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Abstract

The primary objective of this work was to evaluate flexural fatigue properties of high-volume fly ash concrete systems. A total of eight concrete mixtures were proportioned using four sources of fly ash and two Type I portland cements (low-alkali and high-alkali). Both fly ash content (58% of total cementitious materials) and water to cementitious materials ratio (0.33) were kept constant for this investigation. Flexural fatigue loads were applied using a third-point loading system in accordance with ASTM C 78. The resulting data were analyzed to establish stress versus number of cycles to failure curve. Additionally, experiments were also carried out to evaluate the modified cube compressive strength ASTM C 116 of each mixture using portions of the beam, which were previously broken in flexure. Test data showed a non-linear behavior between flexural fatigue stress and number of cycles of loadings. Endurance or fatigue limit was defined as flexural fatigue stress at two million loading cycles. The value of this limit was found to vary from mixture to mixture. However, this variability was greatly reduced when the endurance ratio (endurance limit divided by the static flexural strength) versus number of cycles was used. The endurance ratio was found to generally vary between 0.42 and 0.54 with an overall average of approximately 0.5. These values are similar to those observed for non-fly ash concrete.

Introduction

Concrete structures such as pavements, bridges, offshore structures, etc. experience cyclic loadings. Design of such structures requires information on fatigue characteristics of materials, including concrete made with and without mineral admixtures.

Generally, fatigue failure of materials occur at stress levels much lower than yield strength of materials under static conditions. This is because of the fact that cyclic loads induce micro-cracks in the materials that grow with time. Moreover, microcracks and/or macrocracks are also developed in concrete during its production process. Due to the crack growth, size of these cracks can become equal to critical size and can cause failure of structure at low load when the load is applied for a long time.

Fatigue behavior of materials can be greatly influenced by variables such as type of loading, rate of loading, range of loading, environmental conditions, material properties, etc. Concrete properties are also governed by factors such as water to cementitious materials ratio, cement content, air content, curing, age, admixture content, etc. As a result, fatigue behavior of concrete is quite complex. It is difficult to predict fatigue behavior of concrete using theoretical models.

There is a lack of information on fatigue behavior of fly ash concrete, particularly concrete incorporating large amounts of fly ash. Therefore, the primary objective of this work was to establish fatigue characteristics of high-volume fly ash (HVFA) concrete systems. The specific objectives of this work were:

1. Determine static compressive and flexural strengths of HVFA concrete;
2. Establish fatigue stress versus number of cycles (S-N Curve) for each mixture; and,
3. Determine the effect of fatigue loading on static strength of concrete.

Previous Investigations

Early studies have been reviewed by a number of investigators including Nordby (1), Murdock (2), Lloyd et al. (3), Raithby and Whiffin (4), Naik et al. (5), and Ramakrishnan (6). Recently, Naik et al. (5) carried out an extensive review of past investigations pertaining to fatigue properties of plain portland cement concrete made with and without mineral admixtures. The information collected is briefly described here.

Several parameters such as stress range, load history, rate of loading, rest period, stress gradient, material properties, etc. can affect fatigue characteristics of concrete substantially. Generally, a decrease in the stress range appears to increase fatigue strength of concrete. The frequency of loading on fatigue behavior in the range of 1-30 CPS is insignificant if the maximum stress level remains less than about 75% of the static strength. Several investigations have indicated conservative as well as unsafe prediction of fatigue damage by the Miner hypothesis. This hypothesis ignores the effect of loading sequences on fatigue damage of concrete. The stress reversal causes reduction in fatigue life of concrete when compared to concrete loading with stress cycles having positive stress ratio.

A number of researchers (5,6) have shown beneficial effects of previous cyclic loadings on concrete static strength provided the loadings remain at or below the endurance limit. Ramakrishnan et al. (6) indicated increase in the static strength in the range of 5 to 15 percent for specimen loaded at or below its endurance limit relative to the control. This was attributed to the release of residual stresses and strain hardening effects. Rest periods and sustained loading between the repeated load cycles can also produce a beneficial effect on the fatigue strength of concrete. The effects of parameters such as water to cementitious materials ratio, cement content, curing, age, aggregate properties, admixture content, etc. are known to affect fatigue strength of concrete. The effects of these parameters exhibit the same general trend as observed in the case of static strength.

A few investigations have been directed toward determining fatigue characteristics of concrete incorporating mineral admixtures. Ghosh et al. (7) determined the flexural fatigue strength of low cement content concrete and low cement fly ash concrete (very lean mixtures). Test results indicated that at 75% of the maximum flexural stress level, the number of repetitions to failure was 2,000 and 20,000 cycles for lean mixtures of cement and very lean mixtures of cement-fly ash concretes, respectively. Tse et al. (8) evaluated compressive fatigue strength of concrete containing both Class C and Class F fly ashes. The fatigue strength was determined using cylindrical specimens (150 x 300 mm). The authors reported that concrete with equivalent or higher compressive and fatigue strengths could be obtained with cement replacement of 25% by weight of low-calcium fly ash or 50% by weight of high-calcium fly ash.

Ramakrishnan et al. (9) determined flexural fatigue strength behavior of superplasticized high-volume fly ash concrete systems. They used two concrete mixtures: one reference and the other fly ash concrete with a Class F fly ash content of 58% of total cementitious materials. For each mixture, prism specimens were subjected to cyclic loading using a three point loading system in accordance with ASTM C 78 at 20 CPS. The values of endurance ratio were 0.65

for the no-fly ash concrete and 0.70 for the high-volume Class F fly ash concrete. They further reported a 15 to 30% increase in the static flexural strength for specimens made with both mixtures which were previously subjected to four million cycles of fatigue loading compared to the specimens not loaded before.

Recently Naik and Singh (11) evaluated flexural fatigue characteristics of concrete incorporating ASTM Class C fly ash. Two concrete mixtures were proportioned to have fly ash as a replacement of 18% and 56% of total cementitious materials. Test specimens were subjected to cyclic loading using a three point loading system in accordance with ASTM C 78 at 20 CPS. The authors reported that concrete containing 18% Class C fly ash was stronger in both compression and flexural modes of loading compared to concrete containing 56% fly ash. The flexural fatigue limit was taken as a flexural stress at two million cycles of loading. The fatigue limit for the 18% fly ash mixture was substantially higher than that for the 56% fly ash mixture. Based on pooled data, an endurance ratio of 0.55 was established for these fly ash concrete systems. Their results further revealed 0-6% decrease in the static flexural strength for the 18% fly ash concrete and 11-19% decrease for the 56% fly ash concrete specimens after two million cycles of loading compared to the reference specimens.

A plot of ratio of fatigue flexural stress to static flexural stress (S) versus logarithm of number of cycles (N), becomes independent of the specimen shape, strength properties, curing condition, age, moisture condition at loading, etc. Aas-Jakobsen (12) established an empirical model to express the relation between the ratio S as a function of the ratio of minimum stress to maximum stress (R) and number of load cycles. In other investigations this model was found to be adequate to describe fatigue strength of plain normal weight and lightweight concretes in both compression (13) and tension (14). Oh (15,16) developed a linear relation between the ratio S and N. Hsu (17) proposed a more general model to take into accounts the four parameters S-N-T-R. This includes an additional variable T (time). The product of T and N denotes duration of loading; and, thus, the model presents the combined influence of time and loading rate on fatigue behavior of concrete. The author established empirical models for both high-cycle and low-cycle fatigue failures.

Experimental Program

An experimental program was designed to establish fatigue behavior of high-volume fly ash concrete systems. The work related to material selection and characterization, mixture proportioning, and specimen preparation was performed at the CANMET, Ottawa, Canada. The work concerning the fatigue testing was performed at the UWM Center for By-Products Utilization, University of Wisconsin-Milwaukee.

Materials

Cement

Two different cements designated as S and G were used. Cement S was a low-alkali (about 0.2% Na_2O) ASTM Type I cement, whereas cement G was a high-alkali (about 1.1% Na_2O) ASTM Type I cement. The physical and chemical properties of these cements are presented in Table 1.

Fly Ash

Four fly ashes obtained from four different sources in the USA were used in this investigation. Their physical and chemical properties are given in Table 2.

Mixture Proportions

The concrete mixture proportions are summarized in Table 3. The parameters such as water to cementitious materials ratio, and water, cement, and fly ash contents were maintained approximately constant for all mixtures. All mixtures were air entrained and a HRWR was used. Appropriate amounts of air entraining admixtures were added to entrain air content of 5 ± 0.5 percent. A napthalene-based HRWR (superplasticizer) was used to obtain the desired level of slump.

Specimen Preparation

Cylindrical specimens (150 x 300 mm) were cast for compressive strength determination. Prism specimens (75 x 100 x 400 mm) were cast for flexural static and fatigue strength measurements of concrete. These specimens were cast in two layers using an internal vibrator. All test specimens were subjected to moist curing in accordance with ASTM C 192. After one year of moist curing at CANMET, all the specimens were shipped to the UWM Center for By-Products Utilization, University of Wisconsin- Milwaukee, where they were stored in lime-saturated water until the time of the test.

Testing of Specimens

Compressive Strength

Concrete compressive strength was determined in accordance with ASTM C 39. The modified cube compressive strengths of concrete mixture using portions of beam specimens which were previously broken in flexure, were determined in accordance with the ASTM C 116 at the time of fatigue testing.

Fatigue Strength

Static and fatigue flexural strength of concrete were determined using third-point loading. In this work, endurance limit was defined as the flexural stress level at which the beam specimen could withstand two million cycles of nonreversed cyclic loading. The static flexural strengths of beam specimens (75 x 100 x 400 mm) were determined using a third-point loading in accordance with ASTM C 78 with a span of 300 mm. Three specimens were used to determine the average static flexural strength of concrete. All specimens were tested with respect to their stronger axis.

The upper and lower limits for the cyclic loading were determined from the average static flexural strength of the mixture. The lower limit was taken as 10% of the static flexural strength of each mixture. In this investigation, the lower limit was kept constant for all specimens and upper limit was varied from about 90% of the static flexural strength down to endurance limit (fatigue limit) of the mixture.

The flexural fatigue test was carried out between the upper and lower limits of the loading using the third-point loading system. Three specimens were tested for each load condition. If three specimens failed before two million cycles, the upper limit was reduced by 10% or more depending upon the number of upper load levels needed to establish endurance limit for a given mixture. Two additional specimens were tested at the load level at which three beams survived two million cycles. The endurance limit was taken as an average flexural strength based on the results of the five specimens which survived two millions cycles of loading. The beams which survived two million loading cycles were also tested in static loading using the third-point loading.

Since fatigue testing of concrete is very time consuming, it was not possible to test all the mixtures at a constant age. Each test specimen took up to about 28 hours to test. Therefore, after completion of testing of one mixture, the next mixture was tested. This resulted in differences in age among test specimens mixtures tested. However, at about one year age, at which the fatigue testing was started, the age effect on strength gain was already negligible. In order to further eliminate the effect of age to a considerable extent, fatigue strength data were expressed as a ratio of fatigue flexural strength to static flexural strength for each mixture.

Results and Discussion

Fatigue behavior

The fatigue stress data were expressed as a ratio of fatigue stress to static strength (S) versus number of cycles (N). The S - N fatigue data are plotted in Fig. 1. The plot of the ratio S versus number of cycles N showed a non-linear trend for all the mixtures (Fig. 1). However, a plot of the ratio S versus logarithmic number of cycles for the mixtures showed a linear trend (Fig. 2). The linear model predictions were found to be adequate for number of cycles less than 2 million cycles.

The data showed that both static flexural strength and fatigue stress were dependent upon source of fly ash used. The effect of type of cement was relatively small compared to effect of source of fly ash.

The mixture having the highest flexural strength did not exhibit the maximum fatigue limit (fatigue stress at two million cycles of loading). This may be attributed to the differences in crack propagation patterns which were probably dictated by presence of size and location of flaws/cracks in the test specimens, brittleness of concrete, etc.

Plots of static and fatigue flexural strength of test mixture (EP1F through EP8F) are shown in Fig. 3. A plot of fatigue limit or endurance limit of the mixtures are also shown in Fig. 4.

The results showed that the fatigue strength varied from 2.6 MPa to 3.3 MPa for the mixtures tested; whereas, the endurance limit ranged between 0.42 and 0.53 for the specimens tested. The results further indicated that endurance limit was relatively unaffected by the type of cement and source and type of fly ash used. This is consistent with results obtained from previous investigations, as the relationship between the strength ratio S and number of cycles N becomes relatively independent of age, strength, and material properties (5). Based on pooled data, the endurance limit for the test mixtures was determined to be approximately 0.5.

Static Flexural Strength After Two Million Cycles

The test specimens which survived 2 million cycles of fatigue loading were also tested for static flexural strength. In general, with one exception, all test specimens which had undergone 2 million cycles of fatigue loading showed reduced static flexural strength compared to the respective reference specimens not loaded previously. The reduction in flexural strength of test specimens was found to vary between 1.6 and 33.3%. This means that high-volume fly ash concrete specimens tested in this work exhibited strain softening behavior, as opposed to strain hardening behavior reported by some researchers (6). This may have been due to slippage caused between the unreacted fly ash particles and the paste during the cyclic loading, and creation of microcracks during the fatigue loading.

Modified Cube Compressive Strength

The modified cube strengths were determined for all test specimens of each mixture used for fatigue stress determinations. Average modified cube strengths were 52.0 MPa for EPIF, 57.9 MPa for EP2F, 56.8 MPa for EP3F, 58.8 MPa for EP4F, 53.2 MPa for EP5F, 51.3 MPa for EP6F, 56.3 MPa for EP7F, and 55.2 MPa for EP8F. The corresponding compressive strengths for these mixtures measured using 150 x 300 mm cylinders were 52.0, 56.8, 58.8, 53.2, 51.3, 56.3, and 55.2 MPa at one year age. There is a some difference between the strength values determined by these two methods. The main reason for the difference is due to variation in geometry of test specimens. Other factors such as difference in age and previous strain history would also affect the strength results. The specimens used for the modified cube compressive tests might have experienced some prior strain because they were derived from specimens which were broken in flexure.

Conclusions

Based on the results obtained in this investigation the following conclusions were drawn.

1. The static flexural strength of high-volume fly ash concrete systems varied with source of fly ash used. However, the effect of cement type was relatively small on the static flexural strength of mixtures.
2. The flexural fatigue limit (fatigue strength) of concrete was also influenced by the source of fly ash used. However, the concrete mixture having the highest static flexural strength did not show the highest fatigue limit. This means that fatigue flexural strength was more sensitive to internal structure of concrete structure, especially presence of flaws.
3. A nonlinear relationship exists between fatigue stress and number of cycles.
4. A linear model was established to represent the relation between the ratio of fatigue stress to static strength and logarithmic of number of cycles, based on pooled data obtained from all eight mixtures.
5. The fatigue or endurance limit values for the mixtures were found to vary in the range of 0.42 to 0.54. Based on the pooled data, the value of endurance ratio was approximately 0.5. Thus, the endurance ratio of high-volume fly ash concrete is similar to that observed for fly ash-free concrete, as reported by other past investigations (5,6).

References

1. Nordby, G.M., "Fatigue of Concrete - A Review of Research," *ACI Journal*, Proceedings, Vol. 55, No. 2, Aug. 1958, pp. 191-220.

2. Murdock, J.W., "A Critical Review of Research on Fatigue of Plain Concrete," Engineering Experiment Station, Bulletin No. 475, University of Illinois, Urbana, Feb. 1965, 25 pages.

3. Lloyd, J.P., Lott, J.L., and Kesler, C.E., "Fatigue of Concrete," Engineering Experiment Station, Bulletin No. 499, University of Illinois, Urbana, 1968, 25 pages.

4. Raithby, K.D., and Whiffin, A.C., "Failure of Plain Concrete Under Fatigue Loading - A Review of Current Knowledge," Ministry of Transportation, RRL Report LR 231, Research Laboratory, Crowthorne, 1968.

5. Naik, T.R., Singh, S.S., and Ye, C., "Fatigue Behavior of Plain Concrete Made With or Without Fly Ash," A Progress Report Submitted to EPRI, March 1993.

6. Ramakrishnan, V., and Lokvik, B.J., "Fatigue Strength and Endurance Limit of Plain and Fiber Reinforced Concretes - A Critical Review, "Proceedings of the International Symposium on Fatigue and Fracture in Steel and Concrete Structures, Madras, India, 1991, pp. 381-407.

7. Ghosh, R.K., Sethi, K.L., and Arora, V.P., "Laboratory Studies on Lean Cement-Fly Ash Concrete as Construction Material," IRC Highway Research Board, No. 19, 1982, pp. 13-26.

8. Tse, E.W., Lee, D.Y., and Klaiber, F.W., "Fatigue Behavior of Concrete Containing Fly Ash," Proceedings of the Second International Conference on the Use of Fly Ash, Silica Fume, Slag, and Natural Pozzolans in Concrete, Madrid, Spain, V.M. Malhotra, Ed., Vol. 1, ACI Special Publication, SP-91, 1986, pp. 273-289.

9. Ramakrishnan, V., Malhotra, V.M., and Langley, W.S., "Comparative Evaluation of Flexural Fatigue Behavior of High Volume Fly Ash and Plain Concrete," Presented at the 70th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1991.

10. Ozaki, S., and Sugata, N., "Fatigue of Concrete Composed of Blast Furnace Slag or Silica Fume Under Submerged Conditions," Proceedings of the Fourth International Conference on the Use of Fly Ash, Silica fume, Slag, and Natural Pozzolans in Concrete, Istanbul, Turkey, V.M. Malhotra, Ed., Vol. II, ACI Special Publication, SP-132, May 1992, pp. 1509- 1524.

11. Naik, T.R., and Singh, S.S., "Fatigue Properties of Concrete With and Without Mineral Admixtures," Proceedings of the V.M. Malhotra Symposium on Concrete Technology - Past, Present and Future, P.K. Mehta, Ed., ACI SP-144, pp 269-288.

12. Aas-Jakobsen, K., "Fatigue of Concrete Beams and Columns," Bulletin No. 70-1, NTH Institute for Betonkonstruksjoner, Trondheim, Norway, Sept. 1970, 148 pages.

13. Tepfers, R., and Kutti, T., "Fatigue Strength of Plain, Ordinary, and Lightweight Concrete," *ACI Journal*, Proceeding Vol. 76, No. 5, May 1979, pp. 635-652.

14. Tepfers, R., "Tensile Fatigue Strength of Plain Concrete," *ACI Journal*, Proceeding, Vol. 76, No. 8, August 1979, pp. 919-933.

15. Oh, B.H., "Fatigue Analysis of Plain Concrete in Flexure," Journal of Structural Engineering, ASCE, Vol. 112, No. 2, Feb. 1986, pp. 273-288.

16. Oh, B.H., "Fatigue-Life Distribution of Concrete for Various Stress Levels," *ACI Materials Journal*, Vol. 88, No. 2, March-April 1991, pp. 122-128.

17. Hsu, T.T.C., "Fatigue of Plain Concrete," *ACI Journal*, Proceeding Vol. 78, No. 4, July-August 1981, pp. 292-305.

Table 1

Physical and Chemical Properties of Portland Cements

Property	**Cement S** **Type 1** **(low alkali)**	**Cement G** **Type 1** **(high alkali)**
Physical Properties:		
Fineness: Passing 45 μm, %	93.6	94.9
Blaine, m^2/kg	371	376
Specific Gravity	3.14	3.14
Compressive Strength (ASTM C 109) of 51-mm Mortar Cubes, MPa		
3 days	21.2	31.5
7 days	31.5	34.5
28 days	45.0	41.9
Chemical Composition (Mass %)		
SiO_2	21.16	19.20
Al_2O_3	4.75	5.79
Fe_2O_3	3.65	2.03
CaO	64.99	63.48
MgO	1.24	2.52
Na_2O	0.07	0.33
K_2O	0.18	1.16
TiO_2	0.31	0.28

MnO	0.02	0.06
P_2O_5	0.10	0.10
SO_3	2.27	3.50
LOI	1.11	2.61
Compound (Bogue) composition:		
C_3S	65.37	63.65
C_2S	11.35	7.03
C_3A	6.41	11.91
C_4AF	11.11	6.18
$CaCO_3$ (TGA)	0.52	3.02
CSH_2 (QXRD)	4.4	4.0

Table 2

Physical and Chemical Properties of Fly Ash

Property	**Fly Ash***			
	Montour (M)	**Bowen (B)**	**Leland Olds (LO)**	**Gibson (G)**
Physical Properties:				
Fineness (% -45 µm)	70.2	79.5	74.5	84.5
Blaine (m^2/kg)	283	224	240	285
Density (g/cm^3)	2.36	2.26	2.48	2.42
Pozz. activity with PC:				
PC G 7d	86.4	83.1	89.5	89.7
28d	91.2	90.5	94.6	99.0
PC S 7d	81.4	80.4	87.1	91.4
28d	88.6	89.9	87.9	91.5
Chemical Composition (%):				
SiO_2	49.02	53.64	46.20	48.87
Al_2O_3	26.69	27.42	15.60	21.12
Fe_2O_3	12.31	7.74	7.70	16.75
CaO	2.37	2.88	14.93	4.49
MgO	0.95	0.99	4.34	1.09
Na_2O	0.21	0.38	5.52	1.43
K_2O	2.34	2.42	1.86	2.40
SO_3	0.77	0.37	1.72	1.85
Carbon	1.65	1.04	0.16	0.28

Mineralogical Composition (%):				
Glass	68 (GI)	64 (GI)	85 (GII)	77 (GI)
Quartz (Qz)	5	6	5	5
Mullite (Mu)	24	29	0	13
Ferrite/Spinels (Sp)	1	1	4	2
Hematite (Hm)	2	1	0	3
Other	--	--	Pc,Mw	Lm

* The letter(s) in each bracket show abbreviated name for the corresponding fly ash source.

** GI/GII = aluminaocilicate glass (glass I or glass II); P_c = periclase; M_w = merwinite; L_m = lime.

Table 3

Mixture Proportions and Properties of Freshly-Mixed Concrete for Mix No. 1 (EP1F) through Mix No. 8(EP8F)

Mix No.	W/(C+FA)	Water (kg/m^3)	Cement Type	Cement (kg/m^3)	Fly Ash Source*	Fly Ash (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	AEA** (mL/m^3)	SP*** (L/m^3)	Slump (mm)	Unit Weight (Kg/m^3)	Entrained Air (%)	28-day f'c (MPa)
1	0.33	120	S	154	M	213	1198	645	405	4.6	125	2230	5.9	32.2
2	0.33	121	G	154	M	214	1210	650	250	4.6	120	2360	4.8	38.0
3	0.33	120	S	153	B	212	1197	641	800	4.0	210	2330	4.5	28.5
4	0.33	120	G	152	B	211	1190	638	485	3.9	160	2320	5.5	33.6
5	0.33	119	S	152	LO	212	1206	648	75	1.3	125	2360	5.0	37.7
6	0.33	119	G	153	LO	212	1205	648	65	2.0	85	2345	5.5	36.8
7	0.33	120	S	153	G	212	1205	647	305	4.1	150	2345	5.2	34.5
8	0.33	120	G	154	G	214	1216	653	160	3.7	125	2370	5.0	41.0

* Four different sources of fly ash were used. Their properties are shown in Table 2.

** Air-Entraining Admixture

*** Superplasticizer

Table 4

Static Flexure Strength After Fatigue Testing of Mixtures

Mix No. (1)	Specimen No. (2)	Maximum Stress in Fatigue (psi), f max (3)	$\frac{f_{max}}{f_r}$* (4)	Static Flexure Stress Before Fatigue (psi), fr ** (5)	Static Flexure Stress After Fatigue (psi), fr1** (6)	Change in Stress, Percent (6) - (5)
EP1F & EP1G	EP1F-10	430	0.39	1092	1055	-3.39
EP2F	EP2F-12	468	0.40	940	799	-15.00
	EP2F-13	374	0.40	940	714	-24.04
	EP2F-14	373	0.40	940	627	-33.30
	EP2F-15	379	0.40	940	657	-30.11
	EP2F-16	374	0.40	940	665	-29.26
	EP2F-17	378	0.40	940	665	-29.26
EP3F	EP3F-8	454	0.61	750	738	-1.60
	EP3F-11	378	0.50	750	580	-22.67
	EP3F-12	383	0.51	750	666	-11.20
	EP3F-14	337	0.45	750	583	-22.27
	EP3F-15	347	0.46	750	639	-14.80

	EP3F-16	340	0.45	750	655	-12.67
EP4F	EP4F-11	432	0.58	747	706	-5.49
	EP4F-13	410	0.55	747	723	-3.21
	EP4F-14	405	0.54	747	694	-7.10
	EP4F-15	375	0.50	747	604	-19.14
	EP4F-16	375	0.50	747	785	+5.09
	EP4F-18	412	0 .55	747	730	-2.28

Table 4 (Cont'd)

Static Flexure Strength After Fatigue Testing of Mixtures

Mix No. (1)	Specimen No. (2)	Maximum Stress in Fatigue (psi), f max (3)	$\frac{f_{max}}{f_r}$ * (4)	Static Flexure Stress Before Fatigue (psi), fr ** (5)	Static Flexure Stress After Fatigue (psi), fr1 ** (6)	Change in Stress, Percent (6) - (5)
EP5F	EP5F-8	540	0.61	884	838	-5.20
	EP5F-12	490	0.55	884	813	-8.03
	EP5F-13	487	0.55	884	745	-15.72
	EP5F-14	445	0.50	884	795	-10.07
	EP5F-15	443	0.50	884	807	-8.71
	EP5F-17	446	0.50	884	755	-14.59
EP6F	EP6F-12	441	0.51	871	694	-20.32
	EP6F-13	430	0.49	871	809	-7.12
	EP6F-14	394	0.45	871	720	-17.34
	EP6F-16	435	0.50	871	813	-6.66
	EP6F-17	441	0.51	871	803	-7.81
EP7F	EP7F-13	440	0.50	878	731	-16.74
	EP7F-14	442	0.50	878	726	-17.31
	EP7F-15	439	0.50	878	743	-15.38
	EP7F-17	437	0.50	878	696	-20.73

EP8F	EP8F-12	491	0.55	885	820	-7.34
	EP8F-14	444	0.50	885	802	-9.38
	EP8F-15	491	0.55	885	773	-12.66
	EP8F-16	485	0.55	885	744	-15.93
	EP8F-17	444	0.50	885	657	-25.76

* f max= maximum flexural fatigue stress at 2 million cycles of loading.

** fr and fr1 are static flexural strengths before and after fatigue testing, respectively.