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Calibration of a Shift-Factor for the Fatigue Prediction of High Strength Concrete Pavement in the Field

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Abstract: From 1997 to 1999, six experimental sections of ultra-thin whitetopping (UTW) using slabs of high strength concrete (HSC) were monitored. A field-based fatigue model for corner cracking development was proposed based on stresses predicted through the finite element program, ILSL2, for concrete slabs and load repetitions of up to 10% of cracked plates. A laboratory investigation was carried out to define fatigue behavior and the performance of beams using the same raw materials and concrete mixture that were used in the aforementioned field study. The simulation of variable stress levels, as verified during the field experiment, made it possible to define the stress-strength ratio (SSR) curves and then compare them to a former field fatigue transfer function defined for the same concrete admixture. Tests show the influence of frequency on the fatigue behavior of beams. The comparison between field and laboratory SSR equations allows the definition of a shift-factor to convert the beam-based fatigue prediction equation into the expected number of load repetitions for field conditions. The shift-factor is dependent on the SSR relation. The resulting data demonstrate the conservativeness of laboratory fatigue models based on beams and the enormous effect of frequency on laboratory results.

***Key words**: Fatigue; High strength concrete; Beam tests.*

Introduction

In-service concrete slabs are subject to several cycles of moisture and drying, daytime and nighttime thermal gradient changes, lateral wander of wheels within lanes, irregular load, tire pressures, loading frequencies, etc. All of these conditions carry consequences for the fatigue endurance of concrete. These features have led some researchers to pursue the construction of fatigue prediction models supported by field experiments. Nevertheless, such model derivation is not an easy task since concrete pavements have long endurance. As seen in several countries, it was more common in the last seven decades for concrete fatigue experiments to be carried out mostly using beams and in laboratory conditions. This paper deals with the particular effort in understanding the laboratory-field differences under a practical adjustment standpoint for high strength concrete.

In 1997, six sections of ultra-thin whitetopping (UTW) were built in a state highway in São Paulo, Brazil, to investigate the specificities of such an innovative solution for overlaying aged asphalt pavements. The sections failed, presenting 10% of cracked slabs in a relatively short period of time (around three months for the thicker sections and under the best performance). This was a result of poor and empirical slab design, which did not take into account the bad condition of the underlying asphalt pavement [1] .

The fatigue prediction model derived from that field study was compared to former in-field fatigue investigations carried out in the United States using data from the American Association of State Highway Officials (AASHO) Road Test [2-4], which showed that these former models are similar. Moreover, the observed and the modeled fatigue performances were poorer than the common results obtained by several laboratory investigations with beams in recent years. However, a direct comparison between results is difficult due to the differences in concrete. One was used for the AASHO road test pavement construction, and the other was a more recent high performance concrete used in the study of reference [1] and this present paper. Another former study based on 51 field test sections of the U.S. Corps of Engineers [5] succeeded in comparing the cracking performance of slabs in the field to several beam fatigue tests in the laboratory. This eventually shed light on the fact that slab and beam fatigue models differ significantly. Although the study compared different concrete mixture formulations, it was very important in disclosing that if 50% of cracked slabs in test sections are adopted as the fatigue threshold (rupture criteria), the beam fatigue model is much less conservative than the slab (field) model. Currently, the Mechanistic-Empirical Pavement Design Guide (MEPDG) uses a fatigue equation for concrete developed in the past from the U.S. Army Corps of Engineers full-scale airfield slab tests. Its adjustments for road pavement design were done based on Long Term Pavement Performance (LTPP) and other data concerning highway concrete pavement performance [6].

The study [5] listed variability in concrete strength and slab curling as the main significant conditions for the observed differences. Factors such as rate of loads, rest periods, and slab thickness variation were estimated to be of medium significance. Stress ratio and thermal shrinkage were considered the least important among the possible effects.

To understand the field and laboratory behavior of the high strength concrete (HSC) in the 1997 UTW experiment [1], a laboratory research program was initiated to discover more details about the fatigue behavior of beams using the same concrete. The field tests from the 1997 experiment provided an interesting database, showing that factors such as curling were less important to

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Table 1. Concrete Mix Proportions.

Material or Property	Values for Field	Values for Laboratory
Early Strength Portland Cement (kg/m^3)	440	420
Silica Fume (kg/m^3)	44	42
Round Quartz Fine Sand (kg/m^3)	493	514
Crushed Granite Stone Max = 19 mm (kg/m^3)	1.194	1.194
W/C Ratio	0.365	0.385
Plasticizer (L/m^3)	1.65	1.65
Superplasticizer (L/m^3)	5.424	5.424
Air Entraining Additive (mL/m^3)	119	119
Air Entrained (%)	5.0	5.0
Slump (mm)	80±10	70
28-day Flexural Strength (MPa)	6.0	6.0

Fig. 1. Servo-controlled Machine for Fatigue Tests.

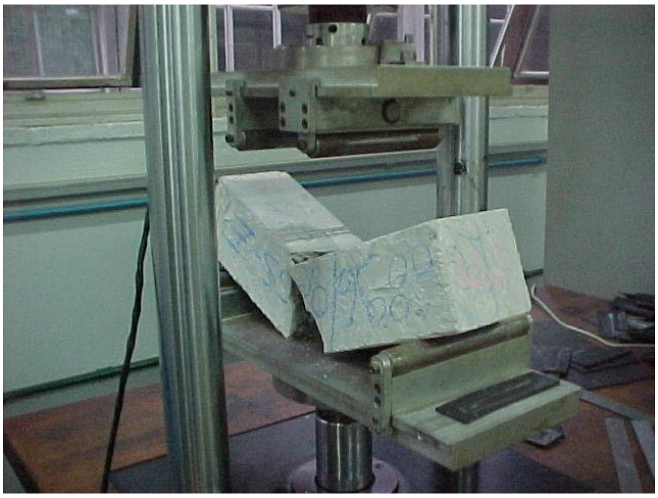

Fig. 2. Half-span Rupture of Concrete.

slab behavior than thickness variation. Besides that, it should be possible to reproduce, with a good degree of accuracy, the concrete mixture used during the construction of UTW, thus allowing the comparison of similar concretes concerning fatigue resistance. All the original materials were available by the same suppliers of the UTW, allowing a new concrete mix preparation to imitate the original mix in the field test.

One of the limitations of the present study was the available time and equipment for fatigue tests carried out at a load frequency of 10 Hz. However, it was possible to test both constant and variable stresses for several stress-strength relations (SSR). The study also tested a fair number of specimens for a reasonable statistics analysis aimed at a further understanding of the impacts of factors such as frequency and variable stresses on test results.

Laboratorial Investigation

Materials for Concrete Beams

Once the construction of the UTW experimental sections was carried out in September 1997, it was necessary to recover the same supplies used in the original concrete mixture— the same early strength cement, silica fume, aggregates, plasticizers and other raw materials. Therefore, the exact same concrete in the field test in 1997 was used to mold the beams for the present study. This task was accomplished by March 2002, when the proportioning and strength measuring tests started to define a concrete mixture similar to the original one. The mixture was made with the same materials and achieved equal flexural strength. The concrete mix proportions used for this investigation are given in Table 1.

Specimens were prepared in prismatic molds of 400 mm x 100 mm x 100 mm. The prismatic mold was filled and then vibrated on a table for 30 seconds. It remained in the laboratory natural condition for up to 36 hours. Then, the concrete specimens were removed from the molds, wrapped with PVC film, and kept in a moisture chamber for up to a period of 7 days. Afterwards, they were again stored in laboratory conditions for up to 365 days. 64 beams of HSC were made for the tests. Fatigue tests were carried out during the years 2003-2004, and flexural strength (or modulus of rupture [MR]) was also measured by third-point beam tests.

Fatigue Tests

The HSC beams were tested using a servo-controlled universal machine with a 100 kN capacity (Fig. 1). For all fatigue tests, a minimum flexural stress, equivalent to 7% of the concrete strength, was constantly applied. This condition did not simulate temperature effects but avoided any lateral displacement of beams during loading cycles. Rupture occurred for all the beams at the half-span (Fig. 2). In order to achieve enough information to seek a laboratory equation describing the fatigue resistance of beams, the following fatigue simulations were applied to the dry beams: (a) Constant stresses at 10 Hz frequency; (b) Constant stresses at 5 Hz frequency; and (c) Tests under variable SSR applications. The load shape applied to samples was like a constant sinusoidal wave.

Six specimens were molded for each level of the constant stress test (Table 2) and analyzed individually to find the average values of fatigue resistance (or number of cycles to fatigue). Any sample with discrepant results from the entire set was discarded, if necessary. Likewise, for the variable stress tests, six equal samples were molded (Table 3), and the sequence of load application for each

Table 2. Fatigue Test Results for Beams under Constant Stress.

SSR (Frequency)	# of Specimens	Cycles to Fatigue
0.65 (10 Hz)	1	635,150
	2	749,080
	3	764,650
	4	899,530
	5	997,460
	6 *	1,165,050
0.69 (10 Hz)	1 *	3,730
	2	397,230
	3	424,430
	4	427,680
	5	444,650
	6	480,380
	7	521,230
0.73 (10 Hz)	1	104,320
	2	175,200
	3	181,150
	4	183,360
	5	199,630
	6	270,770
0.78 (10 Hz)	1	21,050
	2	22,980
	3	25,970
	4	26,700
	5	29,430
	6	32,440
0.80 (10 Hz)	1	8,290
	2	8,970
	3	9,850
0.83 (10 Hz)	1	7,230
	2	7,800
	3	8,220
0.73 (5 Hz)	1 *	6,420
	2	17,690
	3	17,730
	4	18,780
	5	19,280
	6	19,720

* These specimens were discarded because they had substantially different results from the others

specimen is shown as a test number in columns.

Tests at a frequency of 5 Hz were performed at an SSR of 0.73.Tests at a 10-Hz frequency were carried out at SSR levels of 0.65, 0.69, 0.73, 0.78, 0.80 and 0.83. For variable stress tests, the stress levels to be applied to beams were defined according to the field study in 1997 [1], in which field stresses due to actual traffic were predicted for a number of cycles in the field so as to reach the threshold of 10% of cracked slabs. No frequency variation was allowed by the testing machine, and the test sequence followed from the lowest stress to the highest stress during one complete cycle of the field predicted stresses.

Results and Statistical Analysis

The Kolmogorov-Smirnov (K-S) test is a non-parametric and distribution free test used in statistics that verifies if two datasets have significant differences. For the analysis of results, all specimens' set were submitted to K-S statistical tests. Normal probability tests disclosed a normal distribution, as shown in Fig. 3, for all sample sets and all levels of stress in the constant stress tests (Table 2). There was also a normal distribution for all frequencies and even for the variable stress tests conducted on the six samples (Table 3). More scattered results for low values of SSR, such as SSR values of 0.65 and 0.69, are taken as the regular result during fatigue tests due to differences (even minor) in the flexural strength values of specimens. There is actually some heterogeneity among specimens of the same concrete batch. Statistical tests confirmed the normal distribution for variable stress tests. Fatigue probability curves according to K-S tests are shown in Fig. 4.

In Fig. 5, results are compared for different test frequencies. It is clear that, for higher frequencies, the results of the fatigue tests lead to a more optimistic fatigue prediction for beams. The actual load frequency in a highway could barely reach 1 Hz for high traffic roads, and ordinary laboratory tests at higher frequencies are unable to predict failure for field conditions. Such a discrepancy requires a shift-factor for the application of the laboratory model to actual design so as to avoid the risk of under-designing.

This is one facet of the discrepancies. However, variable subgrade and base support, moisture conditions, traffic lateral wander, and concrete parameters themselves (e.g., MR or modulus of elasticity) due to construction heterogeneities (concrete production, laying and curing) are factors that cannot be simulated easily during laboratory tests. All these factors combined can lead to different fatigue behavior in the field (compared to the laboratory).

Nevertheless, frequency is possibly the most important variable to be defined before laboratory investigation. This is also because concrete presents relaxation (albeit minor) between loads when enough period of rest is provided during the tests. On the basis of this concern, a former investigation [7] proposes fatigue prediction equations that clearly show the effects of load frequency on the survival of concrete beams during fatigue tests and defines the increase in fatigue life due to the increase in frequency value.

Fatigue Prediction Model for Logarithmic S-N curve at 10 Hz and Constant Stress

Considering the results in Table 3, it was possible to define a logarithmic function relating SSR and the number of cycles to fatigue (S-N curve) through a regression analysis. The equation presented below for the 30 beams reached a standard error of 0.16 and R2 of 96%. This satisfies the statistical values and is explained by a good homogeneity condition among tested specimens.

$$\log N = 14.13 - 12.41 \times \left(\frac{\sigma}{MR} \right) \quad (1)$$

where σ is the maximum flexural stress due to loading and MR is the modulus of rupture or flexural strength of the concrete. In Fig. 6, the above equation is represented graphically and compared to another laboratory fatigue model for a concrete with the same strength (6 MPa). Nevertheless, the other concrete could be, in some

Table 3. Fatigue Test Results for Beams under Variable Stresses.

σ (MPa)	SSR	Cycles to Fatigue					
		Test # 1	Test # 2	Test # 3	Test # 4	Test # 5	Test # 6
		1st Sequence Application (Complete Cycles for Field 10% Crack)					
2.32	0.39	8,779	8,779	8,779	8,779	8,779	8,779
2.66	0.44	10,862	10,862	10,862	10,862	10,862	10,862
2.96	0.49	8,773	8,773	8,773	8,773	8,773	8,773
3.28	0.55	8,835	8,835	8,835	8,835	8,835	8,835
3.54	0.59	4,242	4,242	4,242	4,242	4,242	4,242
3.72	0.62	17,305	17,305	17,305	17,305	17,305	17,305
3.90	0.65	40,470	40,470	40,470	40,470	40,470	40,470
4.10	0.68	26,187	26,187	26,187	26,187	26,187	26,187
4.26	0.71	7,654	7,654	7,654	7,654	7,654	7,654
4.42	0.74	1,845	1,845	1,845	1,845	1,845	1,845
4.56	0.76	1,399	1,399	1,399	1,399	1,399	1,399
4.68	0.78	1,161	1,161	1,161	1,161	1,161	1,161
4.78	0.80	476	476	476	476	476	476
4.85	0.81	238	238	238	238	238	238
		2nd Sequence Application (Complete Cycles for Field 10% Crack) Equal to 1st Sequence Application					
		3rd Sequence Application (Complete Cycles for Field 10% Crack) Equal to 1st Sequence Application					
		4th Sequence Application (Complete Cycles for Field 10% Crack) Equal to 1st Sequence Application					
		5th Sequence Application (Complete Cycles for Field 10% Crack) Equal to 1st Sequence Application					
σ (MPa)	SSR	Cycles Applied at the 6th Series (Occurring Rupture)					
2.32	0.39	8,779	8,779	8,779	8,779	8,779	8,779
2.66	0.44	10,862	10,862	10,862	10,862	10,862	10,862
2.96	0.49	8,773	8,773	8,773	8,773	8,773	8,773
3.28	0.55	8,835	8,835	8,835	8,835	8,835	8,835
3.54	0.59	4,242	4,242	4,242	4,242	4,242	4,242
3.72	0.62	17,305	17,305	17,305	17,305	17,305	17,305
3.90	0.65	40,470	40,470	40,470	40,470	40,470	40,470
4.10	0.68	26,187	26,187	26,187	26,187	26,187	26,187
4.26	0.71	5,260	7,654	7,654	7,654	7,654	7,654
4.42	0.74	0	740	950	1,845	1,845	1,845
4.56	0.76	0	0	0	130	1,399	1,399
4.68	0.78	0	0	0	0	1,161	1,161
4.78	0.80	0	0	0	0	476	476
4.85	0.81	0	0	0	0	170	200

extent, considered conventional because it had been made using regular Portland cement with no reactive fines incorporated within the mixture [8]. Unfortunately, the authors did not disclose the frequency of loading during its former tests. Although one can consider the fatigue functions in Fig. 6 close to each other, the HSC was manufactured with early strength cement and a small portion of silica fume. What results is more brittle concretes that are more sensitive to crack propagation during fatigue test. This could explain its inferior behavior.

Description of Fatigue Equation for Variable Stress Tests

To describe fatigue endurance by means of received variable stress tests on beams, the Miner hypothesis for linear fatigue damage was adopted:

$$\frac{N_{1,p}}{N_{1,adm}} + \frac{N_{2,p}}{N_{2,adm}} + \ldots\ldots\ldots + \frac{N_{n,p}}{N_{n,adm}} = 1 \quad (2)$$

where $N_{i,p}$ (i=1,n) is the number of repetitive actions of a load p, and $N_{i,adm}$ (i=1,n) is the allowable number of cycles.

Since the field fatigue model for the same concrete as the one studied here was described by means of a nonlinear functional form [1] with $N_{i,adm}$ as a function of the SSR (S-N curve), the same kind of statistical formulation was attempted for the results of variable stress tests following the basic model:

$$N_{i,adm} = k\left(\frac{1}{SSR}\right)^{c} \quad (3)$$

where k and c are empirical or experimental constants obtained through statistical regression. The substitution of Eq. (3) in Eq. (2) results:

$$\frac{N_{1,p}}{k\left(\frac{MR}{\sigma_1}\right)^{c}} + \frac{N_{2,p}}{k\left(\frac{MR}{\sigma_2}\right)^{c}} + \ldots\ldots + \frac{N_{n,p}}{k\left(\frac{MR}{\sigma_n}\right)^{c}} = 1 \quad (4)$$

where $\sigma_1 \ldots \sigma_n$ is the bending stress for each step of the tests on beams, and MR is the modulus of rupture of the HSC (i.e., 6 MPa).

Provided it is acceptable for the curve adjustment, the solution for coefficients k and c can be searched interactively. In this study, the value of 29.745 was adopted, for convenience, for the constant k to coincide with the constant of Eq. (5) for the former HSC field fatigue model [1].

$$N_{field} = 29{,}745 \times \left(\frac{MR}{\sigma}\right)^{3.338} \quad (5)$$

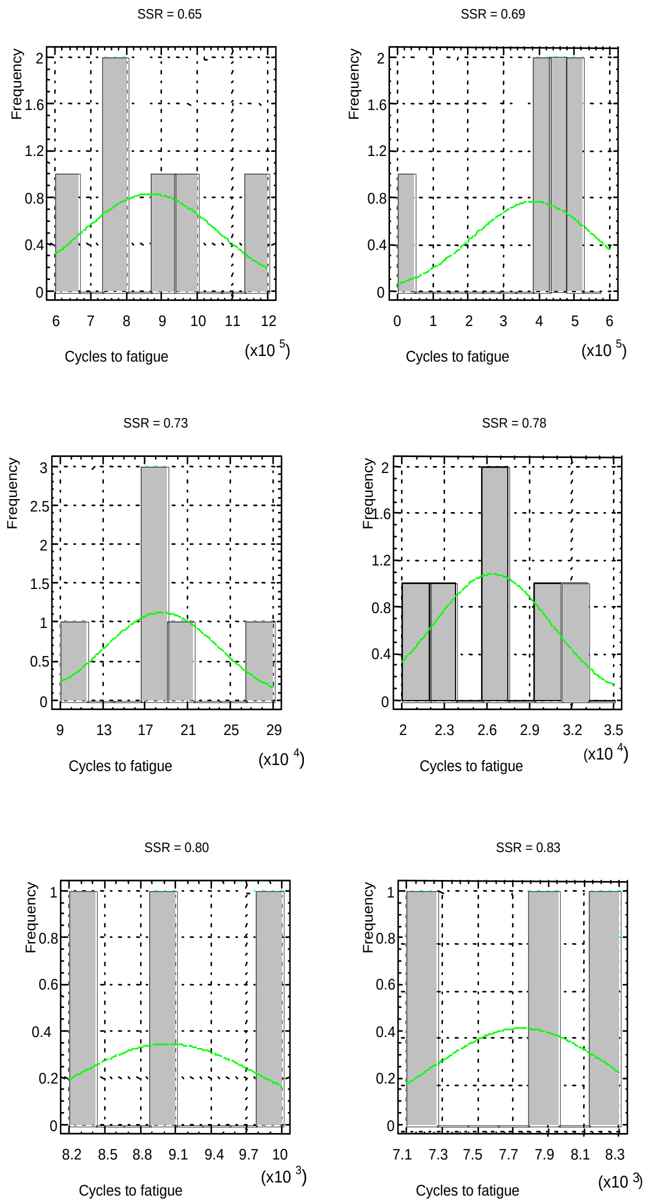

Fig. 3. Normal Distribution Patterns for Several SSR Levels (According to K-S Test).

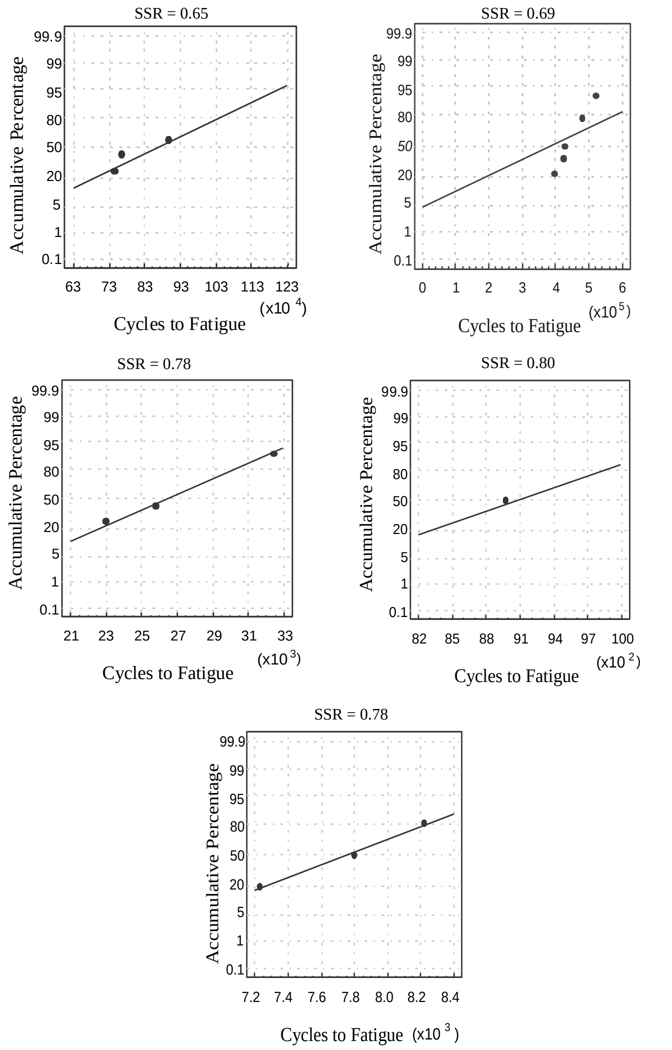

Fig. 4. Failure Probability for Several SSR Levels (According to K-S Test).

The value for constant k in Eq. (3) can be assumed to be another number, such as the constant for a formerly proposed value of k (22,209), as found in reference [3], and c, in this case, should thus result in 8.275. Comparing this result to Eq. (5), one finds two fitting curves that demonstrate the adequacy of the chosen approach. By replacing each individual value of stress (σ) and the cycles to fatigue shown in Table 3, the Palmgren-Miner hypothesis equation results in the following equation for the average of all specimen results, which were very close and homogeneous:

$$\frac{52{,}674}{29{,}745\left(\frac{6}{2.32}\right)^{c}} + \frac{65{,}172}{29{,}745\left(\frac{6}{2.60}\right)^{c}} + \ldots\ldots\ldots + \frac{1{,}250}{29{,}745\left(\frac{6}{4.85}\right)^{c}} = 1 \quad (6)$$

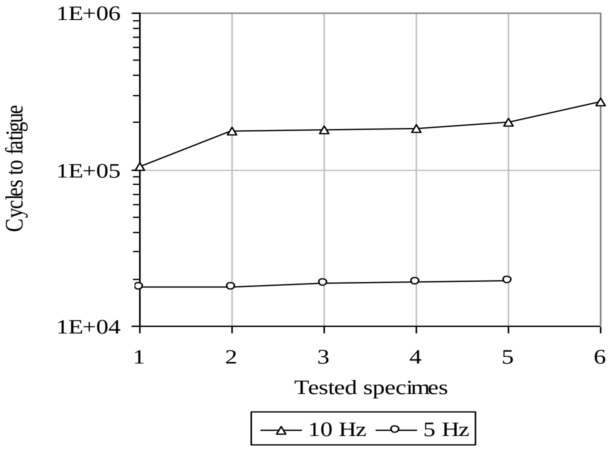

Fig. 5. Cycles to Fatigue Due to Different Load Application Frequencies for SSR = 0.73.

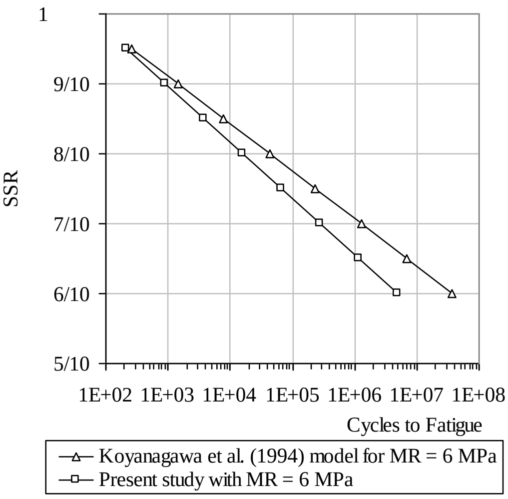

Fig. 6. Results for the Logarithmic Regression Fatigue Model of Constant Stress.

Thus, the determination of coefficient c in Eq. (6) results in the laboratory (non-linear) fatigue prediction model shown below:

$$N_{lab} = N_{i,adm} = 29{,}745\left(\frac{1}{SSR}\right)^{7.54031} \quad (7)$$

A graphic comparison between field Eq. (5) and beam fatigue Eq. (7), for the same concrete, is presented in Fig. 7, where it can be seen that the laboratory model for variable stress tests is still optimistic if compared to the former field model for prediction of 10% of cracked slabs due to fatigue consumption, and more optimistic as SSR decreases.

Calibration of a Shift-Factor

Direct comparison between Eqs. (5) and (7) permits the allowed number of cycles to fatigue in the field to be expressed as a function of the allowed number of cycles to fatigue in beams (laboratory). In the case of the HSC mixture herein studied, which is found directly by dividing Eq. (7) with Eq. (5), the following equation is given:

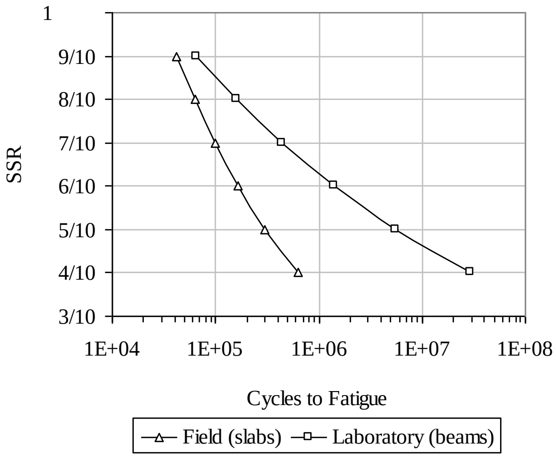

Fig. 7. Field and Laboratory Fatigue Curves of the Investigated Concrete.

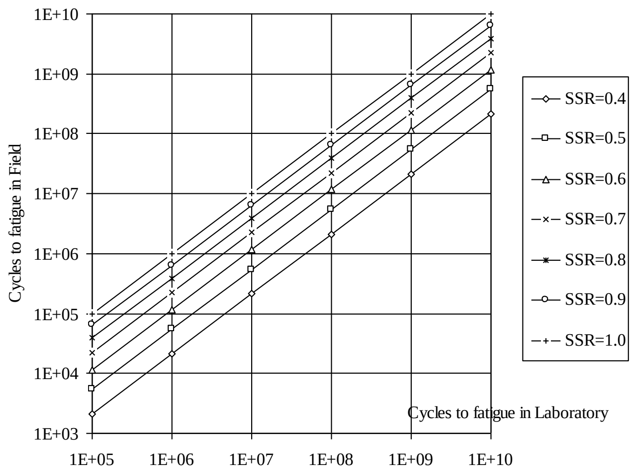

Fig. 8. Cycles to Fatigue in the Field and for Beams as a Function of the Stress-strength Ratio (SSR).

$$SF = \frac{N_{field}}{N_{Lab}} = \left(\frac{1}{SSR}\right)^{-4.20231} \quad (8)$$

Eq. (8) defines the so called shift-factor (SF) relating field and laboratory fatigue behaviors for the same HSC. From such a correlation function, it is evident that the number of cycles to fatigue in the field due to the same stress history will be smaller than the number measured through beams in the laboratory. Moreover, such a relationship is not linear and is dependent on the ratio between the actual bending stress and the modulus of rupture of the concrete.

Fig. 8 represents Eq. (8) for several SSRs from which it is clear that the higher the SSR value, the closer its fatigue behavior in the laboratory is to the field. Therefore, in-field fatigue behavior is worse for lower SSR values than for higher ones. For any condition other than SSR = 1, the laboratory fatigue in Eq. (7) over-estimates the HSC fatigue resistance. For instance, the number of cycles to fatigue in the field should be around 40% of the number predicted by the beam test equation for SSR = 0.8, as shown in Fig. 9.

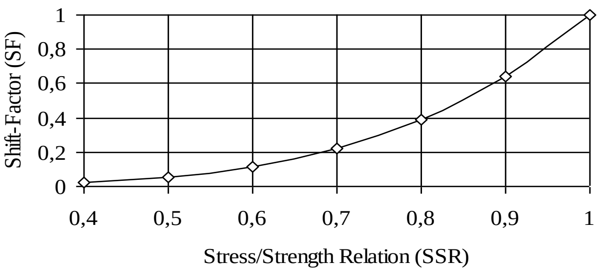

Fig. 9. Shift-Factor as a Function of SSR.

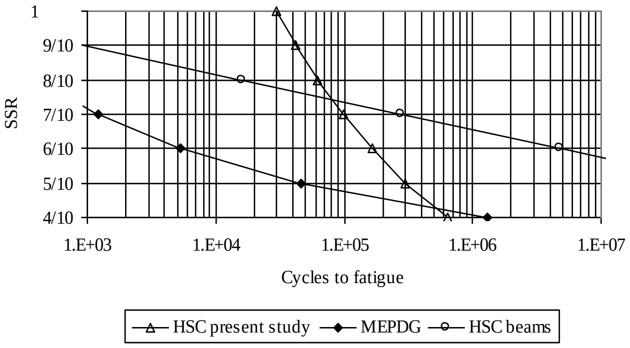

Fig. 10. Comparison of HSC Fatigue Functions to MEPDG.

Discussion

Since the results presented above establish differences between field and beam HSC fatigue behavior, designs based on the limitation of SRR at the 0.5 or 0.45 level are more conservative than designs that consider the actual loads, which are valid when using laboratory-based relations for fatigue predictions developed within high frequency tests, such as 10 Hz.

Optimistic results for high frequency tests must be understood from the fatigue standpoint as being the result of the short period of time for load action. This induces less opening on the preexistent cracks within the concrete microstructure. Therefore, the slower progression of such fissures is achieved, leading to a higher number of load applications as the investigation has demonstrated. Former studies [9, 10] have shown similar results. However, those studies used load application frequencies varying from 10 Hz to 100 Hz. Very high frequencies are uncommon in concrete beam tests for pavement analysis. Moreover, these tests have been performed in compression.

In order to allow an accurate view of the gap between field and laboratory frequencies of load applications, the field test in 1997 resulted in 146,336 axles passing before a section reached 10% of cracked slabs (adopted threshold), and it took 32 days. This represents one load application for every 19 seconds, or a frequency of 0.05 Hz (on average) if one consider each axle separately. This means one load application for every 19 seconds of rest period, or a frequency of 0.05 Hz if we consider each axle separately. For trucks with three axles ("(one front axle plus two rear single axles) at a constant speed of 80 km/h, the frequency between axles would be 2.8 Hz but with intermediate long relaxing periods of 57 seconds.

Fig. 10 presents a graphical comparison between the HSC models herein presented to the MEPDG fatigue model for plain concrete pavements. The field HSC fatigue transfer function is quite different from the MEPDG model for SSR. However, for practical purposes, when the design is conducted by a fixed SSR of 0.4 to 0.5, results tend to be closer. On the other hand, it is clear that a beam fatigue function can be far from the realistic field adjusted function

According to Roesler, J. et al. [11], the beam fatigue curves supply no accuracy for fatigue failure prediction. It is possible to build slabs specifically for fatigue tests in laboratory; although such a test with actual size slabs (on grade) could be too realistic to simulate field conditions. This would allow for fatigue development due to the biaxial state of stress, supporting even simulations of environmental conditions (temperature, frost, water table, etc.). It also be too costly and time consuming." However, even slabs tests in a laboratory are lead with homogeneous mixtures and subgrade conditions that actually differ from general construction aspects of a road. All tests, in the field or laboratory, present limitations to yield the desired accuracy by engineers. Nevertheless, beam tests are easily made using simple theories of its interpretation. On the opposite side, field tests require possible instrumentation in order to achieve accurate flexural stresses and can be interpreted only by more complexes theories, such as finite element analysis.

The practical value of the research presented herein can be used only with particular HSC when early strength hydraulic binders or other high fineness cements are used, since HSC beams reveal worse fatigue performance than other conventional concretes studied in the literature. Nowadays, we can consider two conceptual schools for concrete pavements design and construction. In one, thicker slabs are combined to concretes with 4 MPa to 4.5 MPa of MR. On the other hand, HSC between 6 MPa to 7 MPa of MR and thinner or more conventional 220-240 mm slabs are considered to fulfill high traffic requirements. The model developed during this research is sounder for the second conceptual school of thought.

In conclusion, shift factors must be considered through experiences comparing slabs versus beam performances (field and laboratory) for equivalent concretes. For instance, it is not fair to take a semi-empirical formulation for a shift-factor defined for the HSC in this work and apply it to regular concretes with coarser cements and aggregates. The internal microstructure of concretes that influence its fracture performance may vary around the world, even within the same province in a country. This study, however, shows the dependence of such a shift-factor in stress levels. One might consider, in the absence of a field-based fatigue function, that it is necessary to consider the effect of SSR on realistic fatigue behavior for thickness design purposes.

Summary and Conclusions

Many design methods for concrete pavements do not specify whether their fatigue models are representative for field conditions or not. That may cause performance issues for pavement structures since laboratory beam fatigue models developed at a high frequency and constant stress tend to lead to a misconception about concrete fatigue behavior. This is especially true if the field frequency of loads and its probabilistic and variable characters are not considered.

This has led professionals to recognize the need to establish shift-factors to convert laboratory forecasted load repetitions into actual field performance in terms of fatigue. This kind of goal can be accomplished only by the comparison of laboratory and field behaviors of the same concrete mixture. This kind of investigation is not usual since field fatigue signals on concrete pavements actually take several years to appear and achieve figures that allow fatigue thresholds to be defined.

However, the concrete used in the present investigation was identical to that used in a former field test in which design misconceptions induced fatigue on the concrete in a relatively short period of time. Studies from that previous field test yielded a mechanistic-empirical model for the prediction of fatigue in field conditions assuming 10% of cracked slabs as the threshold for fatigue. Therefore, it was sound to carry out a laboratory investigation to confront beam and slab fatigue cracking, which led to the following conclusions:

- Laboratory investigation with beams has allowed the construction of fatigue prediction functions for the studied concrete (a high strength concrete). Tests were accomplished at 10 Hz for both constant and variable stresses.
- A comparison between the fatigue endurance at frequencies of 5 Hz and 10 Hz in constant stress tests disclosed better or more optimistic behavior for the 10 Hz test samples. A high frequency test induces less opening on cracks within the concrete for each load application. By doing so, a slower progression of fissures is achieved, leading to a higher number of load applications to fatigue. Besides that, high frequency tests do not permit periods of relaxation to the material.
- It is strongly suggested that beam fatigue tests be performed at low frequency values, such as 1 Hz or 2 Hz, since the load application period must endure enough to develop the necessary stress at crack opening boundaries (similar to what occurs with field openings under tire pressures).
- Through the comparison of a beam fatigue equation to the former field equation for the fatigue prediction of HSC under analysis, it was possible to define a shift-factor between beam and field fatigue transfer functions.
- Such a shift-factor proved to be dependent on the SSR. The lower the applied load during its repetition cycle, the more optimistic the laboratory fatigue function appears to be. Hence, the lower the load, the lower the shift-factor to adjust laboratory to field fatigue conditions.

Finally, some closing comments on the differences between both types of fatigue model formulations (laboratory and field) must be emphasized. During laboratory investigations, the entire set of concrete samples that lead to fracture is much more homogeneous when compared to field construction processes. Therefore, both a lower load frequency and concrete heterogeneity in the field are key factors to understanding the conservativeness of field-based fatigue prediction models. Field-based criteria seem to be sounder in both aspects, since the concrete in field conditions always results in more heterogeneous properties. After establishing a threshold for field cracking, concrete in the field is more connected to realistic maintenance issues for road management purposes.

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