Fatigue Strength of Roller Compacted Concrete

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INTRODUCTION

Current interest in Roller Compacted Concrete (RCC) was, in part, initiated by the placement of pavements in British Columbia, Canada nearly 13 years ago. This pioneer paving application consisted of a dockside storage area for the forest industry (1), at that time the pavement was designed as a slab for a given maximum load. A significant number of similar applications followed. In many instances, the similarities of RCC with cement-treated bases and soil-cement has been considered. For thickness design and construction of RCC pavements, a combination of criteria from specifications of various existing materials has been used.

The definition of RCC is based on its consistency, with no specific requirements on strength. According to ACI Committee 207.5R (2):

> Roller Compacted Concrete is a dry concrete material which has been consolidated by external vibration ..., RCC must be dry enough to support the weight of the vibratory equipment, but wet enough to permit adequate distribution of the paste binder throughout the mass during the mixing and vibration process.

It is difficult to draw a clear line to distinguish between what is known as lean concrete and roller compacted concrete. Figure 1 gives an idea of the place RCC takes among portland cement bound materials. In general, a cement treated base (lean concrete) has less cement than RCC and requires surface protection against traffic abrasion, while RCC is rich enough to yield equal or better strength than Conventional Concrete (CC), needing no surface protection.

For pavement design, there are still some questions about the structural strength and fatigue characteristics of RCC. Although the experiences on the performance of RCC under heavy traffic and severe environment conditions have been satisfactory (3). Laboratory information on durability of RCC helps to predict field performance. Laboratory results on attempts to improve the durability of RCC by air entraining a cement mortor prior to the addition of coarse aggregate are presented in this paper. Also some strength correlations are presented to give a more complete view of the RCC properties.

STATEMENT OF THE PURPOSE

The purpose of this laboratory investigation was to compare some of the fatigue characteristics of roller compacted concrete and conventional concrete, under the same testing conditions.

The flexural fatigue life of RCC was examined based on load stress history, and compared with that of CC prepared with the same aggregates and cement content but having a measurable slump.

LITERATURE REVIEW

At the time this research was initiated, there were no publications available that dealt with fatigue of roller compacted concrete. Little has been reported on the subject. On the other hand, no major failures of existing RCC pavements have been reported. Therefore, literature on conventional concrete was reviewed essentially to consider the factors that have been found to be important in determining the flexural fatigue properties of plain concrete. The reason for choosing this option was based on previous investigations, which are part of this research. The results reported elsewhere indicated that the elastic properties of RCC seem not to be different from those that can be achieved with a conventional concrete.

Klaiber and Lee (4), reported work involving testing over 350 beams of plain concrete for fatigue using third point loading. Among the factors studied, air content and coarse aggregate type were determined to have the greatest effect. Water-cement ratio was found to be less significant and the type of fine aggregate was not significant. They also reported that concrete made with crushed limestone had lower fatigue life than concrete made with gravel, but concluded that at lower levels of stress, the difference in fatigue strength between concrete made with limestone and concrete made with gravel did not seem to be significant.

Murdock and Kesler (5) were not able to find any fatigue limit, a stress level below which no failure will occur regardless of the number of cycles of loading, for plain concrete at low stress levels. This agrees with ACI Committee 215R-74 (6), in the sense that fatigue limit is not mentioned in its 1981 revised report. Fatigue strength of concrete for a life of 10 million cycles for compression, tension or flexure is roughly about 55 percent of static strength.

Award and Hilsdorf (7), found that at higher stress levels, a reduction of frequency of testing results in a significant reduction

of the fatigue life of the concrete. However, for lower stress levels (less than 75 percent of static strength), ACI Committee 215 (6) reports that according with several investigations, frequencies in the range 1.2-15 hertz (Hz.) have little effect on the fatigue life.

More recently (8), fibers were added to RCC for a composite beam with the idea of "enhancing" fatigue life. However, no final conclusion was reached as to whether the fatigue improvements on the composite section studied were due to the presence of the fiber reinforcement, or the RCC construction.

EXPERIMENTAL INVESTIGATION

Cyclic Loading Pattern

In the investigation reported herein, a constant amplitude and frequency were maintained throughout the fatigue tests. The amplitude characterized the maximum and minimum stress levels as percentages of the ultimate static flexural strength of the beams. Figure 2 illustrates the cyclic loading utilized, where: S_{max} is the maximum stress during the test; S_{min} is the minimum stress; A is the amplitude of loading, T is the period of the cycle, considered as 1/f where f is the frequency of loading normally expressed in hertz or cycles per second, and r is the stress range factor. The loading pattern was sinusoidal.

The stress levels utilized were 60, 80, 85 and 90 percent of the modulus of rupture and the stress range factor S_{min}/S_{max}, was 0.20, maintaining the bottom fibers of the beams always in tension. All fatigue tests were carried out by controlling the load, therefore, all the stresses were converted into loads for operational purposes.

Laboratory Mixes

The mix proportions, two for RCC and two for CC, are presented in Table 1. The RCC mixes were designed following recommendations of ACI Committee 207 (2), since it was the most extensive reference at the time this research was initiated.

As shown in Table 1, the cement content of RCC and CC were the same for mixes made with the same aggregate size. The water to cement ratio was 0.30 for both roller compacted concretes, and 0.53 for the conventional concretes. The constant cement content resulted in the w/c of conventional concrete exceeding that of normal practice. Normal practice would have a cement factor sufficient to provide a w/c of 0.45 or less.

The conventional concrete mixtures were prepared with slumps of about 1-1/2 inches and Vebe times of about 4 sec. The roller compacted concrete mixtures were prepared with zero slumps and Modified Vebe times of about 55 sec., with 16 lb. surcharge on the regular Vebe set.

Laboratory simulation of roller compaction was accomplished in the following manner. From each batch, two 6x6x21 in. beams were consolidated on the vibratory table of the Vebe apparatus, with the aid of a 50 lb. surcharge. Modifications were made for fastening the beam molds to the vibratory table to assure good transmission of vibration. The beams were removed from the molds after 24 hours of initial curing, and then placed in a water bath box at $35 \pm 3°$ C for 24 hours. Subsequently, the samples were stored in a moist room for two additional weeks. The curing procedure adopted was predicated on obtaining an equivalent 28 day strength in a shorter time because of restrictions on equipment availability.

Each of the pair of beams was assigned a number. Beam 1 was tested to determine the modulus of rupture in psi, at third-point loading according to ASTM C78, and beam 2 was tested in fatigue at a selected stress level. The stress level for beam 2 was always a percentage of the modulus of rupture obtained with beam 1.

Equipment

Testing was conducted with an MTS control unit 458.20 capable of controlling displacement or load, MTS actuator with LVDT and load cell, and loading frame. Figure 3 shows the control unit which also has a digital function generator that can generate various types of cyclic waveforms. The main control panel can store and display the number of cycles at any time and maximum (valley) and minimum (peak) loads. Excessive load variations in the fatigue test were controlled by a programmable interlock system that regulates the maximum and minimum of the loading wave within limits. Whenever these limits are exceeded the program stops and the hydraulic pressure is shut down.

The MTS controller adjusts the load for both static and cyclic loadings according to the signals received. Considerable preliminary testing was done with trial specimens to optimize the signals to generate the required amplitudes of loading.

Figure 4 shows the fatigue testing apparatus and a failed RCC beam.

The Experiment

Factors and Levels. The following factors were considered in the study:

1. Type of Mix (M), includes two levels: roller compacted concrete, RCC, and conventional concrete, CC.
2. Aggregate size (A), includes two levels: 1/2 in. and 1 in. maximum size.
3. Level of stress (S), includes four levels: 60, 80, 85, and 90 percent of the modulus of rupture.

Unless otherwise specified, three replications at random were run per treatment combination, Table 2 presents the experimental layout.

Response Variable. The response variable considered was the number of cycles at failure (n). The logarithm to the base ten, logn, causes the results to be more normally distributed. Fatigue results are often characterized by scatter. The amount of scatter may be significant even for materials more homogeneous than concrete such as steel.

Statistical Model. The statistical model of the experiment (9) can be represented as:

$$Y_{(ijk)1} = \mu + M_i + A_j + MA_{ij} + S_k + MS_{ik} + AS_{jk} + MAS_{ijk} + \varepsilon_{(ijk)1}$$

where:

$i = 1,2$, $j = 1,2$ and $k = 1,2,3,4$ represent the levels of each factor.

$Y_{(ijk)1}$ is the response per specimen tested,

μ is the overall mean,

M_i, A_j, S_k are the effects of individual factors,

MA_{ij}, MS_{ik}, AS_{jk}, MAS_{ijk} are the interactions among factors, and

$\varepsilon_{(ijk)1}$ represents the experimental error.

FATIGUE EVALUATION OF RCC

Statistical Analysis

The results of the experiment are summarized in Table 3. An Analysis of Variance (ANOVA) was run on the dependent variable, log n, according to the model given in Equation 1. The ANOVA results are presented in Table 4.

From ANOVA,

1. Among the factors studied, only the level of stress (S) had significant effects at an α level of 0.0001.
2. Neither the type of concrete nor the maximum size of aggregate had any significant effects on the fatigue life.
3. None of the interactions among the factors studied were significant.

To compare the fatigue life of RCC and CC, the stress ratio (R) is plotted in Figures 5 and 6 against the logarithm of the Number of cycles to failure (n) for RCC and CC respectively. The stress ratio, R, is the maximum stress (S_{max}) over the modulus of rupture (MR). R eliminates the strength and age differences between beams and in this case, had better correlation with the dependent variable. Comparing the plots, it can be seen that RCC and CC seem to have similar fatigue lives under similar test conditions. Furthermore, the slopes of the lines fitted to the data are statistically equal according to an F test (10).

However, the S-N curve presented in Figure 7, where only the maximum stress (S_{max}) is plotted against the number of cycles to failure (log n), shows that RCC at a given stress level would be expected to have a longer fatigue life than CC. Another interpretation could be that for the same fatigue life (n), RCC would be capable of taking a greater stress amplitude (more load) than CC.

The mode of failure for RCC and CC are depicted in Figures 8, 9 and 10, where the strain at the extreme fibers was plotted against the number of cycles. Electrical resistance strain gages four times larger than the maximum aggregate size, were epoxy bonded longitudinally to beams to monitor strain during some of the tests. These figures indicate that the strain increased with the number of cycles and asymptotically approaches a level of cycles to failure. During the fatigue test, the progressive deflection under constant stress played an important role in the shift of the neutral axis of the cross section of the beam. Presumably, the first crack suggests that failure is imminent. The results shown in Figures 7 to 10 suggest that for an equal fatigue life, RCC withstood higher flexural stresses and strains than CC.

Strength Correlations

From each broken beam tested to obtain the modulus of rupture, one piece was used for a compression test (ASTM C116), and the other piece was used to run two indirect tensile tests (11) from which the average was considered. The strength results are presented in Table 5. Although no satisfactory equation to predict the modulus of rupture was found (low correlation coefficients). Figures 11 and 12 obtained with a regression program, could be used to estimate roughly the modulus of rupture when either the compressive, or the splitting stress are known.

The compressive strength of the modified cubes, were found to be slightly higher than those of 6x12 in. cylinders, made with the same mix proportions and the same consolidation procedure. The latter was reported elsewhere.

Frost Protection

Roller compacted concretes with and without air entraining admixtures were subjected to ASTM C666, "Resistance of Concrete to Rapid Freezing and Thawing". Both methods A, freezing and thawing in water and B, freezing in air and thawing in water were considered.

Concrete was made with 1/2 in. maximum aggregate size as a key element in creating an acceptable void system. With small aggregate, more paste is needed per unit volume of concrete, and there is a better chance to create air bubbles.

Three air entrainment admixtures were used, namely: Micro-air (Mi), Vinsol resin (Vr) and a non commercial admixture designated as Jm. Once all brands had entrained about the same volume of air in a control mortar mix, and a void system was created in the concrete, the amount of admixture was fixed. Nine fluid ounces per one hundred pounds of cement was the dosage determined for all brands. The air void system in RCC is first created in the mortar component. Mixing was accomplished in a Lancaster Counter Current Batch Mixer. Microscopic observations of polished sections of concrete detected the void system.

The results of the experiment studying the frost protection are summarized in Figure 13, the histogram for both methods of ASTM C666 displays the average Durability Factor for the mixes involved. The mixes designated as I, II and III had water to cement ratios of 0.30, 0.40 and 0.50 respectively. The experiment included control mixes with no admixture. These were designated as "No". It can be seen that mixes without admixture had the lower averages.

A statistical analysis of the results indicated that among the factors studied, only the type of admixture resulted in significant effects. Significant differences existed between mixes with no admixture (control), and those with admixture. However, no significant differences existed among mixes with admixture.

Figure 14 tabulates the relationship observed for strength, density and workability. Although no new relationships were found, it is noted that the density for the wettest air-entrained RCC was about 145 lb/cu.ft., with a cement consumption slightly over 3 sacks per cubic yard. Similar densities can be obtained with a conventional air entrained concrete with about 6 sacks per cubic yard. Therefore, relatively high densities can be reached with RCC by packing more aggregate per unit volume. However this will require frost resistant aggregate when freezing and thawing is a problem. In this investigation a local pit-run gravel was used which was rated as fair considering freezing and thawing. It is believed that the rather low durability factors reported reflect aggregate failures with the specimens.

SUMMARY OF FINDINGS

When the fatigue behavior of roller compacted concrete and conventional concrete were compared under the same testing conditions, and with the same cement content per unit volume of concrete, it was concluded that:

1. The fatigue life of RCC and CC seem to be similar at upper and lower levels of the stress ratio (R).
2. RCC would have a longer fatigue life if subjected to the same level of stress (S) than CC when each has the same cement content. Similar fatigue life could be obtained with a lower cement factor for RCC than for CC.
3. The fatigue mode of failure of RCC is similar to that of CC.

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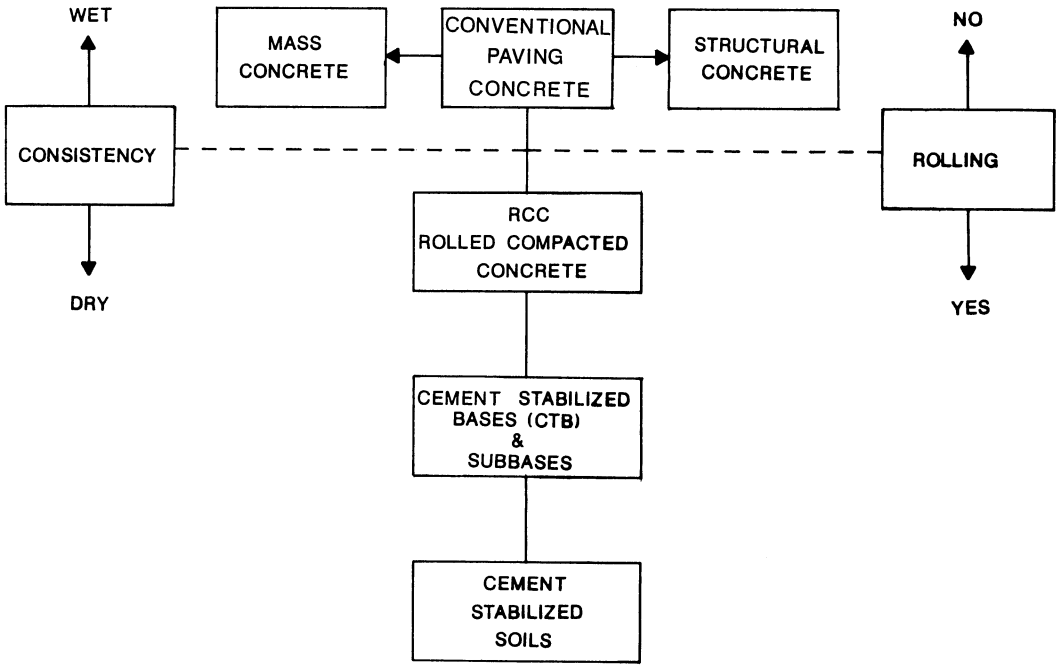


Figure 1 Place of RCC in Cement Bound Constructing Materials.

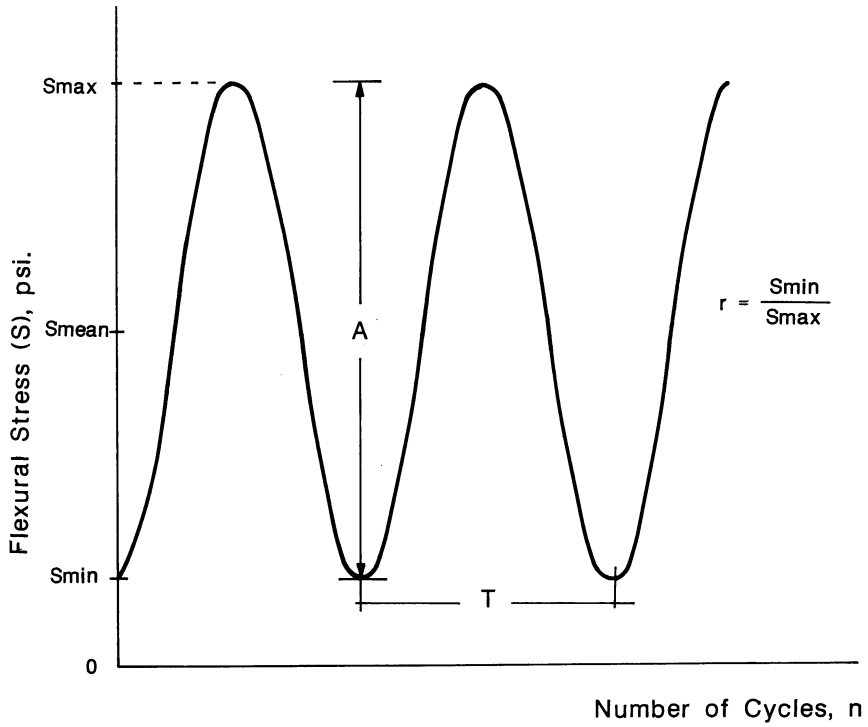


Figure 2 Cyclic Loading, Definition of Loading Parameters in Fatigue Tests.

Table 1. Mix proportions for Roller Compacted Concrete (RCC), and Conventional Concrete (CC) for Fatigue Tests, in lb/cu. yd.

RCC		CC	
Gravel size		Gravel size	
1/2 in.	1 in.	1/2 in.	1 in.
c = 475	c = 393	c = 475	c = 393
w = 143	w = 118	w = 251	w = 208
s = 1244	s = 1028	s = 1530	s = 1464
g = 2287	g = 2689	g = 1870	g = 2050

Notes:

RCC = roller compacted concrete
CC = conventional concrete
c = cement
w = water
s = sand
g = gravel

The aggregate is in dry condition

Table 2 Experimental Layout for Fatigue Tests.

Stress Level (S) % MR	RCC Aggregate size (A) 1/2 in.	RCC Aggregate size (A) 1 in.	CC Aggregate size (A) 1/2 in.	CC Aggregate size (A) 1 in.
90	1, 2, 3	, ,		
85	, ,			
80				, ,
60			, ,	1, 2, 3

Notes:

RCC = roller compacted concrete
CC = conventional concrete
MR = modulus of rupture

Table 3 Data for Analysis of Variance of RCC and CC

SAS

Obs	Typeconc	Aggsize	Levstres	Ncycles	Logn	Stress	Percmr
1	1	1	1	133	2.124	730	90
2	1	1	1	11	1.041	785	90
3	1	1	1	32	1.505	750	90
4	1	1	2	263	2.420	645	85
5	1	1	2	516	2.713	705	85
6	1	1	2	150	2.176	770	85
7	1	1	3	175	2.243	730	80
8	1	1	3	7645	3.883	625	80
9	1	1	3	292	2.465	695	80
10	1	1	4	287316	5.458	445	60
11	1	1	4	1223159	6.087	395	60
12	1	1	4	2616727	6.418	495	60
13	2	1	1	346	2.539	505	90
14	2	1	1	160	2.204	610	90
15	2	1	1	65	1.813	630	90
16	2	1	2	134	2.127	555	85
17	2	1	2	69	1.839	520	85
18	2	1	2	538	2.731	495	85
19	2	1	3	298	2.474	545	80
20	2	1	3	23438	4.370	530	80
21	2	1	3	639	2.806	490	80
22	2	1	4	1258920	6.100	375	60
23	2	1	4	1584900	6.200	375	60
24	2	1	4	398100	5.600	400	60
25	1	2	1	349	2.543	635	90
26	1	2	1	640	2.806	615	90
27	1	2	1	84	1.924	745	90
28	1	2	2	514	2.711	625	85
29	1	2	2	152	2.182	780	85
30	1	2	2	58	1.763	610	85
31	1	2	3	165	2.217	575	80
32	1	2	3	1490	3.173	640	80
33	1	2	3	1898	3.278	660	80
34	1	2	4	1873062	6.273	490	60
35	1	2	4	77870	4.891	460	60
36	1	2	4	1061880	6.026	495	60
37	2	2	1	444	2.647	445	90
38	2	2	1	275	2.439	565	90
39	2	2	1	79	1.898	450	90
40	2	2	2	232	2.365	550	85
41	2	2	2	99	1.996	405	85
42	2	2	2	40	1.602	535	85
43	2	2	3	339	2.530	525	80
44	2	2	3	1923	3.284	410	80
45	2	2	3	543	2.735	450	80
46	2	2	4	2982400	6.475	305	60
47	2	2	4	1379451	6.140	305	60
48	2	2	4	100000	5.000	340	60

SAS

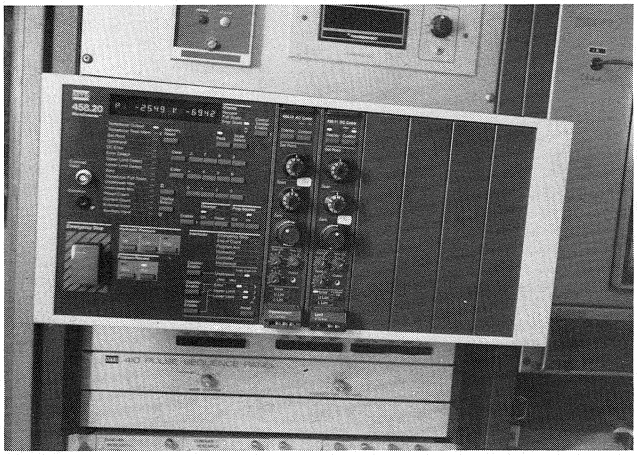


Figure 3 MTS Control Unit for Fatigue Tests.

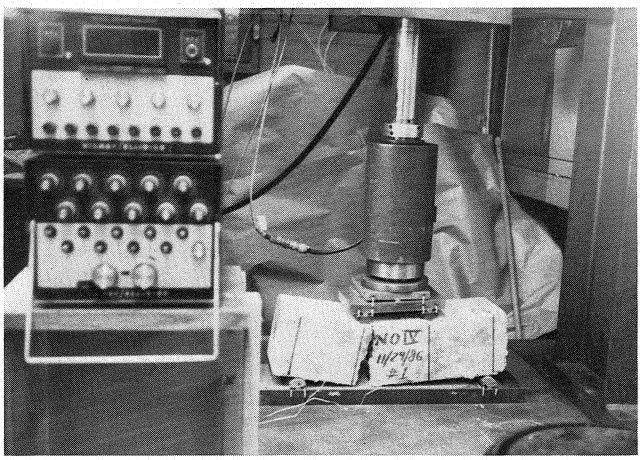


Figure 4 Fatigue Failure of RCC Beam and Equipment.

Table 4 Analysis of Variance for Fatigue of RCC and CC

Analysis of Variance Procedure

Class Level Information

Class	Level	Values
TYPECONC	2	1 2
AGGSIZE	2	1 2
LEVSTRES	4	1 2 3 4

Number of Observations is Data Set = 48

SAS

Analysis of Variance Procedure

Dependent Variable: LOGN

Source	DF	Sum of Squares	Mean Square	F Value
Model	15	114.57666458	7.63844431	23.39
Error	32	10.45078533	0.32658704	PR > F
Corrected Total	47	125.02744992		0.0001

R-Square	C.V.	ROOT MSE	LOGN Mean
0.916412	17.3357	0.57147795	3.29654167

Source	DF	ANOVA SS	F Value	PR F
TYPECONC	1	0.05293408	0.16	0.6899
AGGSIZE	1	0.00399675	0.01	0.9126
TYPECONC*AGGSIZE	1	0.18081075	0.55	0.4623
LEVSTRES	3	112.50085108	114.82	0.0001
TYPECONC*LEVSTRES	3	0.38607242	0.39	0.7581
AGGSIZE*LEVSTRES	3	1.10255908	1.13	0.3534
TYPEC*AGGSI*LEVST	3	0.34944042	0.36	0.7846

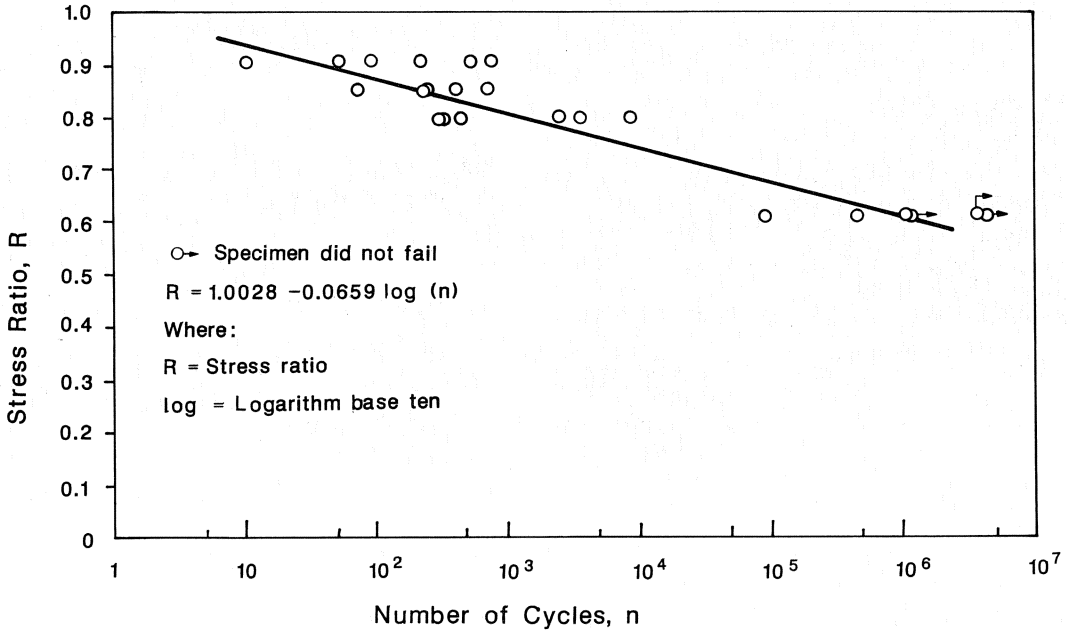


Figure 5 Fatigue Life of Roller Compacted Concrete.

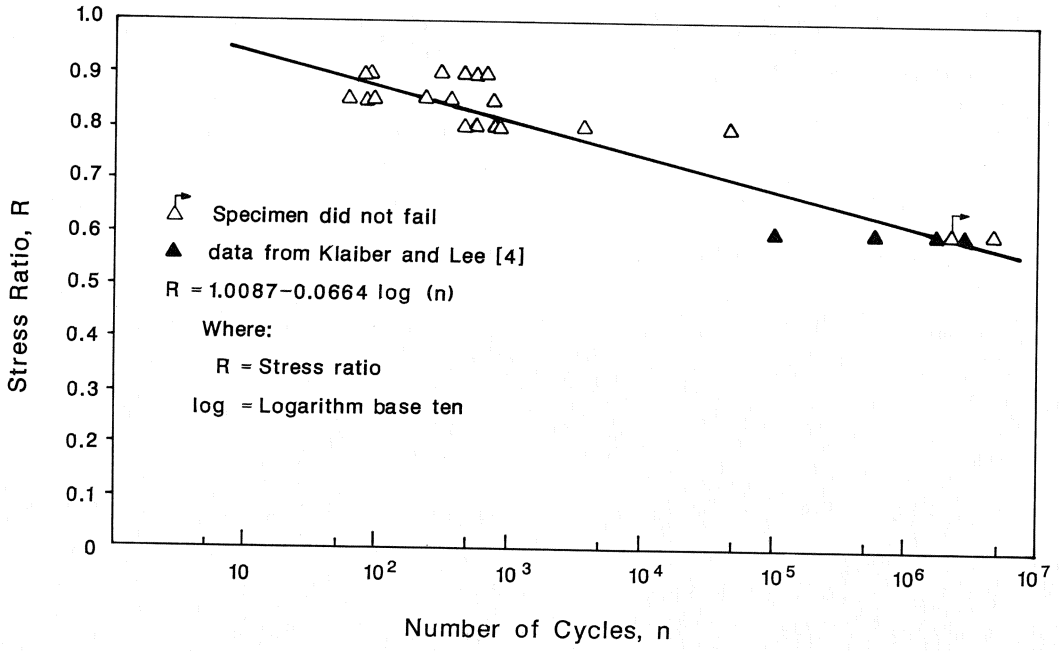


Figure 6 Fatigue Life of Conventional Concrete.

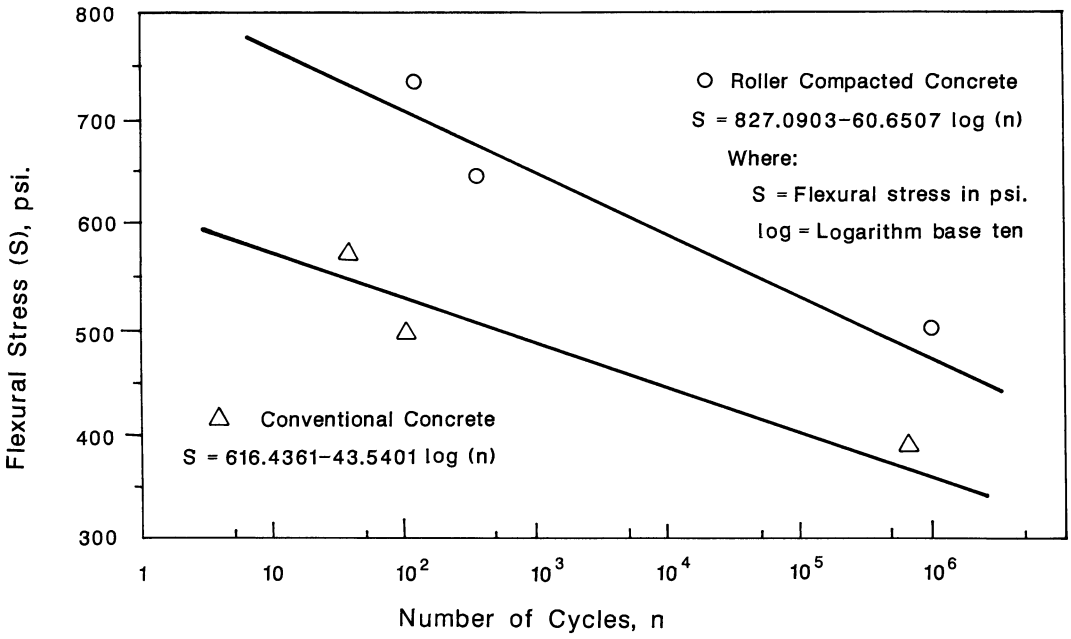


Figure 7 Effect of Maximum Flexural Stress on the Fatigue Life of RCC and CC, with Equal Cement Factors.

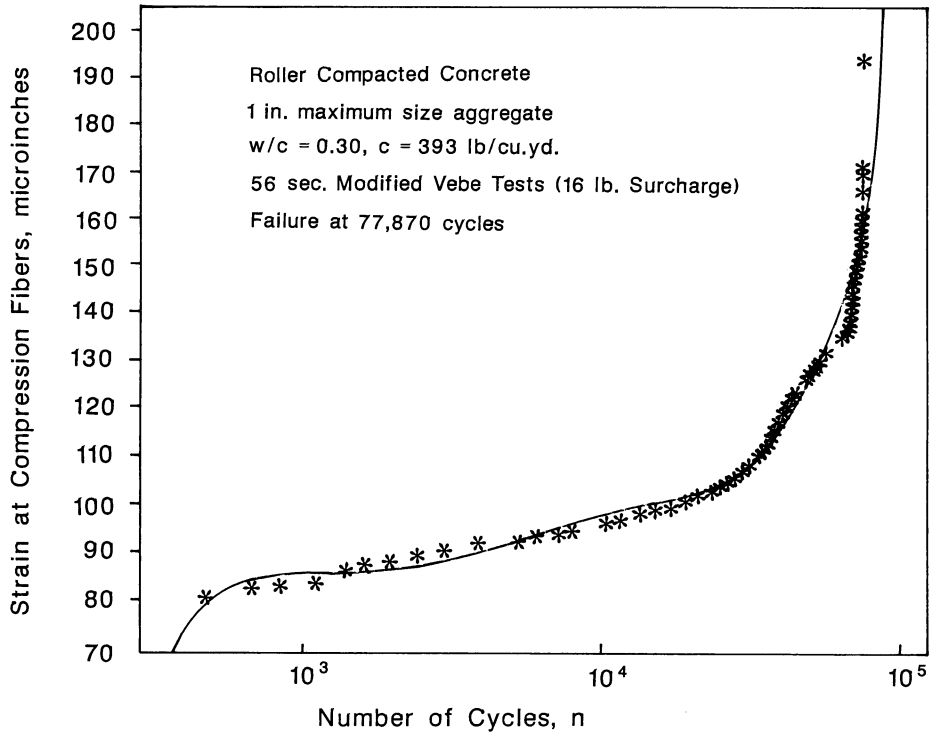


Figure 8 Strain Vs. Number of Cycles on Fatigue of a Roller Compacted Concrete Beam, Replicate 1.

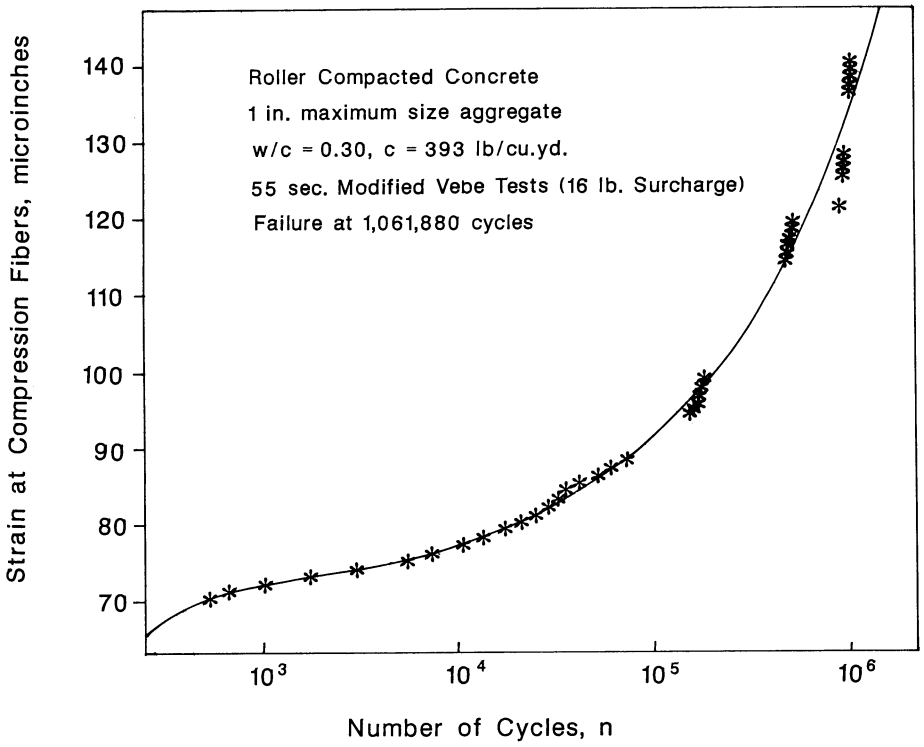


Figure 9 Strain Vs. Number of Cycles on Fatigue of a Roller Compacted Concrete Beam, Replicate 2.

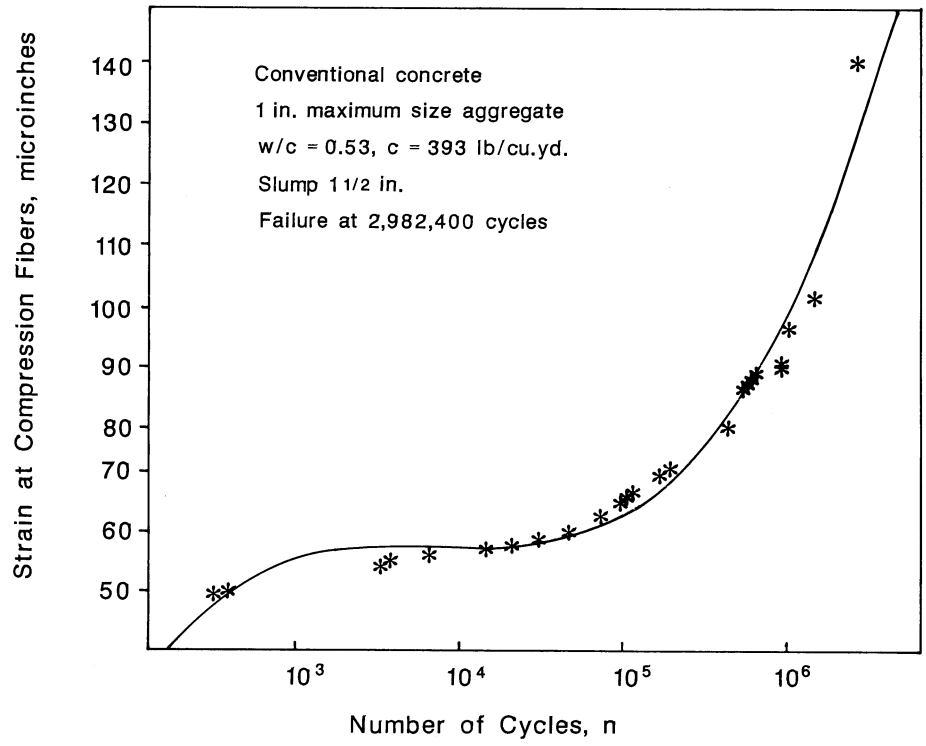


Figure 10 Strain Vs. Number of Cycles on Fatigue of a Conventional Concrete Beam.

Table 5 Strength Results for RCC and CC, psi

OBS	MIX	STRENGTH	MRUPTURE	SPLITCUB
1	RCC 1"	6560	800	550
2	RCC 1"	6350	685	525
3	RCC 1"	6930	755	680
4	RCC 1/2"	7420	810	685
5	RCC 1/2"	6220	816	830
6	RCC 1/2"	8110	780	860
7	RCC 1"	9500	705	685
8	RCC 1"	8580	720	750
9	RCC 1/2"	8050	870	870
10	RCC 1/2"	8000	760	745
11	RCC 1"	8110	800	735
12	RCC 1/2"	8230	835	750
13	RCC 1/2"	8360	830	680
14	RCC 1"	8140	655	670
15	RCC 1/2"	9060	905	765
16	RCC 1/2"	8470	890	700
17	RCC 1"	8330	830	840
18	RCC 1"	7750	825	805
19	RCC 1/2"	8190	740	700
20	RCC 1/2"	9490	870	780
21	RCC 1"	7850	720	800
22	RCC 1/2"	8360	730	660
23	RCC 1"	6830	650	750
24	RCC 1"	8320	820	655
25	RCC 1"	7150	765	780
26	CC 1/2"	3100	530	385
27	CC 1"	2930	445	410
28	CC 1"	4845	520	540
29	CC 1"	5030	760	640
30	CC 1/2"	5290	680	650
31	CC 1"	5780	730	645
32	CC 1"	4400	655	555
33	CC 1"	4780	645	515
34	CC 1/2"	4360	635	500
35	CC 1/2"	5850	655	555
36	CC 1"	5140	630	550
37	CC 1/2"	5610	665	630
38	CC 1/2"	5170	610	530
39	CC 1"	4670	510	530
40	CC 1"	4170	500	470
41	CC 1/2"	4320	615	455
42	CC 1/2"	4960	580	495
43	CC 1/2"	5600	700	495
44	CC 1"	4790	495	485
45	CC 1"	5230	565	455
46	CC 1"	4350	510	515

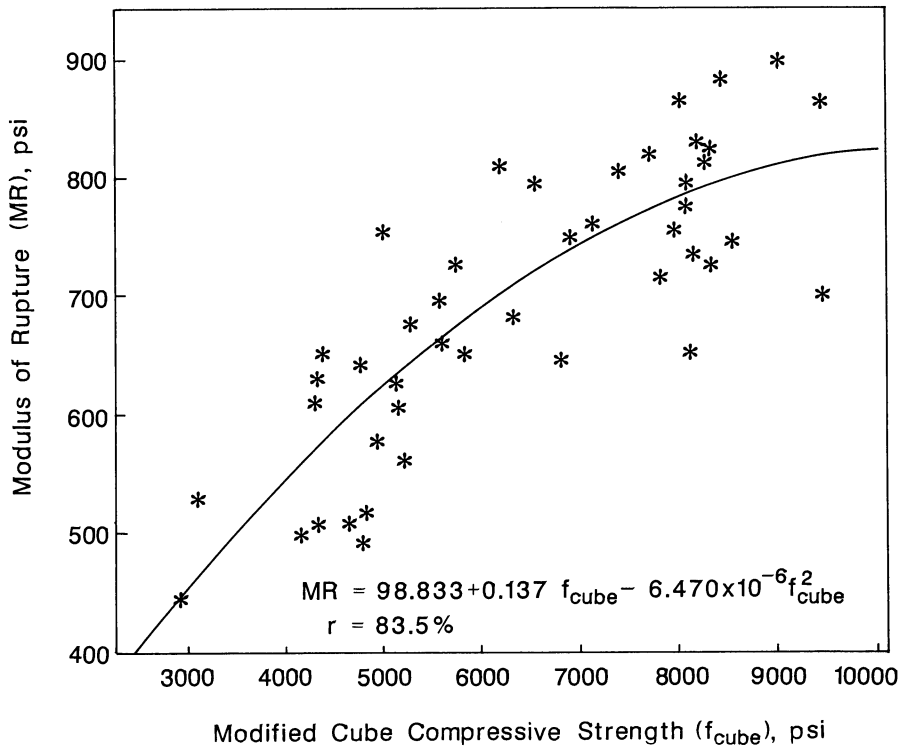


Figure 11 Relationship Between Modulus of Rupture and Modified Cube Strength. (Includes both RCC and CC Specimens.)

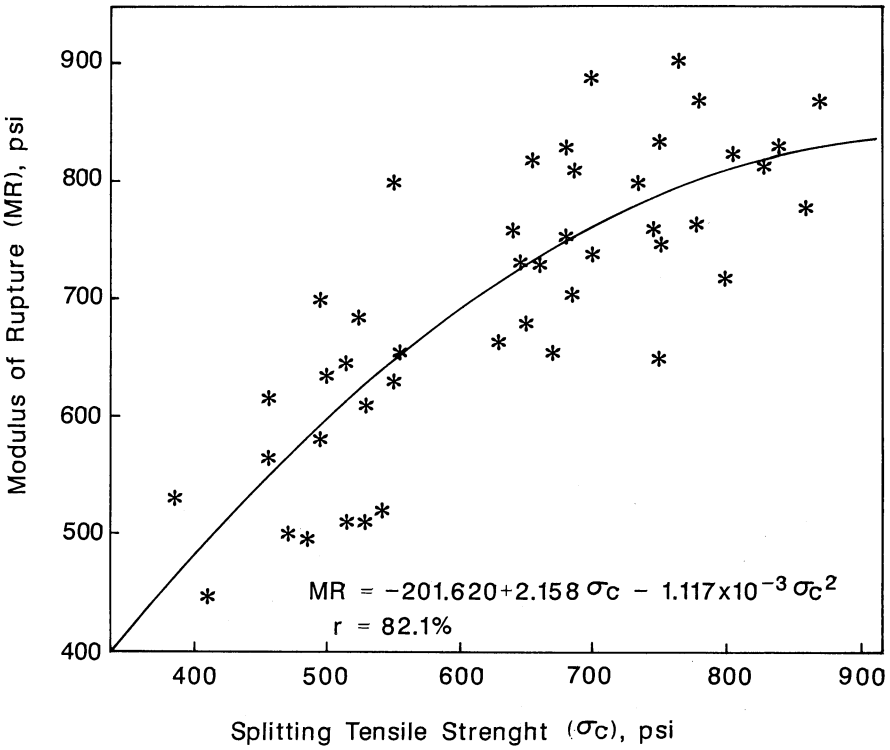


Figure 12 Relationship Between Modulus of Rupture and Splitting Tensile Strength (Modified Cubes). (Includes both RCC and CC Specimens.)

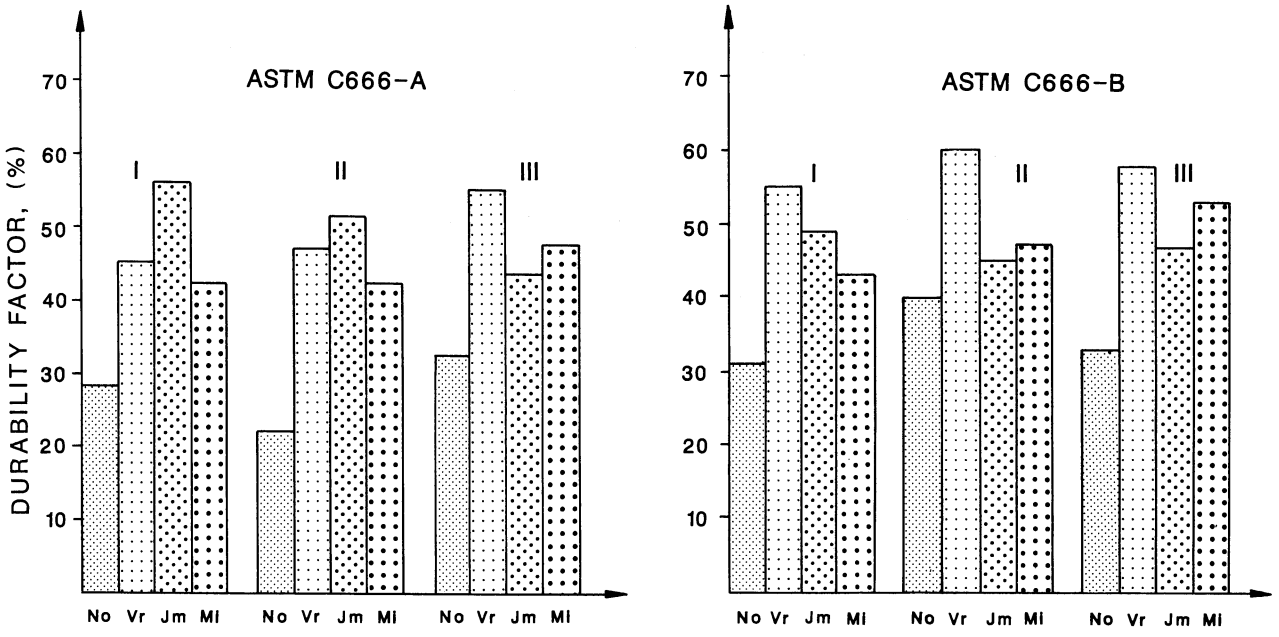
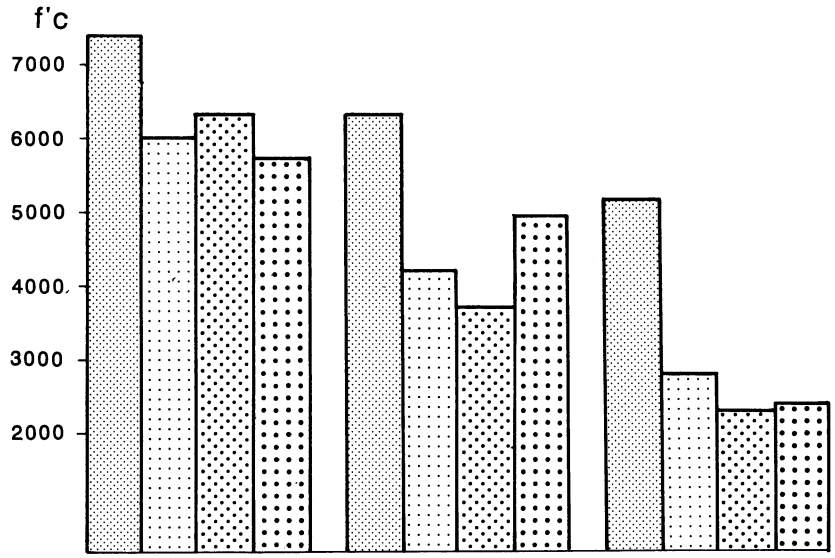


Figure 13 Average Durability Factor for all RCC Mixes. (Durability Factor Based upon 300 Cycles of Freezing and Thawing for a Complete Test.)



	No I	Vr I	Mi I	Jm I	No II	Vr II	Mi II	Jm II	No III	Vr III	Mi III	Jm III
f'c	7560	6060	6400	5760	6410	4270	3790	5020	5210	2780	2400	2500
Density	156.5	151.6	152.5	151.4	154.9	148.1	149.2	149.1	154.2	145.8	145.2	145.8
Mod.Vebe	50	17	22	23	45	13	15	20	42	9	9	11

Note:

f'c = Average compressive strength, 3 cylinders, psi.

Density = Average density 4 beams, lb/cuft.

Mod. Vebe = Modified Vebe test with 16 lb. extra surcharge, sec.

Figure 14 Strength and Related Characteristics of RCC Mixes.