Fatigue Behavior of a Lime-Fly Ash-Aggregate Mixture

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The use of lime-fly ash-aggregate mixtures for highway base courses is a relatively recent application to the expanding highway program. Rational methods of analysis for the behavior and design of pavements built with lime-fly ash-aggregate base courses are extremely limited. As a prelude to the development of sound rational methods, it is necessary to understand the behavior of the material when it is subjected to repeated loading.

This paper reports on the fatigue behavior of a lime-fly ash-aggregate mixture. Specimens, 6- by 6- by 38-in., were tested after a 28-day curing period by subjecting them to constant, repeated flexural loads. The relationship between the cycles required to produce failure and the ratio of the applied stress to the static strength is shown.

Repeated flexural loads applied to the specimens tested caused the material to fracture as a rigid-type structure at stress levels considerably below the static strength of the specimens. The test results indicate that the concept of fatigue should be considered in development of a rational method of analysis for the behavior and design of pavements in which lime-fly ash-aggregate mixtures are used.

• A QUALITY lime-fly ash-aggregate mixture is a composite of relatively inert materials cemented together by the combination of lime, fly ash, and water. Fly ash is a pozzolanic material that when combined with lime in the presence of water will form a cementitious material. After mixing the proper proportions, the material is in a moist, nonplastic state, but it can be readily compacted to form a dense mass. Following a curing period, the compacted material exhibits rigid, concrete-like properties (1).

Lime-fly ash-aggregate mixtures have been investigated by many agencies and have been found by field experience to produce a satisfactory base course material for highway pavements. However, a rational structural design method for the use of lime-fly ash-aggregate is not available.

A highway pavement is subjected to repeated loads of varying magnitudes and frequencies. Recognizing this type of loading, it seems only reasonable that a knowledge of the "fatigue" behavior of the material should be understood and evaluated in any rational design procedure. The term "fatigue" refers to progressive fracture of a material caused by repeated cycles of stress at amplitudes of stress smaller than the ultimate strength of the material (2).

The primary purpose of this research is to provide a basic concept of the fatigue properties of lime-fly ash-aggregate mixtures. With no previous fatigue data available, the scope of this study is limited to constant, repeated flexural loads. The authors feel this type of test will give a basic concept of the fatigue properties and pave the way for further and more extensive studies in this field.

PROCEDURES

The specimens used to evaluate the fatigue behavior of the lime-fly ash-aggregate mixture were tested to failure by repeated loadings. The magnitude of the applied load, which was held constant for each test specimen, and the number of cycles of repeated loading required to fracture each specimen were measured.

The most common method of reporting the results of repeated load tests is by a σ-N diagram in which the relationship between the number of cycles required to produce failure and the applied maximum stress is shown. This method is satisfactory for relatively homogeneous materials with little variation in static strength.

However, a lime-fly ash-aggregate mixture is heterogeneous in character and the strength of the material will vary considerably even under controlled laboratory conditions. Other investigators working with concrete have encountered the same problem and have found that the scatter of fatigue test results could be reduced considerably if another method of reporting the data was used. In this method, the relationship between the number of cycles required to produce failure and the ratio of the applied stress to the static strength is shown. In a diagram of this type, the scatter in test results can be attributed to the uncertainty of determining the correct static strength and the probability of a fatigue failure.

Kesler (3) has done considerable work with the fatigue testing of concrete and has developed methods that may be used to reduce the uncertainty of determining the correct static strength. The methods presented by Kesler are used to estimate the static strength of each specimen by tests on the portions of the specimen remaining after fracture of the original specimen.

Static tests were made on lime-fly ash-aggregate specimens similar to those tested by repeated loading to develop the relationships required to estimate the static strength of the specimens, which were tested by repeated loading.

All loads carried by specimens were reduced to stresses before evaluation. The stress distribution in the specimens is not known exactly, especially when it is recognized that the stress-strain relationship and the distribution of stresses may change during the fatigue test. Because an extensive test program would be necessary to determine this stress distribution, the stresses were computed by assuming a linear stress-strain relationship. At failure this stress value is defined as the modulus of rupture. The stress caused by the dead weight of the specimen is included in all computations as its maximum value.

NOTATIONS

The following notations are used:

f' = compressive strength as determined by modified cube tests;

M_r = modulus of rupture;

M_{re} = estimated modulus of rupture;

M_{re_1} = estimated modulus of rupture by method 1;

M_{re_2} = estimated modulus of rupture by method 2;

M_{re_3} = estimated modulus of rupture by method 3;

M_{re_4} = estimated modulus of rupture by method 4;

$M_{r'}$ = modulus of rupture of the remaining pieces after the original specimen has fractured;

N = number of cycles of stress required to cause fracture;

σ_{min} = minimum applied stress;

σ_{max} = maximum applied stress; and

σ'_{max} = computed maximum applied stress when minimum applied stress is equal to zero.

MATERIALS

The material investigated was composed of a single mixture of lime, fly ash, and aggregate. The particular materials used were selected as being similar to those in widespread use in several sections of the country.

The aggregate used in the mixture was taken from the subbase material stockpile from the AASHO Road Test at Ottawa, Ill. Gradation of the material as determined by ASTM D 422 (4) is given in Table 1.

The fly ash was obtained from the Public Service Electric and Gas Company, Sea Warren, N.J. The particle-size distribution of the fly ash is given in Table 1. The loss on ignition was 7.2 percent.

The lime used was a monohydrated dolomitic lime supplied by the Marblehead Lime Company, Chicago, Ill.

The materials were combined by dry weight in the following proportions: 82 percent aggregate, 14 percent fly ash, and 4 percent lime. The proportions were established from a previous laboratory investigation of these materials (1). The moisture-density relationships of the mixture were determined by ASTM D 698 (5). The maximum dry density was 135.4 pcf and optimum moisture content was 7.8 percent.

TABLE 1

GRADATION OF MATERIALS

Sieve Size	Percent Passing Aggregate	Fly Ash
¾ in.	100[a]	
⅜ in.	87	
No. 4	73	
No. 8	55	
No. 16	41	100
No. 30	31	99
No. 50	16	97
No. 100	11	92
No. 200	8	87
0.05 mm	6	79
0.02 mm	4	34
0.005 mm	2	11
0.002 mm	1	10

[a] All material larger than 3/4 in. was discarded.

PREPARATION OF SPECIMENS

Specimens 6- by 6- by 38-in. were molded in steel forms. The lime-fly ash-aggregate mixture was mixed at or near optimum moisture content in a 2½-cu ft Lancaster PC mixer with a mixing time of 4 min. Various methods of compaction were investigated to determine a method that would consistently compact the specimens to maximum dry density at optimum moisture content as found by ASTM D 698. The method selected consists of compacting three equal layers with 100 well-distributed blows of a 10-lb rammer dropped 18 in. The rammer had a circular head 3.87 in. in diameter. To insure bond between the layers of the specimens, each layer was scarified before the placing of the next layer.

The specimens were cured for 28 days at ambient temperatures in moist sand. This consisted of covering the molded specimens with a 1-in. thick layer of moist concrete sand and sprinkling the sand daily at a rate of ⅜ gal per sq yd.

Before testing, all specimens were rotated so that the load was applied perpendicular to the direction of compaction to minimize any effects of nonuniform layers or poor bond between layers. Full contact between the specimen and the bearing plates was insured by using a capping material at all points of contact.

TESTING MACHINES

A schematic diagram of the fatigue testing machine used in this study in shown in Figure 1. A repeated load of constant magnitude was applied by the loading lever which was connected to an eccentric by an adjustable connecting rod. The eccentricity and the connecting rod could be adjusted to produce the desired magnitude of load. The load was applied to the specimen by means of a loading plate made of cold rolled steel. Several sets of electrical resistance strain gages were mounted on the loading plate which was calibrated and used as a dynamometer to measure the loads. The frequency of load application was approximately 450 cycles per min. A combination of ball-bearings and rollers was used at the supports to insure simple loading.

For the static tests, a Baldwin hydraulic testing machine was used.

Estimating Static Strength

Twelve static tests were made on specimens of this material using the same conditions of loading as was used in the repeated load tests. In most cases, the failure occurred near enough the center of the specimen to permit a modulus of rupture test to be made on each of the two remaining pieces. The conditions of loading for these two tests are shown in Figure 2. Values for the modulus of rupture were calculated for the original specimen and for the remaining pieces after fracture of the original specimen. The remaining pieces of the specimen were then tested as modified 6-in. cubes as shown in Figure 2 and a value for the compressive strength of the material was obtained.

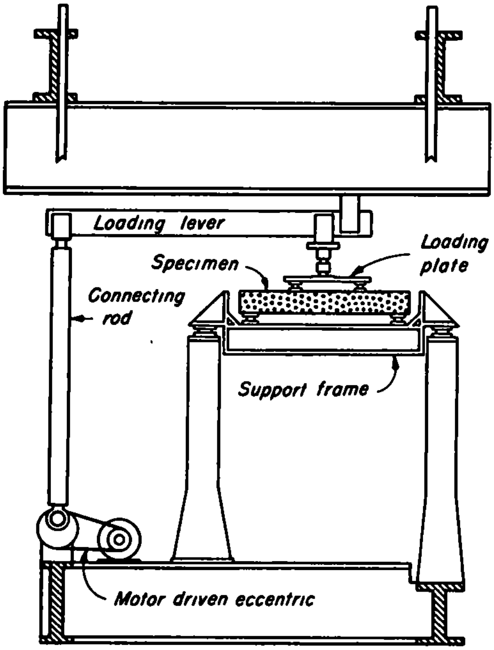


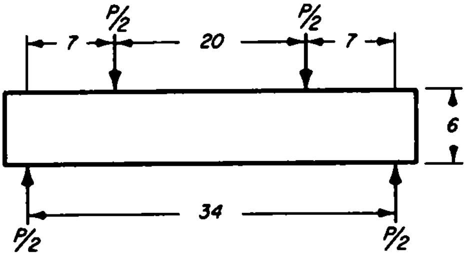
Figure 1. Schematic diagram of fatigue-testing machine.

As stated previously, the main purpose of the static tests was to find a relationship that could be used to predict the static strength of a specimen that had failed under repeated loading. When a specimen has failed by repeated loading, the modulus of rupture (M_r) of the specimen will be unknown. Various methods of estimating the modulus of rupture are shown herein. This estimated modulus of rupture is denoted as M_{re} with an additional numerical subscript to denote the method used in estimating M_r. M_{re} can be compared to the known M_r of the specimens tested statically to determine the reliability of the various methods that have been used to determine M_{re}. All comparisons are made on the basis of the ratio M_{re}/M_r. The results of the static tests are shown in Table 2.

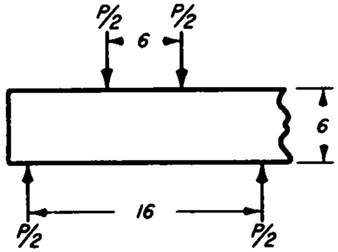
Because the procedures used in these static tests to predict the modulus of rupture are to be applied to fatigue specimens, the question arises of the validity of the procedure when applied to specimens that were originally subjected to repeated loads. No attempt was made to answer this question in this study, but Kesler (3), while working with a much larger number of concrete specimens, shows that confidence in the validity of the procedures used is justified for concrete. Because this material is quite similar to concrete it has been assumed by the authors that the strengths of the fractured specimens remains unaffected. Results of the estimated values of the modulus of rupture for the specimens tested by repeated loading tend to justify this assumption because the average for all the estimated values is 184 psi as compared with an average value of 178 psi for those specimens tested statically.

The first method to estimate the modulus of rupture was to determine the average M_r of all of the specimens tested and use this average value as the estimated value. This is denoted as M_{re_1} and is given in Table 2 along with the values for M_{re_1}/M_r. The standard deviation of the ratio M_{re_1}/M_r was determined to be ±0.19 with 95 percent confidence limits of ±0.11.

The second method related M_r to the compressive strength (f') of the specimens. The compressive strength was determined from the modified 6-in. cubes. The average for the ratio M_r/f' was determined to be 0.187. Assuming that the flexural strength and the compressive strength of the specimens are linearly related, the second estimate

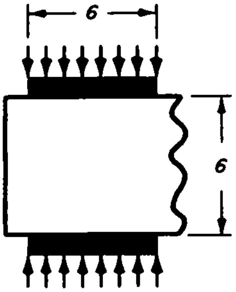


(a) Modulus of rupture of specimen



(b) Modulus of rupture of broken specimen

All dimensions in inches



(c) Compressive strength from modified cubes

Figure 2. Loading details for static tests.

of the modulus of rupture (M_{re2}) may be computed from

$$M_{re2} = 0.187\,f'$$

The standard deviation of the ratio M_{re2}/M_r was determined to be ± 0.08 with 95 percent confidence limits of ± 0.05.

The third method was to assume M_r equal to the modulus of rupture of the broken pieces of the specimens (M'_r). The average value for the ratio M_r/M'_r was determined to be 1.04 with a standard deviation of ± 0.08 and a 95 percent confidence limit of ±0.05. The assumption of M_r/M'_r equal to 1.00 lies within the 95 percent confidence limit and is therefore statistically justified. Thus, the value of $M_{re3} = M'_r$ was taken as the third estimated value of M_r. The average value for the ratio M_{re3}/M_r was found to be 0.96 with a standard deviation of ±0.08 and a 95 percent confidence limit of ± 0.05.

Three methods of estimating the modulus of rupture have been shown. A fourth method was developed as a combination of two of these methods. It is fairly apparent by a comparison of the standard deviations, that M_{re2} and M_{re3} are about of equal correctness in predicting M_r. On the other hand, using M_{re1} in combination with either or both of these would give a deviation greater than by using M_{re2} or M_{re3} separately. At this point M_{re1} was disregarded and M_{re2} and M_{re3} were combined, each method receiving equal weight. Thus, a fourth value for M_{re} was found from $M_{re4} = \frac{1}{2}(M_{re2} + M_{re3})$.

TABLE 2

STATIC TEST RESULTS

Test No.	M_r (psi)	M_r' (psi)	f' (psi)	M_{re1} (psi)	M_{re2} (psi)	M_{re3} (psi)	M_{re4} (psi)	$\frac{M_{re1}}{M_r}$	$\frac{M_{re2}}{M_r}$	$\frac{M_{re3}}{M_r}$	$\frac{M_{re4}}{M_r}$
19	139	131	748	178	140	131	136	1.28	1.01	0.94	0.98
20	165	161	893	178	167	161	164	1.08	1.01	0.98	0.97
21	221	228	1,055	178	197	228	213	0.80	0.89	1.03	0.97
22	130	125	748	178	140	125	132	1.37	1.08	0.96	1.01
23	219	222	1,108	178	207	222	215	0.81	0.95	1.01	0.98
24	197	168	965	178	180	168	174	0.90	0.91	0.85	0.89
25	206	183	1,138	178	213	183	198	0.86	1.03	0.89	0.96
26	186	174	931	178	174	174	174	0.96	0.94	0.93	0.94
27	142	141	874	178	163	141	152	1.25	1.15	0.99	1.07
28	187	188	956	178	179	188	184	0.95	0.96	1.00	0.99
29	161	181	998	178	187	181	184	1.10	1.16	1.12	1.14
30	188	156	1,009	178	189	156	173	0.95	1.01	0.83	0.92
Avg.								1.03	1.01	0.96	0.99
Std. Dev.								±0.18	±0.08	±0.08	±0.06
Conf. Limit[a]								±0.11	±0.05	±0.05	±0.04

[a] 95 percent.

The average value for the ratio M_{re4}/M_r was determined to be 0.99 with a standard deviation of ± 0.06 and a 95 percent confidence limit of ± 0.04. The fourth method (M_{re4}) of estimating the M_r was determined to be the most reliable.

EVALUATION OF FATIGUE BEHAVIOR

Procedure

The apparatus used for the repeated load tests has been described. Loading details for the specimens subjected to repeated loads are shown in Figure 3. The general type of repeated load that was applied was a continuous cycle fluctuating between a maximum and a minimum value, with the stress-time pattern forming a sine wave as shown in Figure 4. The actual type of cycle that the material might be subjected to when used as a highway base course material is shown in Figure 5. This figure shows the random frequencies and stresses applied to the material. Effects of rest periods and varying magnitudes of repeated loads are extremely complex and require a basic understanding of the fatigue behavior of the material.

The minimum applied stress was due to two factors, the stress caused by the dead weight of the specimen and a small load that was constantly held on the specimen to prevent the loading apparatus from applying an impact load. The total minimum stress level applied was held at approximately 0.12 for all tests.

After the specimens had failed by repeated loading, the portions of the specimen that remained were subjected to the static tests as previously described in this paper so that the modulus of rupture of the specimen could be estimated.

Test Results

Results of the repeated load tests are given in Table 3. Columns 2 and 3 give the maximum and minimum applied stresses, σ_{max} and σ_{min}, respectively. The estimated modulus of rupture for each specimen is shown in column 4. The ratios of the maximum and minimum applied stresses to the estimated modulus of rupture, σ_{max}/M_{re} and σ_{min}/M_{re}, respectively, are shown in columns 5 and 6. Column 7 gives the number of applications (N) required to produce failure.

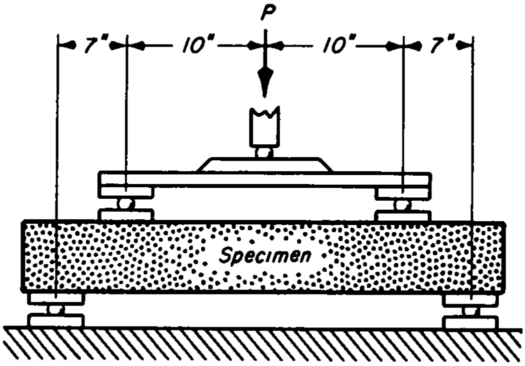


Figure 3. Loading details for repeated load tests.

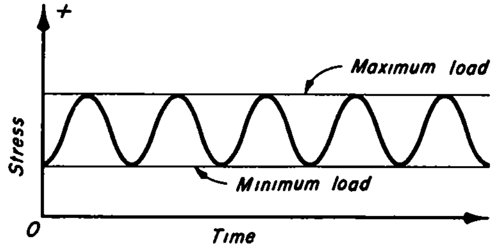


Figure 4. Stress-time relationship for repeated load tests.

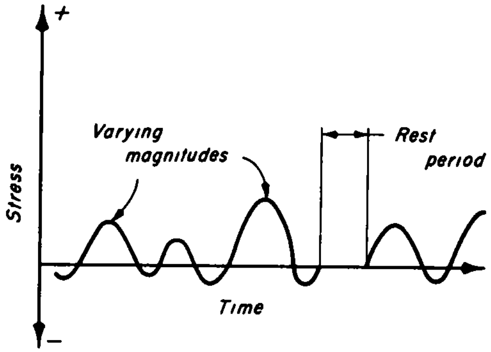


Figure 5. Hypothetical stress-time relationship for highway loading.

Tests 1 through 15 were all completed in less than 32 hr after the loading was initiated, but tests 16, 17, and 18 required 17, 11, and 10 days, respectively, for completion. Inasmuch as a lime-fly ash-aggregate mixture continues to gain strength at a relatively rapid rate for a long period of time, the estimation of the modulus of rupture made at the end of the test would be higher than the modulus of rupture of the specimen during the testing. Specimens made by identical procedures and tested at an age of 40 days, or 12 days after the 28-day strength had been reached, gave a strength

TABLE 3

FATIGUE TEST RESULTS

Test No. (1)	σ_{max} (psi) (2)	σ_{min} (psi) (3)	M_{re} (psi) (4)	$\frac{\sigma_{max}}{M_{re}}$ (5)	$\frac{\sigma_{min}}{M_{re}}$ (6)	N (7)	$\frac{\sigma'_{max}}{M_{re}}$ (8)
1	124	23	173	0.718	0.133	1,900	0.670
2	96	20	168	0.571	0.119	86,800	0.510
3	83	20	187	0.444	0.107	819,600	0.376
4	124	24	194	0.640	0.124	63,100	0.585
5	112	23	201	0.557	0.114	454,000	0.497
6	95	23	172	0.552	0.134	135,100	0.484
7	97	22	170	0.570	0.129	301,600	0.510
8	119	24	167	0.714	0.144	77,300	0.661
9	127	23	183	0.694	0.126	10,000	0.650
10	106	22	190	0.558	0.116	204,300	0.498
11	109	23	165	0.660	0.140	16,100	0.600
12	115	23	169	0.681	0.136	48,600	0.624
13	105	22	195	0.538	0.113	542,200	0.479
14	130	24	206	0.631	0.116	26,000	0.581
15	131	23	192	0.684	0.120	19,800	0.640
16	64	23	204	0.317	0.113	10,432,900[a]	0.228
17	89	21	194	0.459	0.108	6,599,700	0.395
18	88	23	192	0.459	0.120	4,828,700	0.388

[a] Specimen did not fail under repeated loading.

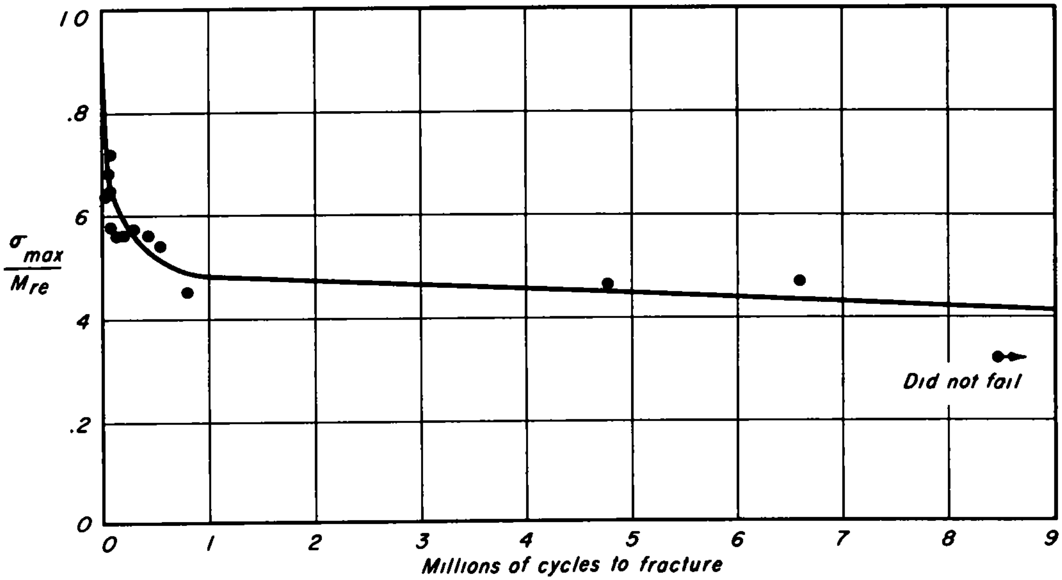


Figure 6. Relationship between maximum stress level and number of cycles to fracture (minimum stress level approximately 0.12).

equal to 118 percent of the 28-day strength. If a linear rate of gain is assumed, this is equal to a gain of 1½ percent of the 28-day strength for each day after 28 days. Because this would make a significant difference for specimens 16, 17, and 18, the modulus of rupture of these specimens was estimated by using the average modulus of rupture (M_{re1}) and adding the estimated strength gain that would have occurred after half of the test time. For all other specimens, the modulus of rupture was estimated by method 4.

Figure 6 shows a plot of the relationship between the number of cycles required to produce failure and the ratio of the applied stress to the estimated static strength. The same relationship is shown in Figure 7 except that the number of cycles required to produce failure are plotted on a logarithmic scale.

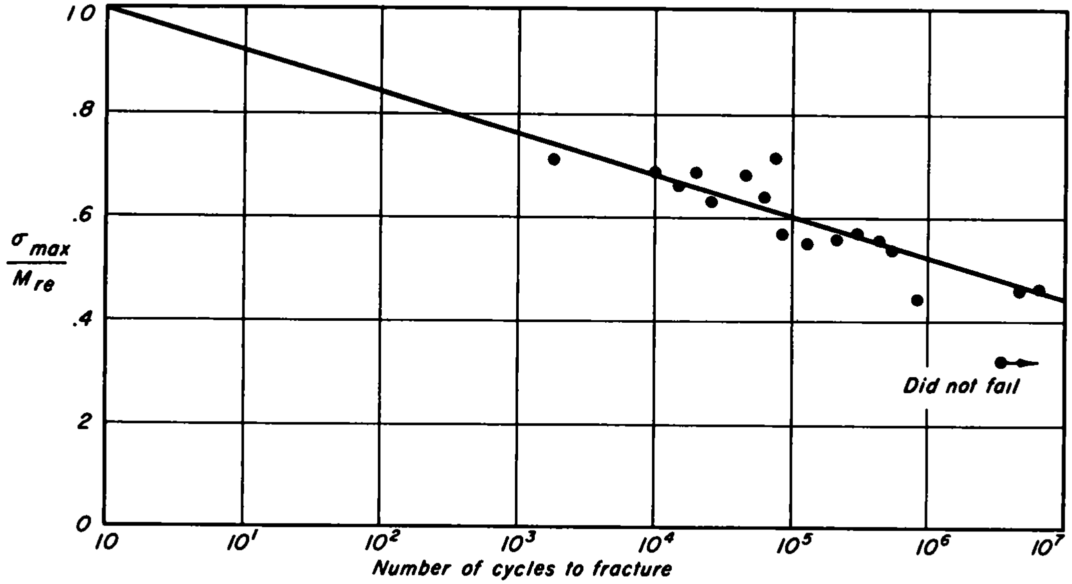


Figure 7. Relationship between maximum stress level and logarithm of number of cycles to fracture (minimum stress level approximately 0.12).

The method of least squares was used to determine the straight line of best fit for the data as shown in Figure 7. The equation determined is

$$\frac{\sigma_{max}}{M_{re}} = 1.00 - 0.0798 \log N.$$

Because all tests were conducted with a minimum stress of about 12 percent of the modulus of rupture, it was necessary to determine the effect of this stress on the test results. The minimum applied stress has the effect of increasing the

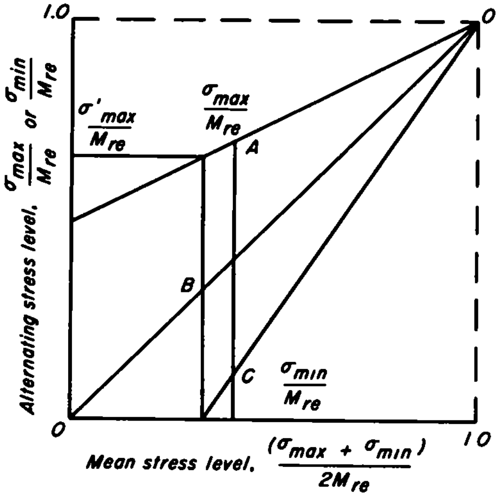


Figure 8. Modified Goodman diagram.

number of cycles required to cause fracture at some given maximum applied stress.

A modified Goodman diagram (such as shown in Fig. 8) was used to determine the maximum stress level corresponding to a minimum stress of zero. For each test, the mean stress level $(\sigma_{max} + \sigma_{min})/2M_{re}$ was plotted as the abcissa against the maximum and minimum stress levels (σ_{max}/M_{re} and σ_{min}/M_{re}) plotted as ordinates. The lines OA and OC were then drawn through these points, the point O corresponding to the modulus of rupture of the specimen (stress level of 1.00). To determine exactly the lines OA and OC, many tests would have to be made at various stress levels and a constant number of cycles to failure. However, because the distance to be extrapolated is small, the corresponding error in assuming that these lines are straight is also small. Hence, as a matter of convenience, lines OA and OC were assumed to be straight.

With the lines OA and OC established, the mean stress level at which there is zero minimum stress is found at the intersection of line OC with the horizontal axis. The maximum stress level corresponding to this mean is then found on line OA.

This procedure was applied to the test results to find the maximum stress that could have been carried by the specimens if there had been no minimum stress. The ratio of this maximum stress (σ'_{max}) to the estimated modulus of rupture (M_{re}) is given in column 8 of Table 3. A plot of this data is shown in Figure 9. The equation of the straight line representing the fatigue behavior is

$$\frac{\sigma'_{max}}{M_{re}} = 1.00 - 0.0916 \log N.$$

General Discussion

The assumption of the linear relationship between the applied stress level and the logarithm of the number of cycles required to cause fracture may not be entirely true, especially at stress levels that require over 1,000,000 applications to cause fracture. It has been fairly well established for concrete exhibiting the same general pattern for the relationship of the applied stress level and the number of cycles required to cause

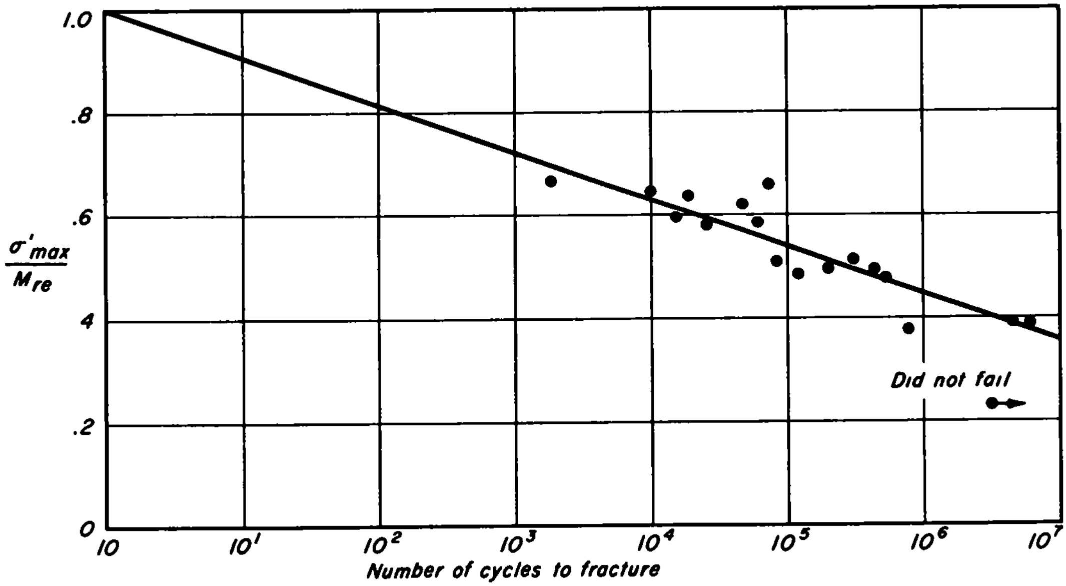


Figure 9. Relationship between maximum stress level and logarithm of number of cycles to fracture (zero minimum stress level).

failure, that at some number of cycles in the range of 1 to 10 million that an applied stress level is reached below which fatigue fracture will not occur.

In attempting to select a design stress level, the interrelationship of several factors must be considered. The tests reported in this paper were performed on 28-day old specimens at rates of loading (450 cycles per min) far in excess of what might be expected for service loading. The age at which loading is initiated and the rate of application of loading would appear to cause considerable effect on the number of cycles required to cause fracture. Both laboratory and field investigations of the effect of time on the strength of lime-fly ash-aggregate mixtures have shown that there is a significant gain in strength for a long period of time (6). The rate of strength gain is dependent on the composition of the mixture, the age of material, moisture conditions, and the prevailing temperatures. The interrelationship of this strength gain and the progressive fracture by repeated loading is not known. Though supporting data is not available, it appears reasonable to assume that the increase in strength of a lime-fly ash-aggregate mixture that is developed over a considerable period of time would influence the fatigue behavior by greatly extending the number of cycles required to cause fracture.

CONCLUSIONS

Repeated flexural loads applied to the lime-fly ash-aggregate mixture investigated caused the material to fracture as a rigid-type structure at stress levels considerably below the static strength of the material.

The relationship between the applied stress level and the number of cycles required to fracture the material can be linearized in range of 1 to 1,000,000 cycles of applied stress by relating the applied stress level to the logarithm of the number of cycles required to fracture the material. A small reduction in the applied stress can greatly increase the number of cycles required to cause fracture.

Further investigation should be conducted to determine the effects of varying magnitudes and frequencies of applied stress, rest periods, and the interrelationship of the continued gain in strength with time of a lime-fly ash-aggregate mixture and the progressive fracture by repeated loading.

The concept of fatigue should be included as one of the criteria in the development of a rational method of pavement design for the use of lime-fly ash-aggregate mixtures.

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