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*Abridgment*

# Pavement Design Characteristics of In-Service Portland Cement Concrete

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The primary objectives of this investigation were (a) to determine the modulus of elasticity and the fatigue life of in-service concrete under repeated loads, (b) to estimate the variations in these properties, and (c) to determine the changes in the modulus of elasticity caused by repeated loads. Cores from four recently constructed portland cement concrete pavements in Texas were tested by using both the static and the repeated-load indirect tensile tests (Table 1), and the tensile strengths, fatigue lives, and moduli of elasticity and the variations of these properties were estimated.

## EXPERIMENTAL PROGRAM

The indirect tensile test involves loading a cylindrical specimen with either static or repeated compressive loads that act parallel to and along the vertical diametral plane. To distribute it and to maintain a constant loading area, the compressive load is distributed through 13-mm (0.5-in) wide steel loading strips that are curved at the interface to fit the specimen.

This loading configuration develops relatively uniform tensile stresses that are perpendicular to and along the vertical axis and are fairly uniform over approximately the center 70 percent of the specimen. Failure generally occurs by splitting along the vertical axis. Estimates of the modulus of elasticity were obtained by using the applied load, the corresponding horizontal deformations ($H_R$), and an assumed Poisson's ratio.

The test specimens were cut from the cores and were 51 mm (2 in) high and approximately 102 mm (4 in) in diameter. A capping compound of high-strength gypsum plaster was applied to smooth the irregularities produced by coring. The apparatus used in the capping produced a radius of curvature that was the same as the radius of the specimens. All specimens were from the lower portion of the core.

In the static tests, a preload of 89 N (20 lbf), which corresponds to a tensile stress of about 11 kPa (1.5 lbf/in$^2$), was applied to the specimen to prevent impact loading and to minimize the effect of seating the loading strip. The specimen was then loaded at a rate of 13 mm/min (0.5 in/min). Loads and vertical deformation were continously recorded on an X-Y plotter.

In the repeated-load test, a preload of 89 N was used to prevent impact loading and to reduce movement of the specimen. Then, repeated total loads that produced total tensile stresses ranging from 2.17 to 3.56 MPa (315 to 516 lbf/in$^2$) were applied in the form of a haversine at a frequency of 1 Hz with a 0.4-s load duration and a 0.6-s rest period.

All tests were conducted at 24°C (75°F) and continued until failure, which was considered to occur when the specimen fractured completely. The recoverable (or resilient) horizontal deformations were measured at 25, 50, and 100 cycles and then periodically monitored during the remainder of the test.

The properties analyzed were the indirect tensile strength, the resilient modulus of elasticity, and the fatigue life, i.e., the number of load applications required to completely fracture the specimen. Values of the indirect tensile strength and the resilient modulus of elasticity were calculated by using the equations

**Table 1. Summary of project data.**

| District Project Identification | Type of Aggregate | Cement Factor (kg/m$^3$) | Water-to-Cement Ratio[a] | Beam Strength[b] (MPa) |
|---|---|---|---|---|
| 2E | Limestone | 240 | 0.58 | 448 |
| 17B | Gravel | 252 | 0.59 | 396 |
| 17M | Gravel | 252 | 0.59 | 396 |
| 19B | Iron ore, slag, and gravel | 279-330 | 0.43-0.53 | 396 |

Note: 1 kg/m$^3$ = 0.018 sack/yd$^3$ and 1 MPa = 145 lbf/in$^2$.
[a]Either by mass or by mass to volume.
[b]7-d field curing, center-point loading, using cast beams.

given by Crumley and Kennedy (1). A Poisson's ratio of 0.20 was used for the calculation of modulus. The coefficient of variation was used to describe the variation in the fatigue life and elastic properties.

## ANALYSIS AND EVALUATION

### Tensile Strength

The tensile strength of the capped specimens [2.74 to 3.84 MPa (393 to 557 lbf/in$^2$)] was approximately 30 percent greater than that of uncapped specimens [3.62 to 4.91 MPa (525 to 712 lbf/in$^2$)] (2, 3).

Generally, the coefficients of variation of the capped specimens were much less than those of the uncapped specimens, which indicates that a large portion of the previously measured variation was caused by errors introduced by surface irregularities of the specimen. For the capped specimens, the coefficients ranged from 8 to 16 percent.

### Fatigue Life

The results of the fatigue tests were expressed in terms of the relationship between the stress-to-strength ratio and the logarithm of the number of load applications to failure, which is generally considered to be linear from about 55 to 85 percent of static strength.

This linear relationship can be expressed as

$$\log N_f = C_1 S + C_2 \quad (1)$$

where

$N_f$ = fatigue life,
$S$ = stress-to-strength ratio (percent),
$C_1$ = slope of semilogarithmic relationship, and
$C_2$ = intercept of semilogarithmic relationship.

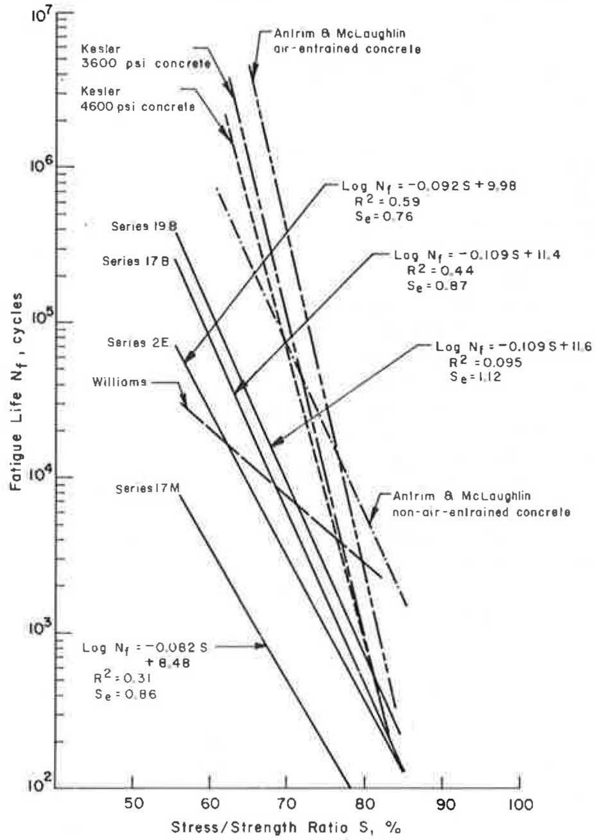
### Fatigue-Life Relationships

The first series of tests, project 2E, involved subjecting specimens to repeated loads at several levels of stress and evaluating the linearity of the relationship between the logarithm of the fatigue life and the stress-to-strength ratio. The resulting S versus N relationship was linear with a coefficient of determination ($r^2$) of 59 percent. Only two levels of stress were used for the three remaining test series (1).

Figure 1 compares the S versus N curves for all four projects, which differed in strength by 35 percent from the results found by Kesler (4), Antrim and McLaughlin (5), and Williams (6). The slopes of all four lines are approximately equal, but the curves are displaced vertically. Thus, the changes in fatigue life produced by a given change in stress were approximately the same, although the fatigue lives differed; an error in estimating the strength could result in a significant displacement of the curves but would not change the slope. Thus, in view of the previous findings that indicated that the relationships should have been similar, it was felt that no definite conclusion could be made.

As expected, the fatigue lives for the cores tested in this study were less than the fatigue lives of the laboratory specimens and their variations were larger (Figure 1). It is apparent that the differences in the slopes of the curves are relatively small, which is significant when it is considered that different test methods were used to evaluate different mixture designs and materials.

**Figure 1. Comparison of relationships between fatigue life and stress-to-strength ratio.**




### Variation of Fatigue Life

Because the distribution of fatigue life is generally log-normal, coefficients of variation for each stress level were based on the logarithms of the fatigue life (Table 2).

The standard error of the estimate ($S_e$) (Table 3) is also of interest. For projects 2E, 17B, and 17M, the values of $S_e$ are very similar, which indicates that the scatter of the test results is about the same. However,

**Table 2. Summary of fatigue data.**

| District Project Identification | Stress-to-Strength Ratio (%) | No. of Specimens | Fatigue Life Predicted by Regression Equation (cycles) | Coefficient of Variation (%) |
|---|---|---|---|---|
| 2E | 75.0 | 4 | 1 108 | 24 |
| 17B | 72.5 | 5 | 3 010 | 21 |
| | 60.0 | 5 | 70 150 | 20 |
| 17M | 72.5 | 4 | 333 | 27 |
| | 60.0 | 5 | 3 548 | 28 |
| 19B | 68.0 | 5 | 16 780 | 16 |
| | 62.0 | 5 | 75 540 | 38 |

**Table 3. Summary of fatigue-test results.**

| District Project Identification | Linear Regression Values | | | |
|---|---|---|---|---|
| | $C_1$ | $C_2$ | $r^2$ (%) | $S_e$ |
| 2E | -0.0924 | 9.98 | 59 | 0.76 |
| 17B | -0.109 | 11.40 | 44 | 0.87 |
| 17M | -0.0822 | 8.48 | 31 | 0.86 |
| 19B | -0.109 | 11.63 | 9.5 | 1.12 |

project 19B has a much larger degree of variation than the other projects, possibly because of the larger range of cement factors and water-to-cement ratios and the use of iron ore slag.

## ELASTIC CHARACTERISTICS UNDER REPEATED LOADING

Almost all the specimens exhibited a slight decrease in elastic modulus in the interval between about 10 and 75 percent of the fatigue life. At approximately 75 percent of the fatigue life, the measured deformations began to increase more rapidly, thereby causing a decrease in elastic moduli.

The means of the modulus of elasticity at selected percentages of fatigue life have been given by Kesler (4). The coefficients of variation for project 2E are much smaller than those for the other series. For project 2E, the decrease in mean modulus between 10 and 90 percent of the fatigue life was approximately 23 percent. The remaining projects apparently experienced seating difficulties during the first 20 percent of the load applications, as evidenced by very erratic behavior in this region. For this reason, the first 20 percent of the load cycles was ignored. Between about 25 and 75 percent of the fatigue life, the mean modulus decreased 3, 14, and 38 percent for projects 17B, 17M, and 19B respectively.

From the available data, it appears that normal-mass aggregate concretes have similar overall behavior with respect to decreasing modulus of elasticity, but that the amount of the decrease varies according to the particular project. The light-mass aggregate concrete (19B) showed much larger decreases in modulus for given percentages of fatigue life. After 50 percent of the fatigue life, the resilient moduli of elasticity varied from 1.65 to 2.80 GPa (2.40 to 4.06 × $10^6$ lbf/$in^2$).

## CONCLUSIONS

The findings and conclusions are summarized below.

### Fatigue Life

1. The semilogarithmic relationships between fatigue life and stress-to-strength ratio for the in-service concrete can be expressed by Equation 1.
2. For the four projects tested, the slopes of the semilogarithmic relationships were essentially equal; the values of $C_1$ ranged from -0.082 to -0.109. Intercept values of $C_2$ ranged from 8.48 to 11.63. These slopes compare favorably with those found in previous studies of laboratory-prepared specimens; however, the intercept values were less, which indicates that the in-service concretes have lower fatigue lives.
3. The variations with respect to the semilogarithmic fatigue-life relationships for the three projects made with normal-mass aggregates were very consistent, as indicated by the range in $S_e$ of 0.76 to 0.87. For the light-mass aggregate concrete, $S_e$ was 1.12.
4. Previous studies had indicated that the fatigue life and stress-to-strength ratio relationship would be essentially the same for all the projects tested. In this study, however, the fatigue-life relationships were not the same (although a small error in the estimated strength could account for the differences). Thus, additional tests should be conducted before a definite conclusion is made.

### Modulus of Elasticity Under Repeated Loads

5. The modulus of elasticity of the concrete decreased with an increase in the number of repeated loads. The magnitude of the decrease ranged as high as 40 percent over the usable life of the concrete, but was different for the various projects. A significant decrease often occurred at about 75 percent of the fatigue life.
6. The variation in modulus for the projects tested was project and material dependent. The coefficient of variation for the resilient modulus of elasticity increased with increasing load applications. At 50 percent of the fatigue life, these coefficients ranged from 7 to 54 percent.

### Tensile Strengths

7. The tensile strengths of the capped specimens tested ranged from 3.62 to 4.91 MPa (525 to 712 lbf/$in^2$).
8. The coefficients of variation of the capped tensile strengths ranged from 8 to 16 percent.

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