static strength tests and fatigue strength tests. The stress waveform of fatigue tests were taken to be sinusoidal curve variations of frequency 5Hz. The rate of maximum stress of this cyclic stress to static strength

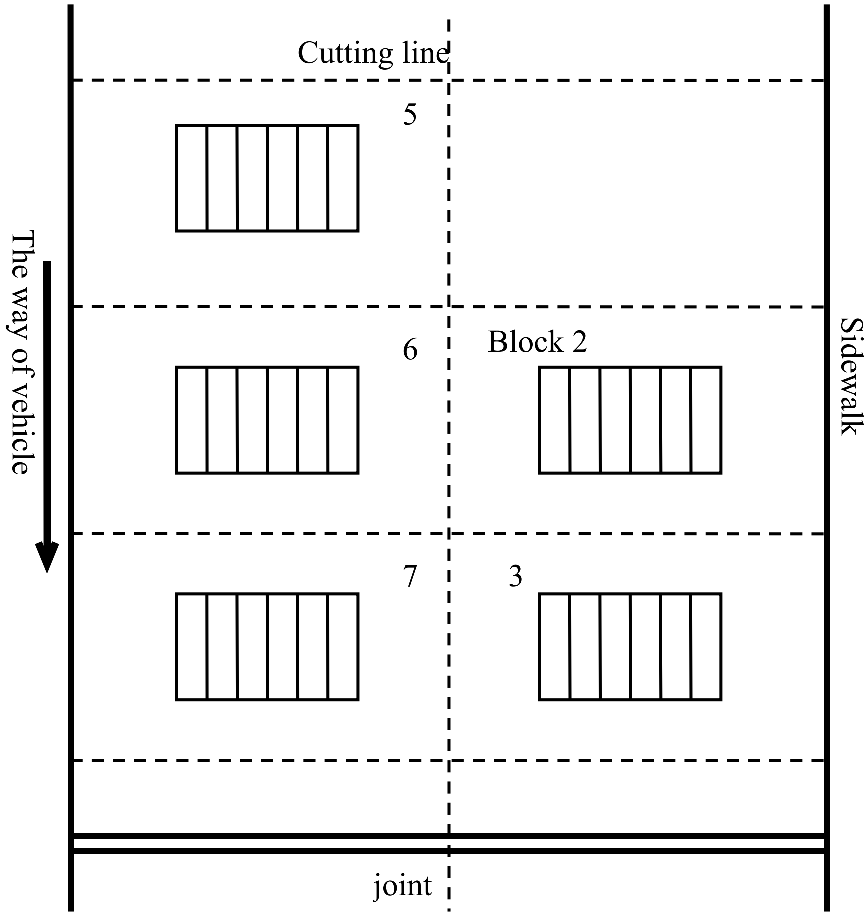


Figure 1: The specimens cutting

is defined as stress level (SL). The stress levels in the fatigue tests of the study were of the two stages of 0.90 and 0.80.

At first, the static flexural strength was tested by two specimens from each block shown as fig.1, and the mean flexural strength of each block was obtained. Then the flexural fatigue tests were operated by remaining 2 specimens for SL=0.9, and 2 for SL=0.8. Consequently, the numbers of specimens of each stress level were 10 for both of cracked and non-cracked slab.

The minimum stress of the cyclic stress waveform was taken to be 2kN under the consideration of stability of testing machine.

## 3 TEST RESULTS

Table 1 gives the static strength test results. From the results, there were no difference between the mean flexural strength of cracked slab and non-cracked slab. And the concrete from each slab showed enough strength after 25 years service.

Table 2 shows the fatigue test results. The result of test under SL=0.9 of non-cracked slab could not obtain because of some accident. As shown in Table 2, the fatigue lives are scattered over broad ranges for each stress level. Therefore, this scatter must be considered when examining difference of fatigue lives between the cracked slab and the non-cracked slab.

In this study, the fatigue lives for each stress level with specimens of the respective slab condition were considered as one sample, and testing of the statistical hypothesis was done

Table 1: Results of Static Flexural Test

($N/mm^2$)

| cracked slab | | non-cracked slab | |
|---|---|---|---|
| block No. | strength | block No. | strength |
| 2 | 6.05 | 2 | 5.82 |
| | 4.88 | | 5.32 |
| 3 | 6.12 | 3 | 5.93 |
| | 5.36 | | 5.13 |
| 5 | 5.51 | 5 | 4.61 |
| | 5.92 | | 5.88 |
| 6 | 5.55 | 6 | 5.02 |
| | 5.59 | | 5.78 |
| 7 | 6.02 | 7 | 5.37 |
| | 5.71 | | 5.38 |
| Mean | 5.67 | Mean | 5.42 |
| S.D. | 0.38 | S.D. | 0.43 |

Table 2: Results of Fatigue Tests

| SL | block No. | cracked slab | non-cracked slab |
|---|---|---|---|
| 0.9 | 2 | 33 | 6166 |
| | | 220 | - |
| | 3 | 19 | 12 |
| | | 135 | 2822 |
| | 5 | 383 | 1446 |
| | | 501 | 171 |
| | 6 | 31 | 484 |
| | | 1700 | 221 |
| | 7 | 2093 | 310 |
| | | 129 | 303 |
| 0.8 | 2 | 2748 | 13341 |
| | | 45017 | 960 |
| | 3 | 5492 | 175 |
| | | 11029 | 811 |
| | 5 | 8113 | 192038 |
| | | 31821 | 109247 |
| | 6 | 51375 | 1577 |
| | | 26351 | 1039 |
| | 7 | 26453 | 42895 |
| | | 768 | 45015 |

Table 3: The failure probability of specimens

| | SL=0.9 | | | SL=0.8 | | |
|---|---|---|---|---|---|---|
| | N | logN | Pf | N | logN | Pf |
| 1 | 12 | 1.079 | 0.05 | 175 | 2.243 | 0.05 |
| 2 | 19 | 1.279 | 0.10 | 768 | 2.885 | 0.10 |
| 3 | 31 | 1.491 | 0.15 | 811 | 2.909 | 0.14 |
| 4 | 33 | 1.519 | 0.20 | 960 | 2.982 | 0.19 |
| 5 | 129 | 2.111 | 0.25 | 1039 | 3.017 | 0.24 |
| 6 | 135 | 2.130 | 0.30 | 1577 | 3.198 | 0.29 |
| 7 | 171 | 2.233 | 0.35 | 2748 | 3.439 | 0.33 |
| 8 | 220 | 2.342 | 0.40 | 5492 | 3.740 | 0.38 |
| 9 | 221 | 2.344 | 0.45 | 8113 | 3.909 | 0.43 |
| 10 | 303 | 2.481 | 0.50 | 11029 | 4.043 | 0.48 |
| 11 | 310 | 2.491 | 0.55 | 13341 | 4.125 | 0.52 |
| 12 | 383 | 2.583 | 0.60 | 26351 | 4.421 | 0.57 |
| 13 | 484 | 2.685 | 0.65 | 26453 | 4.422 | 0.62 |
| 14 | 501 | 2.700 | 0.70 | 31821 | 4.503 | 0.67 |
| 15 | 1446 | 3.160 | 0.75 | 42895 | 4.632 | 0.71 |
| 16 | 1700 | 3.230 | 0.80 | 45015 | 4.653 | 0.76 |
| 17 | 2093 | 3.321 | 0.85 | 45017 | 4.653 | 0.81 |
| 18 | 2822 | 3.451 | 0.90 | 51375 | 4.711 | 0.86 |
| 19 | 6166 | 3.790 | 0.95 | 109247 | 5.038 | 0.90 |
| 20 | | | | 192038 | 5.283 | 0.95 |

regarding the mean values and dispersions of the populations which the respective samples belonging to. In testing of mean value, the hypothesis set up was that “the mean values of two distributions are equal”, and in testing of dispersion, the hypothesis set up was that “the dispersion of two distributions are equal”. And, the t-test was used for mean value and the F-test for dispersion in testing of the hypothesis.

As a result, the hypothesis was affirmed with their levels of significance 5% for both mean value and dispersion. Consequently, there was no difference between the fatigue lives of concrete cut from the cracked slab and cut from the non-cracked slab.

## 4 FATIGUE LIVES OF CONCRETE UNDER SERVICE LOAD

As described above, the influence of crack existence in slab may be ignored. Therefore, all data were used for examining the influence of service load on fatigue lives of concrete. But a statistical study is required in examining the fatigue lives because of their scatters. That is, the probability distribution function for each stress level must be determined considering the test results of each stress level as a single population.

Table 3 shows the failure probability of each stress level which were calculated by using the method of ordered statistics. When these results are plotted on a log-normal probability paper, it will be as shown in Fig. 2. The vertical line of Fig. 2 means the normal standard variable S which corresponding to failure probability Pf, and S=0 corresponds to Pf=50% and S=1 corresponds to about Pf=85%. From Fig.2, it was recognized that the data for the individual stress levels being arrayed on roughly a straight line, consequently, the data for the individual stress levels were shown to respectively belong to a population of log-normal

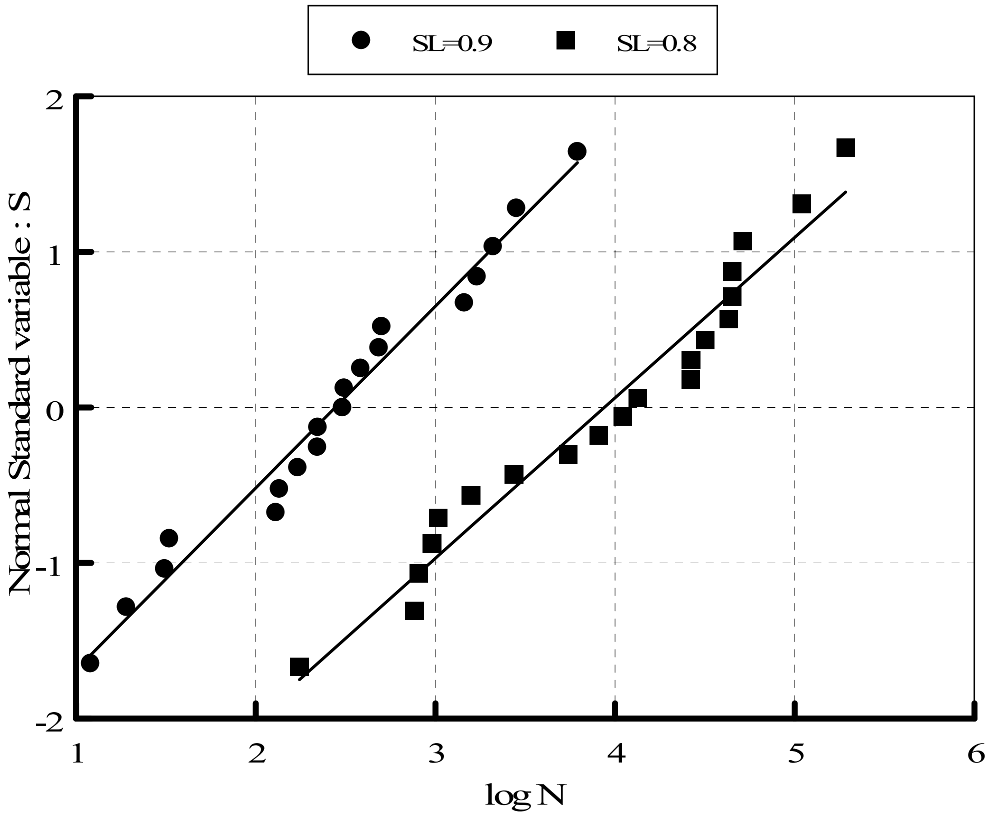


Figure 2: Relationship between failure probability and fatigue life

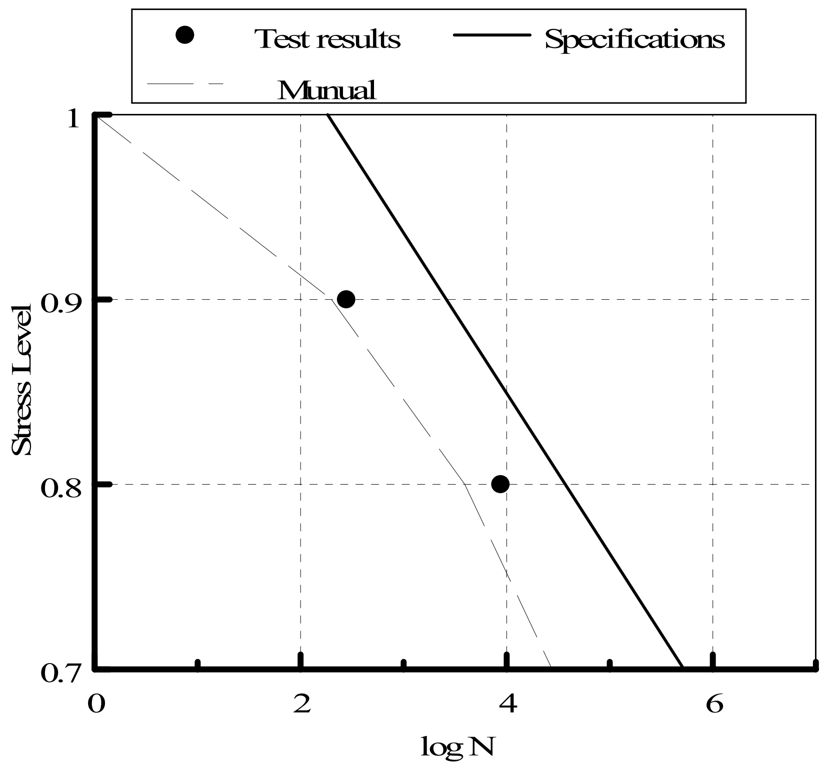


Figure 3: Test results and fatigue curves

distribution. Generally, the fatigue lives of concrete belong to log-normal distribution[2], and same result was shown in this study.

In the Fig. 3, the individual fatigue life of each stress level corresponding to Pf=50% which calculated from the regression line mentioned above were plotted. Also in Fig. 3, there showed the fatigue curve corresponding to Pf=50% which is indicated the Standard Specifications for Concrete[3], and the fatigue curve which was used for the design of this pavement slab indicated Manual for design and construction of concrete pavement.[4]

As shown in Fig.3, the plotted test results showed about 30% short life in case of SL=0.9 and about 15% in case of SL=0.8 compared to the life which calculated from the fatigue curve in Specifications obtained by the test for virgin concrete. On the other hand, the test results showed the longer fatigue lives compared to the fatigue curve in the Manual. But the fatigue curve in the Manual was decided under consideration of safety, so it did not show the real fatigue properties of concrete.

## 5 VERIFICATION OF MINER’S RULE

As mentioned above, the fatigue lives of concrete under service load showed short lives compared to virgin concrete. Therefore the validity of Miner’s rule was examined by the comparison of test results and the result of fatigue simulation under Miner’s rule.

### 5.1 Condition of Simulation

The fatigue simulation was operated for the point of 75cm from the longitudinal edge of the

Table 4: Distribution of wheel passing position of surveyed slab

| Distance from the edge(cm) | 55 | 75 | 95 | 115 |
|---|---|---|---|---|
| Frequency(%) | 27 | 46 | 27 | 0 |

Table 5: Calculated wheel load stresses at the position of specimen cutting

(N/mm2)

| Wheel load (kN) | Load position 55cm | 75cm | 95cm |
|---|---|---|---|
| 10 | 0.123 | 0.1886 | 0.1186 |
| 20 | 0.2458 | 0.3119 | 0.2415 |
| 30 | 0.3601 | 0.4566 | 0.36 |
| 40 | 0.4787 | 0.6013 | 0.4775 |
| 50 | 0.5937 | 0.7324 | 0.5911 |
| 60 | 0.7061 | 0.8562 | 0.7015 |
| 70 | 0.8157 | 0.9733 | 0.8086 |
| 80 | 0.9273 | 1.098 | 0.9183 |
| 90 | 1.0316 | 1.2042 | 1.0194 |
| 100 | 1.1322 | 1.3046 | 1.1167 |
| 120 | 1.3243 | 1.4918 | 1.3012 |
| 140 | 1.514 | 1.6816 | 1.4843 |
| 160 | 1.6831 | 1.8389 | 1.6448 |

surveyed slab and this point was the most frequent wheel passing point which observed by this survey. Table 4 shows the distribution of wheel passing position obtained by the survey. The wheel stresses at the position of specimen cut caused by each wheel positions were calculated by plate FEM method and the results of calculation were shown as Table 5.

## 5.2 Result of Simulation

According to the simulation under condition mentioned above, the fatigue ratio FD was shown as follows.

FD=0.129

That means about 13% of fatigue life were consumed by the service loads repetition. It showed small difference with the test results mentioned before, but it could be considered as good agreement with considering that the estimated traffic volume was used in the simulation. Consequently, it seems to be valid to apply the Miner’s rule for the analysis of fatigue failure of concrete. And it was shown that there is a possibility to estimate the residual life of concrete slabs by the fatigue test using the cut-off specimens. But there must be needed considerable numbers of specimens to estimate the residual life of concrete pavement, because the fatigue life of concrete will show a large scatter.

# 6 VERIFICATION OF DESIGN FATIGUE CURVE

The concrete pavement investigated in this study was paved 25 years ago, and according to the results of surface survey of this pavement, there already existed the cracks in the slab. Therefore, the validity of design method of concrete pavement slab especially the design fatigue curve was verified by examining the fatigue analysis of this pavement slab.

## 6.1 Results of cracks survey

The cracks survey was operated for 1km concrete pavement composed of 100 slabs. According to the figure by sketch, there existed two types of cracked slab which cracked for transverse way from the longitudinal edge and cracked for longitudinal way from the transverse edge. Among these cracked slabs, the numbers of slab cracked for transverse way which was the design criteria for this concrete pavement was 32. That is to say it could be regarded the failure probability of this pavement slab against the transverse cracks was about 30%

## 6.2 Fatigue simulation of concrete slab

The fatigue damage of surveyed concrete slab was estimated by the method of fatigue analysis shown in the Specifications. The calculation condition was shown in table 6.

The flexural strength of concrete for this slab was estimated as about 5.5N/mm$^2$ shown as Table 1. But for the flexural strength of concrete, it was recognized the depth effect of the specimen. Consequently, the flexural strength of real slab was estimated as 5.0N/mm$^2$ by the next equation.

$$f_{300} = 0.8 \times \left( 0.6 + \frac{2.25}{\sqrt[4]{300}} \right) \times f_{150}$$

$f_{300}$ : flexural strength of depth of 30cm

$f_{150}$ : flexural strength of depth of 15cm

Table 6: Calculation conditions

| | |
|---|---|
| Period of analysis | 25years |
| Depth of slab | 30cm |
| Flexural strength of concrete | 5.0N/mm2 |
| Elastic modulus of concrete | 35KN/mm2 |
| Coefficient of thermal expantion of concarete | 0.00001/C |
| Poisson's ratio of concrete | 0.2 |
| Failure probability of fatigue curve | 30% |
| Reaction modulus of base course | 0.15N/mm3 |

And the base course reaction modulus was estimated by the results of plate loading tests.

6.3 Result of calculation

The fatigue damage of target slab was calculated at the longitudinal edge. And the calculated fatigue damage FD for 25years service was as follows.

FD = 1.24

FD=1.0 means the start of fatigue crack, and the service years for FD=1.0 was estimated 20. This estimated service years corresponded to the design life of this pavement. From this result, the design fatigue curve in consideration of the failure probability which shown in Specification seems to be valid for design of concrete pavement.

The relationship between the failure probability of concrete pavement slab and the failure probability of fatigue curve was not clear up to now. Fatigue curves must be prepared under consideration of failure probability, because the fatigue lives of concrete show a large scatter even if it was estimated under same concrete or same test conditions. On the other hand, the fatigue failure of concrete pavement slabs were affected not only by fatigue properties of concrete but also by many kind of factors such as the materials and structural characteristics of base course, the magnitude and distribution of wheel load, the distribution of wheel load passing position, the temperature distribution and frequency distribution of temperature within the slab. These factors also have their own properties of variations. Therefore, it was not confirmed that the fatigue failure probability of concrete correspond to the failure probability of concrete slab.

The authors have already reported about the choice of failure probability of fatigue design curve. According to this report, the failure probability of concrete slab was smaller than the failure probability of fatigue curve. For example, the failure probability of concrete slab was estimated as about 15% by using the fatigue curve of 25% failure probability for the same conditions as surveyed this study[5]. But this result was obtained under the assumption that the design factors except the fatigue properties of concrete showed any variations.

From the result of the survey analysis and the examination of fatigue failure, it was shown that there is a possibility to estimate the failure probability of concrete slab by the failure probability of fatigue curve. Of course this possibility was obtained by only one examination, and there need more surveys and examinations for concrete pavements under service loads to confirm this result.

## 7 CONCLUSIONS

The purposes of this study was to verify the design fatigue curve and the Miner's rule for fatigue failure of concrete by the survey results of concrete pavement under service load. The main conclusions drawn are as follows.

(1) From the result of the fatigue tests of specimens cut from the concrete pavement slab under service load, the real residual life of concrete could be estimated by the simulation under the Miner's rule in consideration of wheel passing position. And a possibility was shown that the residual life of concrete pavement will be estimated by the test of cut off specimens.

(2) The validity of fatigue design curve in Japan was confirmed by the survey results and examination results of concrete pavement under service load. Also a possibility to estimate the failure probability of concrete pavement slab by the failure probability of fatigue design curve was shown.

In this investigation, the fatigue tests were operated by the authors, and the performance surveys and specimens cut were operated by Utsunomiya national highway work office, the ministry of Land. Infrastructure and Transport.

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