INFLUENCE OF HIGH STRAIN RATE AND CYCLIC LOADING ON BEHAVIOR OF UNCONFINED AND CONFINED CONCRETE IN COMPRESSION

by

B. Bresler and V.V. Bertero

1. INTRODUCTION

The behavior of different types of concrete subjected to high strain rates and repeated loads, particularly to a small number of cycles of high stress intensity, is of interest in connection with the response of reinforced and prestressed concrete structures to severe earthquake ground motions, such as that developed during the 1971 San Fernando Earthquake. The damage to concrete structures from that earthquake has given rise to questions regarding the behavior of both confined and unconfined concrete under earthquake conditions.

A number of studies on the influence of strain rate and cyclic loading on unconfined concrete under compression have been reported (1-3, 5-15). Most of the investigations were limited to the study of the behavior of normal weight aggregate concrete. Data from these studies indicated that both the strength and stiffness of concrete were higher under dynamic than static conditions, but no reliable data on the effect of dynamic loading on the ductility of concrete were available. Lateral reinforcement is usually relied on to increase the ductility of concrete subjected to dynamic conditions, but this assumption has been based on tests carried out on normal weight aggregate concrete under low strain rate monotonic loading. Results of a limited series of tests conducted on high strength plain light-weight aggregate concrete indicated that under static loading reductions in ductility for this type of concrete may be greater than that for normal weight concrete with good rock aggregates (4).

2. OBJECTIVES AND SCOPE

In order to provide more complete information on the strength and deformational capacities of confined and unconfined concretes with different aggregates and under varying rates of compression loading, the following principal variables were investigated experimentally:

a) type of concrete,

b) rate of loading,

c) monotonic and cyclic loading, and

d) amount and type of confinement.

Five types of concrete with three different aggregates and two strength levels were used in the study (Table 1). The unconfined specimens were 6 x 12 in. cylinders tested at the age of approximately 50 days under monotonic and cyclic compression at prescribed strain rates. The confined specimens were 6 x 18 in. cylinders confined by steel spirals of varying wire diameter and yield strength. Some of the confined specimens had concrete cover over the spiral, while most were cast without cover. The test procedure for the confined specimens was essentially similar to that used for the unconfined concrete specimens.

TABLE 1 - TYPES OF CONCRETE AND SPECIMENS TESTED

TYPES OF CONCRETE				NUMBER AND TYPES OF SPECIMENS				
Concrete Type	Aggregate Type	Unit Weight pcf	Nominal f'_c ksi	Series I Unconfined		Series II Confined		Total Number
				Mon.	Cyc.	Mon.	Cyc.	
E-5	Normal	147	5	41	12	17	3	73
B-3	Light B	102	3	33	15	13	2	63
B-5	Light B	105	5	43	11	14	2	70
R-3	Light R	96	3	33	13	12	3	61
R-5	Light R	97	5	37	19	13	1	70

3. EXPERIMENTAL PROGRAM

The number and types of specimens tested are shown in Table 1. In the first series of tests, 257 unconfined specimens were subjected to either monotonic or cyclic compression. In the second series, 80 confined specimens were subjected to essentially similar loading conditions. Most of the specimens were tested at the age of about 30-50 days in a 300 kip MTS hydraulic testing machine which was programmed for monotonic or cyclic loading at prescribed constant strain rates.

For both unconfined and confined specimens, concrete was mixed in a 7 cu. ft. pan type mixer. The unconfined concrete specimens were 6 x 12 in. cylinders cast in commercially available sheet metal cans. The specimens were stripped after one day and then cured in a "fog-room" at about 70°F., 100% R.H. for 27 days. At the age of 28 days, the specimens were placed in the "dry room" at about 70°F., 50% R.H. for a period of about 21 days. Prior to testing, the specimens were capped with sulphur compound, and most of the specimens were tested at the age of approximately 50 days.

Confined concrete specimens were cast in special 6 x 18 in. cylindrical cast iron molds with pre-fitted spirals held in place. After 1 day, the specimens were stripped and placed in a curing room at 100% R.H. and 72°F. for 13 days. At the age of 14 days, the specimens were placed in the dry room for a period of 14 days. Prior to testing, the specimens were capped with sulphur compound; most of the specimens were tested at the age of 28-30 days.

Specimens used for the confined concrete test series are shown in Fig. 1. Confinement was provided by steel wire spirals 1/8 to 3/16 in. diameter, spaced at 0.5 in. to 0.75 in., with yield strength of 40 to 100 ksi. The spirals were so proportioned that at yield strength of spiral wire, confinement pressures, f_r, varying from 0.11 to 0.34 of the compressive strength f_c were produced. The range of confinement pressures corresponding to practical design conditions can be established from the ACI (Sec. 10.9.2) spiral requirement as follows:

$$\rho_s = \frac{4A_{sp}}{D_c s} = 0.425[(A_g/A_c) - 1] \frac{f'_c}{f_s} \qquad (1)$$

where

ρ_s - ratio of volume of spiral reinforcement to total volume of core,

A_{sp} - cross-sectional area of spiral wire

D_c - diameter of core, out-to-out of spiral

s - spacing (pitch) of spiral

A_g - gross cross-sectional area of concrete

A_c - cross-sectional area of concrete core

f'_c - specified compressive strength of concrete

f_s - hoop stress in the spiral wire

The confinement pressure, f_r, defined below can be expressed in terms of Eq. 1 as follows:

$$f_r = \frac{2A_{sp}f_s}{D_c s} = 0.2125[(A_g/A_c) - 1]\ f'_c \qquad (2)$$

For values of (A_c/A_g) ranging from 0.4 to 0.7, the confinement pressure f_r falls in the range of 0.09 to $0.32f'_c$.

Monotonically loaded specimens were tested at strain rates varying from 10 to 100,000 microinches/inch per second. Specimens subjected to cyclic loading were tested at a strain rate of 20,000 microinches/inch per second, with varying stress amplitudes. A minimum compressive stress of about $0.1f_c$ was maintained in all cycling tests, with the maximum varying from about 0.5 to 0.9 of dynamic compressive strength.

The MTS control system allows cycling between preset strain limits. These were selected from the monotonic loading data at the same strain rate, and, therefore, the stress amplitude during the first cycle conformed closely to the desired stress amplitude. Changes in the material caused by cycling between preset strain limits produced changes in the stress amplitudes due to changes in concrete stiffness. To obtain the desired stress range, particularly at high stress levels, the strain controls had to be reset. The controls were reset as necessary after 5 successive cycles in most cases.

Longitudinal and lateral strains were measured during the tests using a special compressometer. After about 20 cycles of repeated loading, post-cycling load-deformation characteristics and strength were determined under monotonic loading at a strain rate of 10 microinches/inch per second.

4. TEST RESULTS

The results are divided into two groupings: (1) the results of tests on unconfined concrete specimens (Figs. 2-9), and (2) the results obtained from tests on confined specimens (Figs. 10-12).

Figure 2.a shows typical stress-strain diagrams for the five different concretes used in the study. The data were obtained from monotonic loading at a slow strain rate ($\dot{\varepsilon} = 10 \times 10^{-6}$ in/in

per second). Data from earlier studies of normal and lightweight aggregate concretes are shown in Fig. 2.b.

Comparison of these data shows that the deformation characteristics are sensitive to the type of aggregate used and to the strength of the mix. The modulus of elasticity of concrete in compression, E_c, as shown in Table 2, varies not only with compressive strength and unit weight, but also with type of aggregate. Although the compressive modulus is usually predicted by the equation:

$$E_c = A\, w^{1.5}\sqrt{f'_c} = 33\, w^{1.5}\sqrt{f'_c} \qquad (3)$$

It can readily be seen from Table 2 that the assumption of A equal to 33 can significantly overestimate the value of E_c. The observed value of E_c is taken as the average secant modulus at a compression stress level of 0.45 of the compressive strength based on tests of 6 x 12 in. control cylinders at the age of 28 days. Two interpretations of compressive strength are used for this comparison. The value of (f_c) is taken as the maximum compression stress observed in the test; the value of (f'_c) is the design strength as specified in the code, and is reduced in accordance with the ACI Code (Sec. 4.2.2.1). For the concretes tested here, an error in the predicted value of E_c can reach 30%, regardless of whether the value of maximum compressive test strength (f_c) or the reduced value of design strength (f'_c) is used in the calculation.

Similarly, strain at maximum compression ε_o, and deformability - i.e., ultimate strain ε_u - are highly sensitive to particular aggregate and concrete mix. For example, values of ε_o shown in Fig. 2.a range from 2600 for mix B-3 to 3700 x 10^{-6} in/in for mix R-5.

The effect of strain rate on stress-strain characteristics of the five different concretes is shown in Fig. 3. Specific effects of rate of strain on compressive strength, modulus of elasticity, and strain at maximum compression are shown in Figs. 4, 5, and 6.

TABLE 2 EFFECT OF CONCRETE STRENGTH AND TYPE OF AGGREGATE ON COMPRESSIVE MODULUS, E_c

Concrete Type	Compress. Strength ksi		Observed E_c	Coefficient A (Eq. 3)	
	Maximum (f_c)	Design (f'_c) (1)	10^3 ksi	$\frac{E_c}{w^{1.5}\sqrt{f_c}}$	$\frac{E_c}{w^{1.5}\sqrt{f'_c}}$
E-5	5.62	4.92+	3.07	23.0	24.6
B-3	3.52	2.97*	1.81	29.6	32.2
B-5	5.27	4.57+	2.08	26.7	28.6
R-3	3.73	3.18*	1.47	25.6	27.7
R-5	5.57	4.87+	1.75	24.5	26.2

(1) Reduced for estimated scatter in strength values in accordance with ACI Sec. 4.2.2.1. $*(f'_c) = [(f_c)-0.55]$ksi $+(f'_c) = [(f_c)-0.70]$ksi

Comparison of the data for different concretes in Figs. 3 and 4 indicates that for both normal weight and lightweight aggregate concretes, compressive strength (maximum observed compressive stress) increases with strain rate. For different concretes, the maximum increase in strength ranges from about 20 to 40%, with proportionately higher increases in strength for lightweight aggregate concretes. The increase in compressive strength is significant with increasing strain rates up to 50,000 x 10^{-6} in/in per second. At higher strain rates, strength does not increase proportionately.

Modulus of elasticity also increases with increasing strain rate (Fig. 5), but the increase is substantially smaller than in the case of compressive strength. For different concretes, the increase in values of E_c ranges from 8 to 20%.

Strain, ε_o, at maximum compression does not show a consistent increase with strain rate. A slight reduction is observed in some concretes, while an increase is observed in others (Fig. 6), as the ratio of $(\varepsilon_o)/(\varepsilon_o)_{10}$ ranges from 0.97 to 1.2.

A number of specimens were subjected to cyclic loading at high strain rates with various stress amplitudes. The effect of cyclic loading on the stress-strain characteristics of the five concretes used in this study is shown in Fig. 7. Specific effects of cyclic loading on the compressive strength and modulus of elasticity are shown in Figs. 8 and 9. No significant changes in concrete were observed as long as the maximum stress did not exceed about one half the dynamic compressive strength at $\dot{\varepsilon} = 20{,}000 \times 10^{-6}$ in/in per second (Figs. 8 and 9). As the maximum stress range was increased to about 3/4 of the dynamic compressive strength, hysteretic loops in the stress-strain curves were generated, resulting in some residual deformation and causing some degradation in strength and stiffness observed during post-cycling static reloading (Figs. 7.c, 8, and 9). However, damage associated with cycling at this level of maximum stress was slight and reduction in post-cycling static strength and stiffness was relatively small (Figs. 8 and 9).

Further increases in the level of peak stress to 88 and 92% of $(f_c)_{20,000}$ during cycling showed significant degradation in post-cycling stiffness and strength. The post-cycling static strength of normal weight aggregate concrete (E-5) after 32 cycles of loading exhibited a reduction of 20% in strength, Fig. 7.a, and the post-cycling static strength of one lightweight aggregate concrete (B-3) after only 10 cycles of loading at the same peak stress, Fig. 7.b, exhibited a reduction of 40% in strength. Furthermore, the lightweight aggregate concrete could not sustain stable cycling and the typical drop-off in the maximum load can be seen in Cycles 6-10 in Fig. 7.b.

From Figs. 8 and 9 it can be seen that large reductions in strength (f_c) and stiffness (E_c) were caused by 20 cycles of loading at high strain rates when the peak stress during cycling reached about 80% of

$(f_c)_{20,000}$ for lightweight aggregate concrete and about 90% of $(f_c)_{20,000}$ for normal weight aggregate concrete.

The effect of confinement pressure on the stress-strain characteristics of the five concretes under monotonic compression at low strain rate is shown in Fig. 10. Deformation characteristics and gain in strength of confined concrete are sensitive to type of aggregate and to relative amount of confining pressure.

Confinement of concrete - with all types of aggregate - is effective in developing large deformability, the ultimate strains in all cases being greater than 0.02 in/in. However, increase in compressive strength due to confinement is much greater for normal weight concrete than for lightweight concrete. After yielding of spiral steel, the strength of confined lightweight aggregate concrete may decrease to values lower than that of unconfined concrete.

It was found that maximum confinement, which can be obtained within practical limits of spiral spacing and yield strength of spiral steel wire, is not sufficient to achieve the expected (about 4 times the lateral pressure) increase in strength of lightweight aggregate concrete.

Increasing rate of strain and cycling of confined concrete produces effects similar to those on unconfined concrete specimens. The effect of high strain rates on the stress-strain characteristics of the five concretes under monotonic compression and moderate confinement pressure is shown in Fig. 11.

Increasing strain rate from $\dot{\varepsilon} = 25 \times 10^{-6} \frac{in/in.}{sec.}$ to $10{,}000 \times 10^{-6} \frac{in/in.}{sec.}$ increases strength about 10 to 20%; a smaller increase in stiffness is exhibited. At high strain rates, just as at low strain rates, confinement is more effective for normal weight aggregate concrete than for lightweight aggregate concrete. For example, the ratio of stress, f_c, to compressive strength, $(f_c)_{10}$, at $\dot{\varepsilon} = 10 \times 10^{-6} \frac{in/in.}{sec.}$ peaks at about 2.1 for E-5, at 1.8 for B-5 and R-5, and at 1.5 for B-3 and R-3. At larger strains, say $(\varepsilon/\varepsilon_0) = 4$, the stress ratios $f_c/(f_c)_{10}$ drop from 2.1 to about 1.8 for E-5, but they drop from 1.8 to 1.15 for B-5 and R-5, and from 1.5 to about 1.2 for B-3 and R-3.

The effects of cyclic loading on the strength and ductility of confined concrete are shown in Fig. 12. It can be seen that when the peak compressive stress during cycling, f_{max}, is in the range of $0.95f_c$ to $1.00f_c$, large residual deformations are developed during cycling, while for $f_{max} = 0.85f_c$, the residual stresses are still quite small, even after 20 cycles.

Also, when peak stress during cycling approaches $0.95f_c$ to $1.00f_c$, significant degradation in stiffness and strength of concrete takes place. Post-cycling stress-strain characteristics show large decrease in stiffness (slope of the stress-strain diagram) and about 10-15% decrease in strength. When f_{max} did not exceed $0.85f_c$, little degradation in strength and stiffness was observed.

5. DISCUSSION

The effectiveness of concrete confinement in producing ductility in earthquake resistant reinforced concrete structures is based on two conditions: (1) that confinement increases compressive strength so that it is possible to offset the loss of strength from the loss of load-carrying capacity due to crushing and spalling, and (2) that confinement increases the capacity of concrete to sustain large deformations without loss of strength, thus transforming concrete from a relatively brittle material (when unconfined) to a relatively ductile material (when confined).

Results presented in the preceding section show that for different concretes, these conditions are satisfied to a varying extent, and that the effectiveness of confinement is highly sensitive to the type of aggregate used. The effectiveness of confinement can be characterized by two material constants, k_o and k_u, which are defined by relating the increased compressive strength, f_c, to the confinement pressure, f_r.

The compressive strength of confined concrete, $f^*_{c\,max}$, occurs at some strain, ε^*_o, and can be defined as follows:

$$f^*_{c\,max} = f_c + k_o f_r \tag{4}$$

where f_c is the compressive strength of the same concrete, but unconfined.

With very large deformations, $\varepsilon^*_u >> \varepsilon^*_o$, the compressive strength usually decreases to a value of f^*_{cu} and can be defined as follows:

$$f^*_{cu} = f_c + k_u f_r \tag{5}$$

The confinement pressure, f_r, depends on the geometric and material characteristics of the spiral and can be expressed as follows (see Eq. 2):

$$f_r = \frac{2A_{sp} f_s}{D_c s}$$

Assuming that the ductile spiral wire yields when the longitudinal strain in the concrete is in the range ε^*_o to ε^*_u, and that strain-hardening of the spiral is negligibly small in the range of these strains, f_s is equal to f_y, and f_r can be calculated for given values of A_{sp}, D_c, and s from Eq. 2. Then, values of k_o and k_u can be calculated from Eqs. 4 and 5 and test results. These values for the five different concretes used in the study are shown in Table 3.

Early investigators have shown that the confinement effectiveness coefficient k varies with lateral pressure intensity and with longitudinal strain. However, in developing ACI criterion for spiral requirement (Sec. 10.9.2) and other similar criteria based on the confinement of concrete, a constant value of k, usually taken as 4.0 or 4.1, has been assumed.

As shown in Table 3, the values of k for normal weight aggregate concrete vary in the range of from 0 to 7.0. For the two lateral pressures ($0.13f_c$ and $0.32f_c$), values of k_o at maximum compression are 7.0 and 5.0, respectively, and values of k_u at ultimate strength are 0 and 3.1, respectively. Based on these values, and noting from Fig. 12 that concrete behaves in a relatively ductile manner throughout a significant range of strains, a constant value of k = 4.0 may be justified for concretes such as E-5.

For concretes B-3, B-5, R-3, and R-5, the values of k vary in the range of from -1.0 to 4.4. Negative values of k_u indicate that compressive failure in the confined concrete may occur at values below the compressive strength of unconfined concrete. For the two lateral pressures ($f_r \simeq 0.1$ and $f_r \simeq 0.3$), values for k_o at maximum compression range from 1.0 to 4.4 and values for k_u at ultimate range from -1.0 to 2.1.

Based on these results, a value for k in the range of from 1.0 to 2.0 should be taken in developing design criteria based on the confinement of lightweight concrete when aggregates similar to those used in this investigation are used. In such cases, the amount of spiral steel required in a column of lightweight aggregate concrete will be 2 to 4 times as great as that currently prescribed by the ACI Code. Because of the geometric limitations introduced by the size of spiral wire and the minimum spacing, it would be virtually impossible to produce a spiral which would also allow normal placing of concrete.

TABLE 3 EFFECT OF CONFINEMENT ON COMPRESSIVE STRENGTH AND DEFORMATION OF CONCRETE

Type of Concrete	Confinement Stress Ratio	Maximum Compression		Ultimate Compression	
		Strain Ratio	Confinement Effectiveness	Strain Ratio	Confinement Effectiveness
	(f_r/f'_c)	$(\varepsilon^*_0/\varepsilon_0)$	k_0	$(\varepsilon^*_u/\varepsilon_0)$	k_u
Normal	0.13	2.8	7.0	11.5	0
E-5	0.32	7.8	5.0	11.5	3.1
Lightweight	0.13	1.9	4.4	8.7	-0.5
R-5	0.32	4.0	2.0	6.7	2.0
B-5	0.13	1.35	3.9	10.6	0
	0.32	1.85	1.0	8.6	0.9
R-3	0.11	1.8	2.7	8.9	-1.0
	0.24	5.9	2.5	8.9	2.0
B-3	0.11	1.7	1.35	11.6	0
	0.24	8.0	2.1	9.0	2.1

The effect of the variable coefficient k is illustrated in Fig. 13. Loss of the capacity to carry load by spirally reinforced concrete columns due to spalling is plotted against k, assuming that the spiral reinforcement was designed in accordance with the ACI criterion. This loss of capacity is expressed as a ratio and derived as follows:

$$\text{Loss} = 0.85f'_c(A_g - A_c) - kf_rA_c$$

$$= 0.85f'_c(A_g - A_c) - 0.5k\rho_s f_s A_c \qquad (6)$$

By substituting $\rho_s = 0.425\,[(A_g/A_c)-1](f'_c/f_s)$ (Eq. 1) into the above, and dividing by $0.85f'_cA_g$, the following ratio is obtained:

$$\frac{\text{Loss}}{0.85f'_cA_g} = \left(1 - \frac{A_c}{A_g}\right) - 0.25k\left(1 - \frac{A_c}{A_g}\right) \qquad (7)$$

For spirally reinforced square columns, (A_c/A_g) varies from approximately 0.4 to 0.6 and for round columns this ratio varies from approximately 0.5 to 0.7. The loss ratio for typical values of (A_c/A_g) is plotted in Fig. 13.

6. CONCLUSIONS

The results of this investigation, as well as some of the results reported in a previous related investigation (16), are highly significant for improved predictions of the behavior of reinforced concrete structures under seismic conditions, particularly for structural elements where confinement of concrete is provided.

For the unconfined concrete specimens, the following conclusions are indicated by the results:

1. The modulus of elasticity of concrete in compression varies not only with compressive strength and unit weight, but also with the type of aggregate used. The presently recommended ACI formula for the prediction of modulus of elasticity, $E = 33w^{1.5}\sqrt{f'_c}$ may significantly overestimate modulus values for normal as well as lightweight aggregate concretes.

2. Increasing the rate of strain up to 50,000 microinches/inch/second increases compressive strength over that observed under a slow rate of loading. Higher strain rates do not increase strength proportionately.

3. Increasing the rate of strain increases the stiffness (modulus) of concrete in compression. The increase in modulus is relatively smaller than the increase in strength.

4. Cyclic loading at high strain rates with peak stresses in the range of static compressive strength may produce significant residual strain and significant reductions in post-cycling stiffness and strength. These reductions were more significant for lightweight aggregate specimens.

For the concrete specimens confined by steel spirals, the following conclusions are indicated by the results. Because recent suggestions for improved design of earthquake resistant reinforced concrete structures rely on the beneficial effects of confinement on concrete behavior, a brief discussion of the implications of the conclusions of this study with respect to the prediction of seismic behavior are also presented.

1. Deformation characteristics of confined concrete are sensitive to type of aggregate and to relative amount of confining pressure.

2. As in the case of unconfined concrete, prediction of modulus of elasticity using the ACI formula may significantly overestimate modulus values of confined concrete, and therefore estimations of natural periods T of reinforced concrete structures can be affected. This effect should be considered in seismic analysis by allowing for corresponding variations in estimated values of T.

3. Confinement of concrete, with all types of aggregate, is effective in developing large deformability, i.e., large ultimate strains. This characteristic is the major factor for the improved performance of elements with spirally confined concrete as it compensates for some of the losses in strength and stiffness of concrete under cyclic loading.

4. The increase in compression due to confinement is much greater for normal weight concrete than the increase for

lightweight concrete, about twice as great. Therefore, caution should be used in applying equations derived from results obtained using normal weight aggregate concrete.

5. The low effectiveness of confinement in some concretes may lead to significant losses in compression capacity when spalling occurs in reinforced concrete elements. This is of the utmost importance in the case of seismic design of column elements since these elements should at all times be able to resist the effects of the gravity loads and effects of overturning moments.

6. Increasing the rate of strain and cycling of confined concrete produces effects similar to those on unconfined specimens. Because cyclic loading at high strain rates with peak stresses in the range of static compressive strength may produce significant reduction in post-cycling stiffness and strength, there is an urgent need to investigate possible effects of the observed deterioration in energy absorption and energy dissipation capacity, as well as in the shear strength and bond characteristics of confined concrete in structural elements subjected to cyclic loading.

The above observations and conclusions are based on the study of only five types of concrete and two types of unconfined and confined specimens. While these results provide a substantial basis for the concluding remarks, the general validity of these comments requires further verification.

7. ACKNOWLEDGEMENTS

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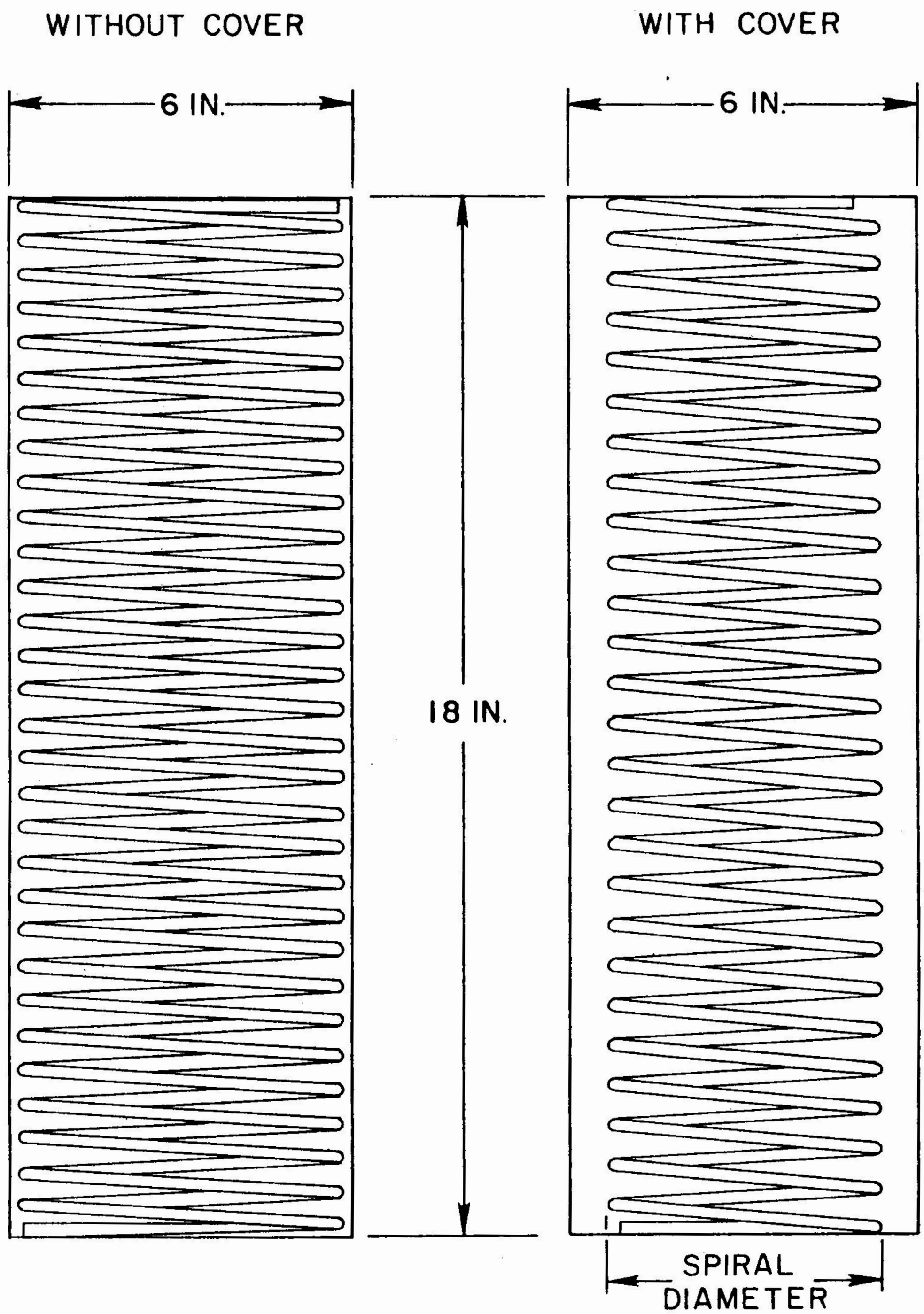

FIG. I CONFINED CONCRETE SPECIMENS

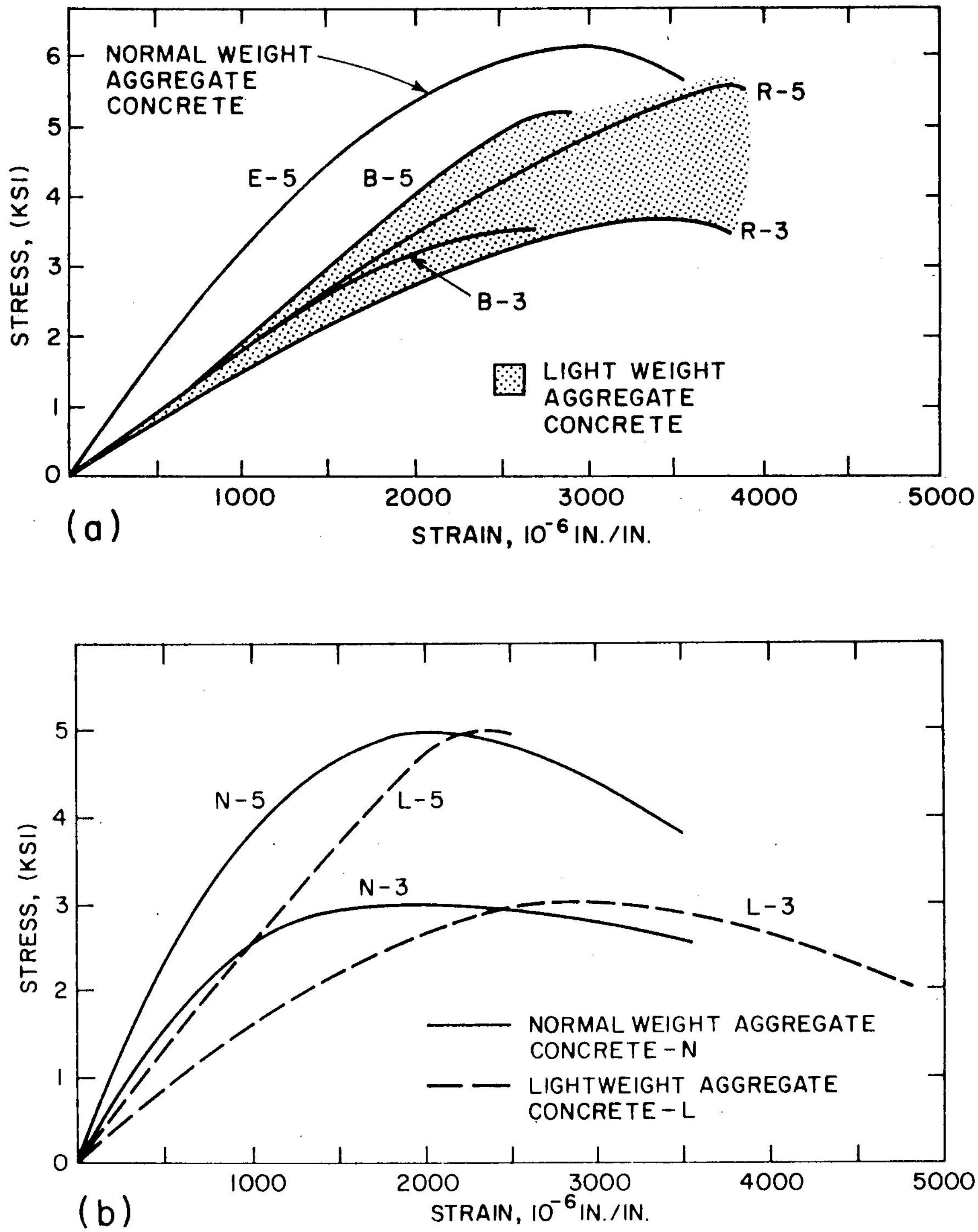

FIG. 2 STRESS-STRAIN DIAGRAMS FOR UNCONFINED CONCRETE-MONOTONIC COMPRESSION

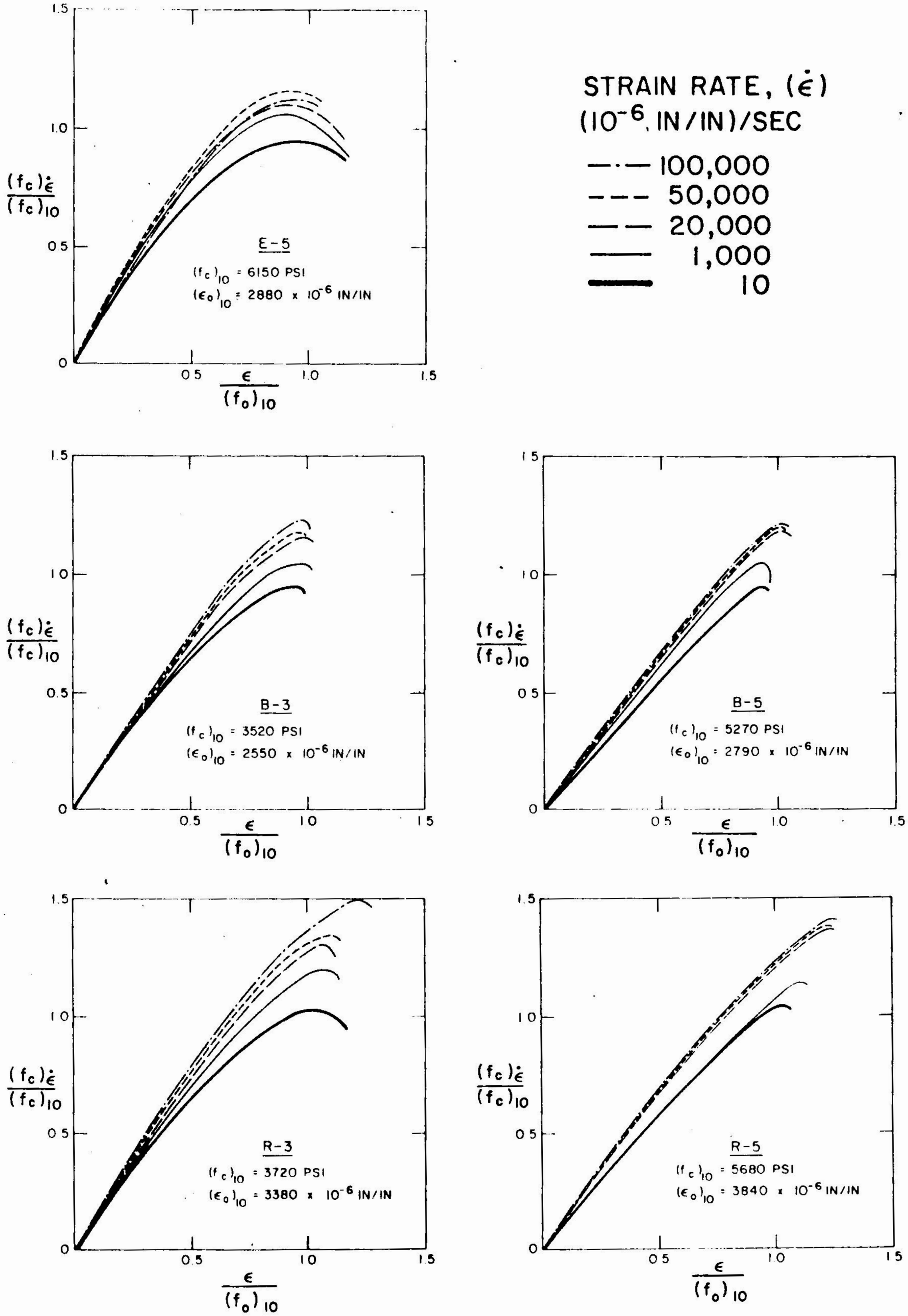

FIG. 3 EFFECT OF STRAIN RATE ON STRESS-STRAIN RELATIONSHIPS OF UNCONFINED CONCRETE

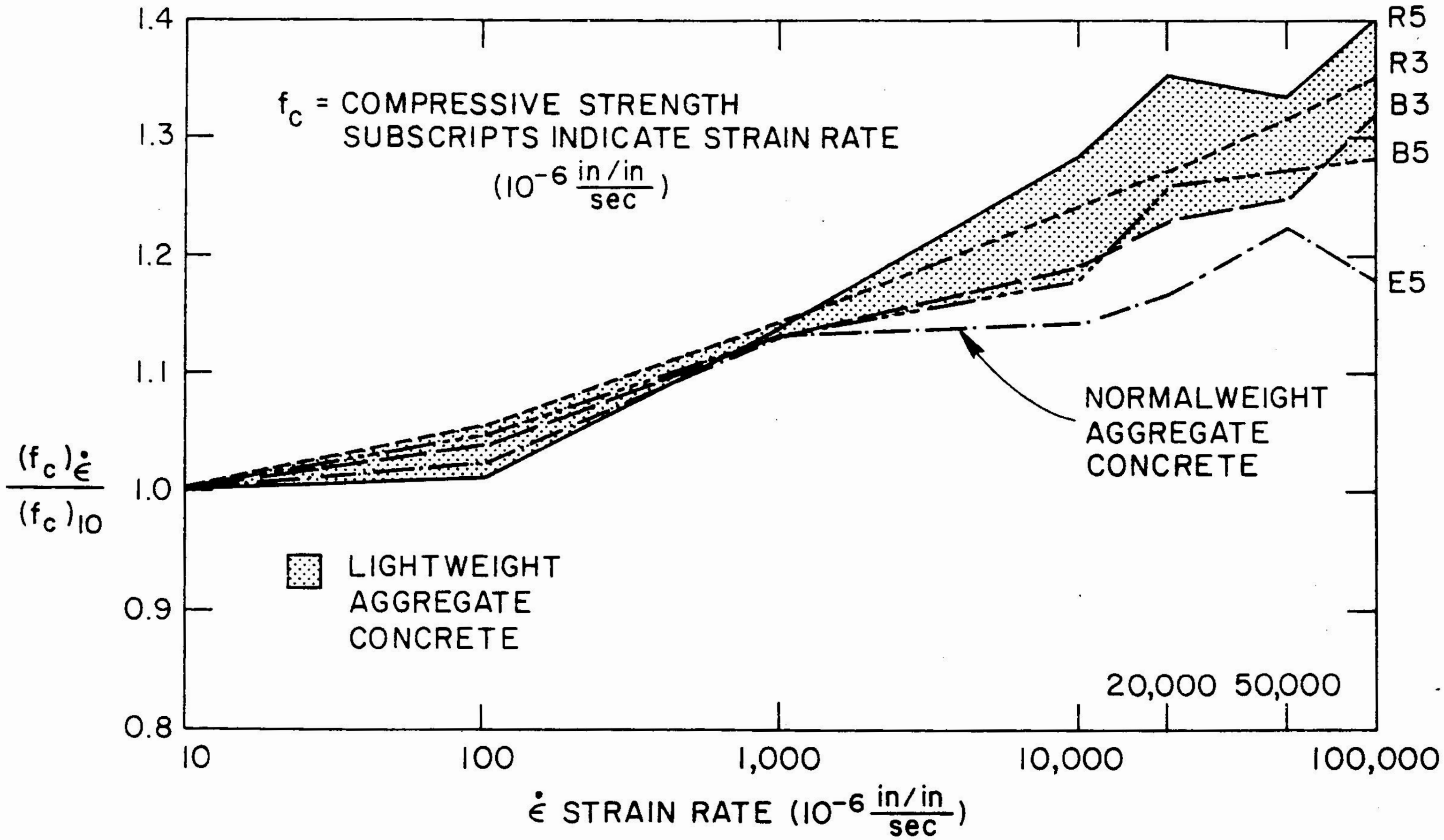

FIG. 4 EFFECT OF STRAIN RATE ON COMPRESSIVE STRENGTH.

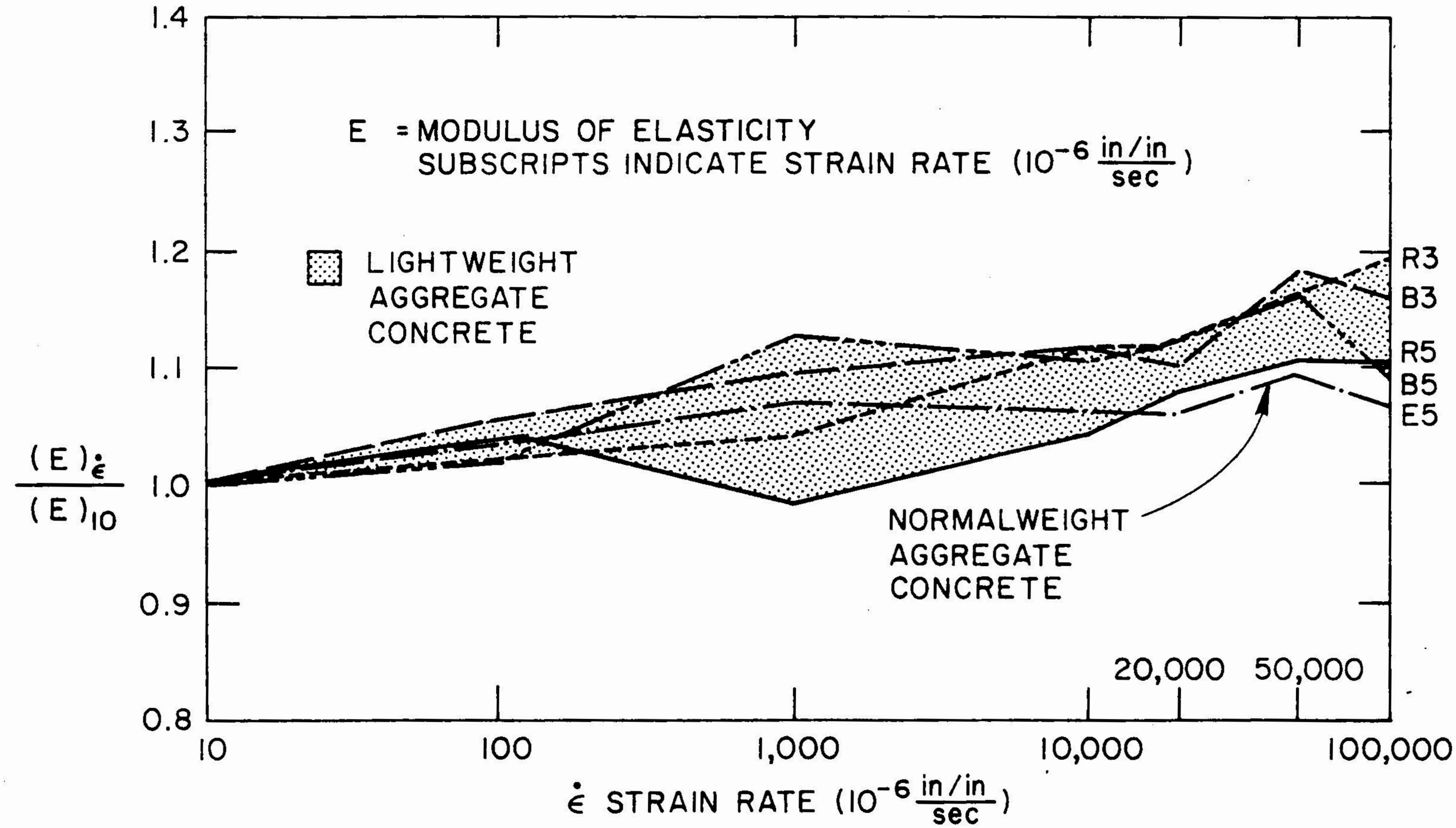

FIG. 5 EFFECT OF STRAIN RATE ON MODULUS OF ELASTICITY.

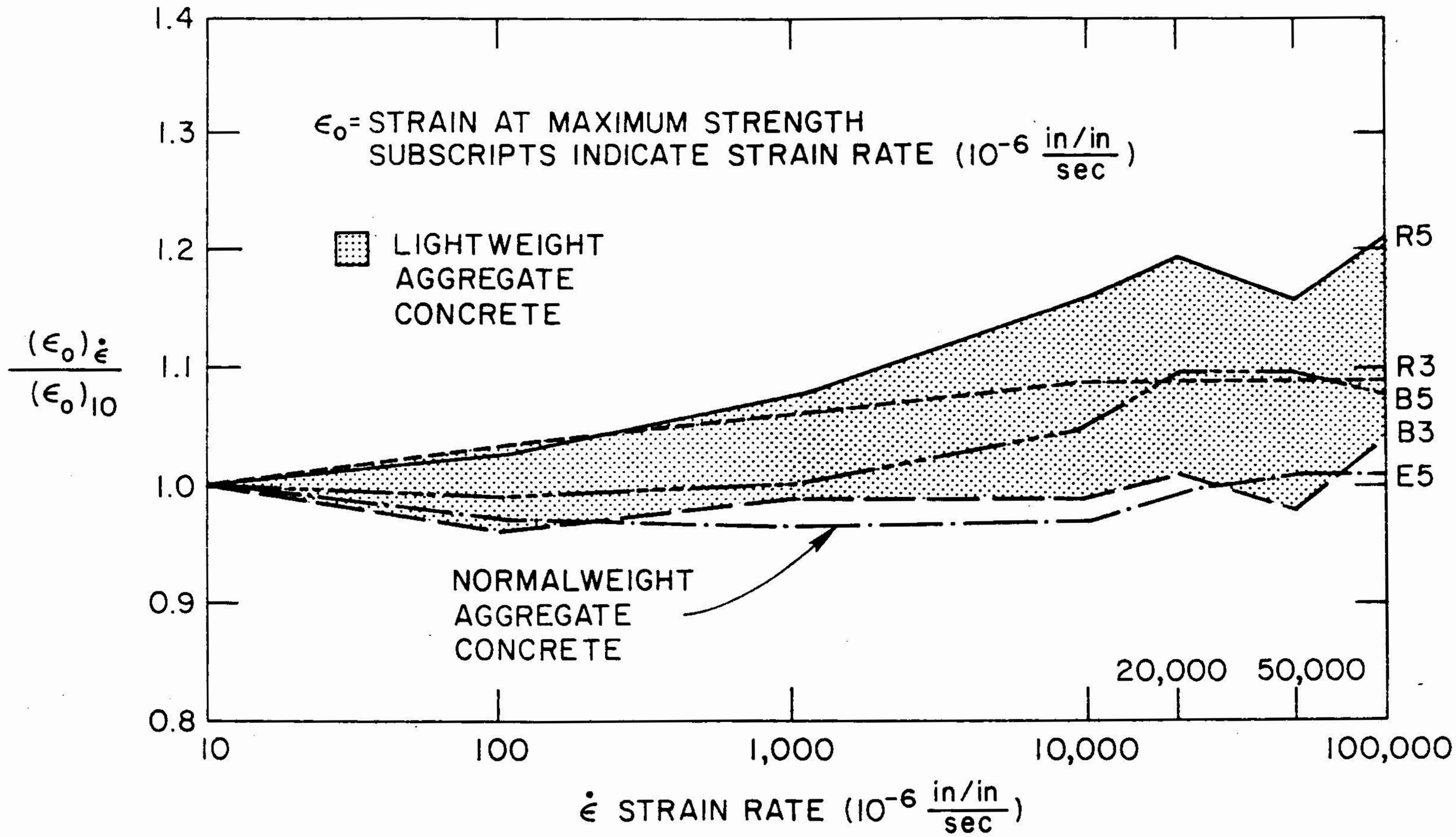

FIG. 6 EFFECT OF STRAIN RATE ON STRAIN AT MAXIMUM STRENGTH.

SUBSCRIPTS INDICATE STRAIN RATE

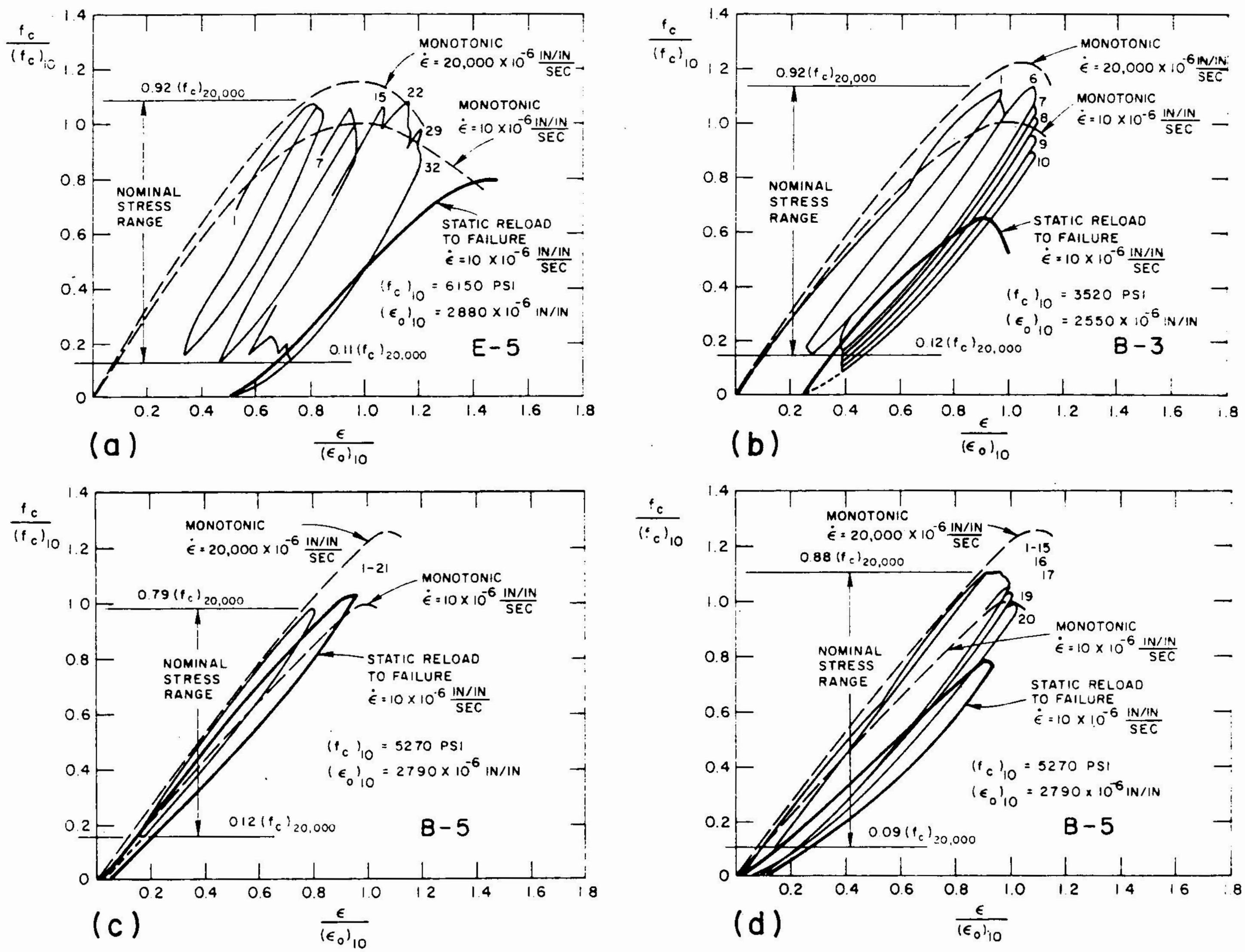

FIG. 7 EFFECT OF CYCLING ON STRESS-STRAIN RELATIONSHIPS OF UNCONFINED CONCRETE

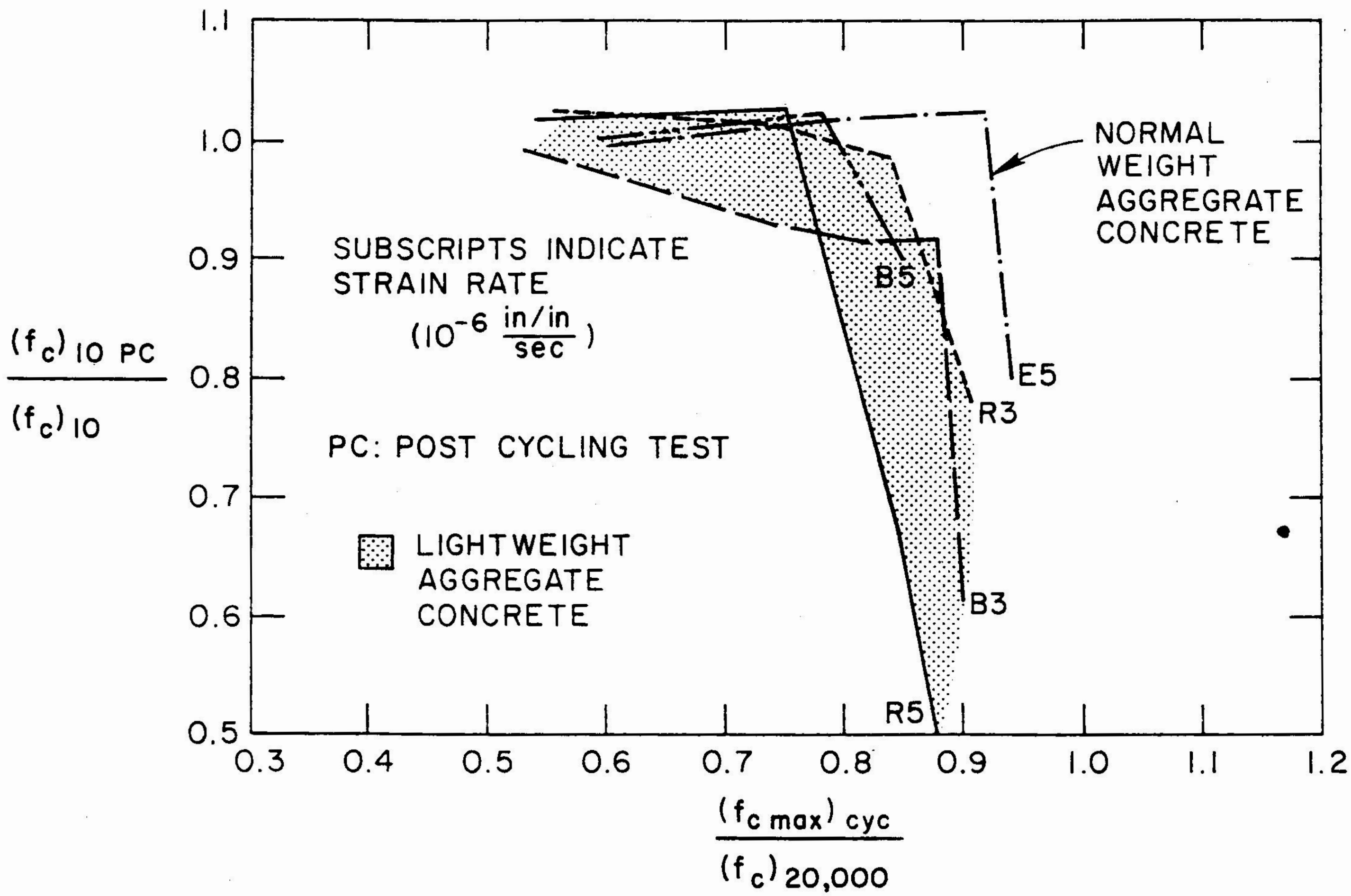

FIG. 8 EFFECT OF CYCLING ON COMPRESSIVE STRENGTH OF UNCONFINED CONCRETE.

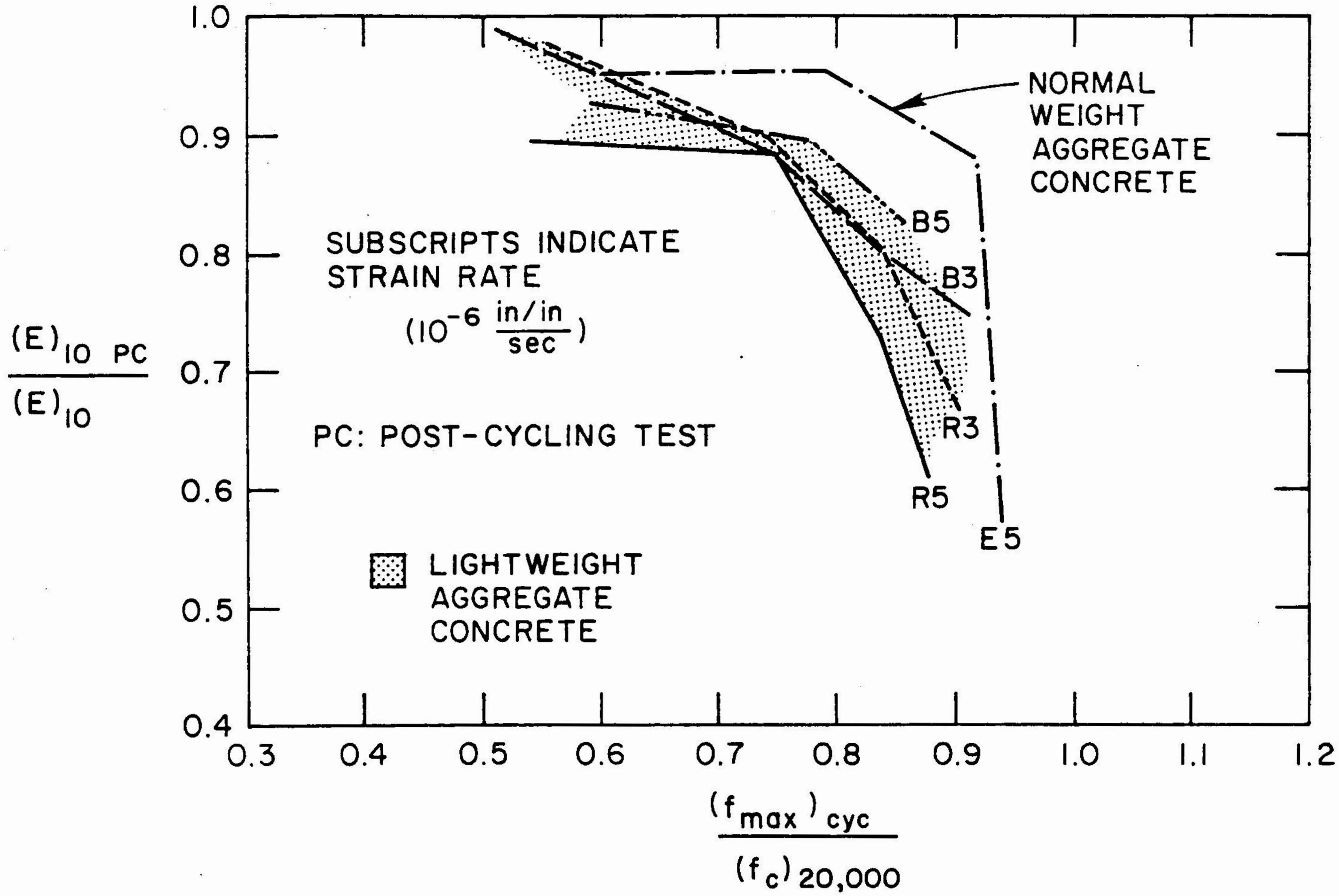

FIG. 9 EFFECT OF CYCLING ON MODULUS OF ELASTICITY OF UNCONFINED CONCRETE

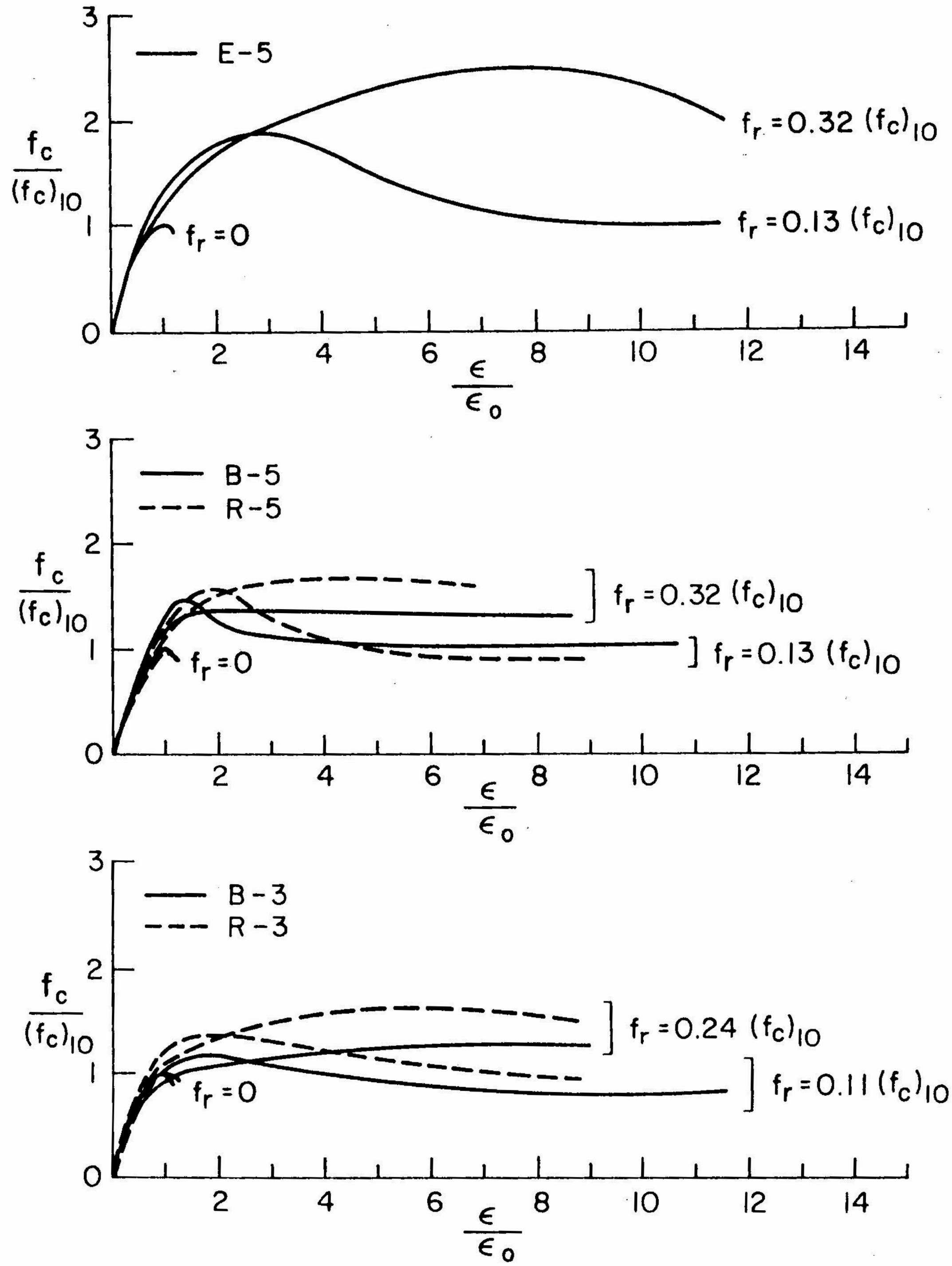

FIG. 10 EFFECT OF CONFINEMENT PRESSURE OF COMPRESSIVE STRENGTH AND DUCTILITY OF CONFINED CONCRETE - MONOTONIC LOADING.

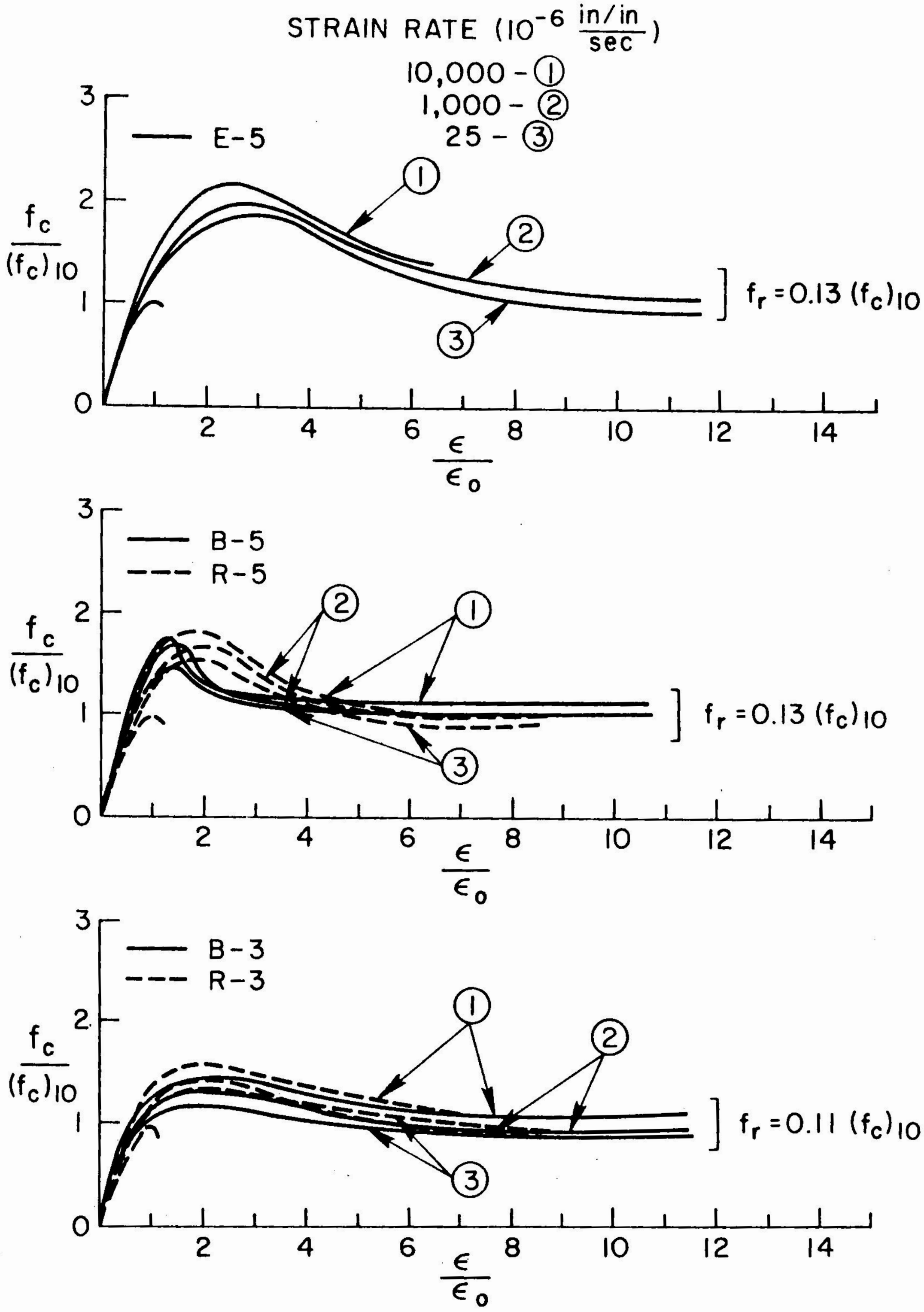

FIG. 11 EFFECT OF STRAIN RATE ON COMPRESSIVE STRENGTH AND DUCTILITY OF CONFINED CONCRETE - MONOTONIC LOADING.

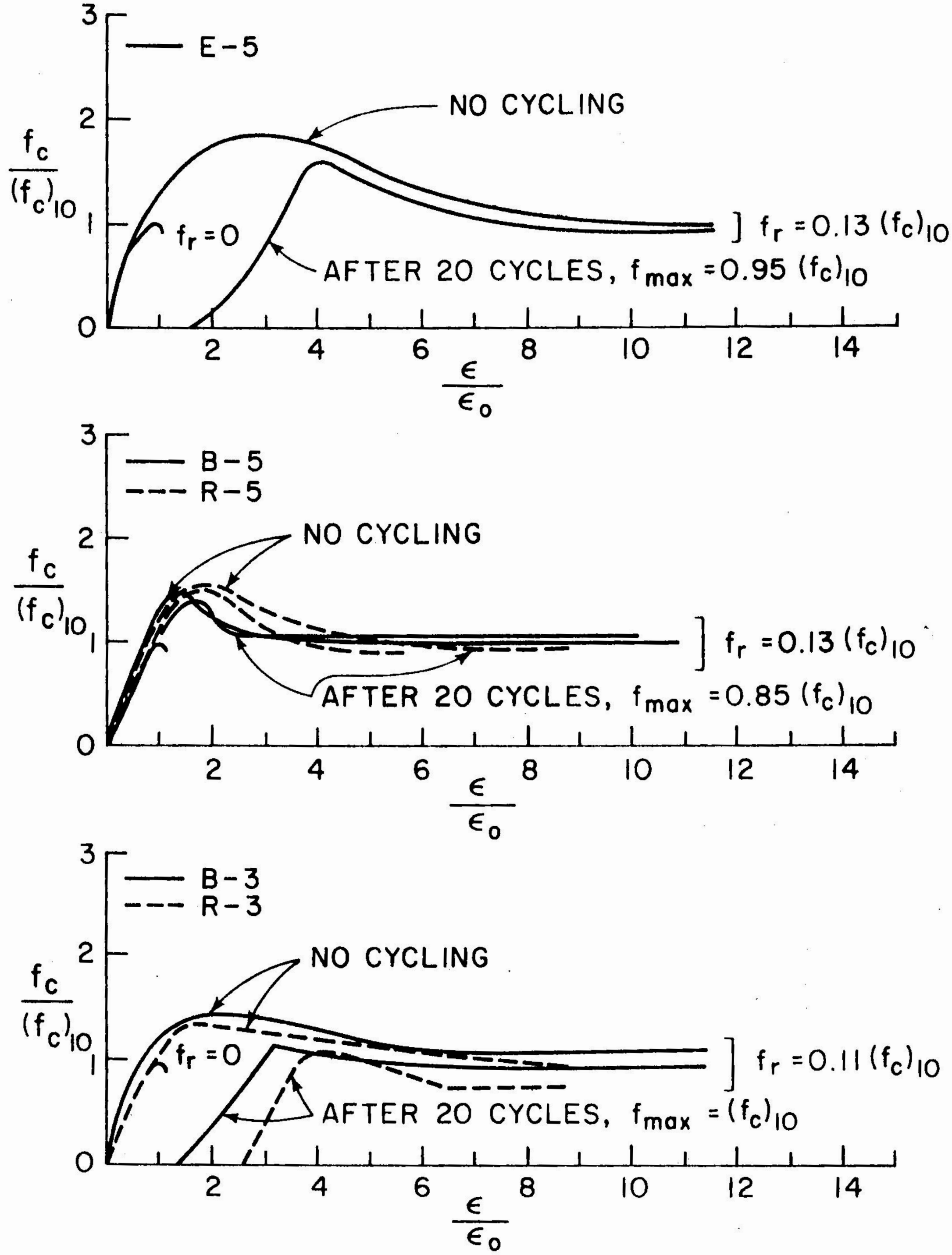

FIG. 12 EFFECT OF CYCLING ON STRENGTH AND DUCTILITY OF CONFINED CONCRETE - STRAIN RATE - $10{,}000 \times 10^{-6} \frac{\text{IN/IN}}{\text{SEC}}$

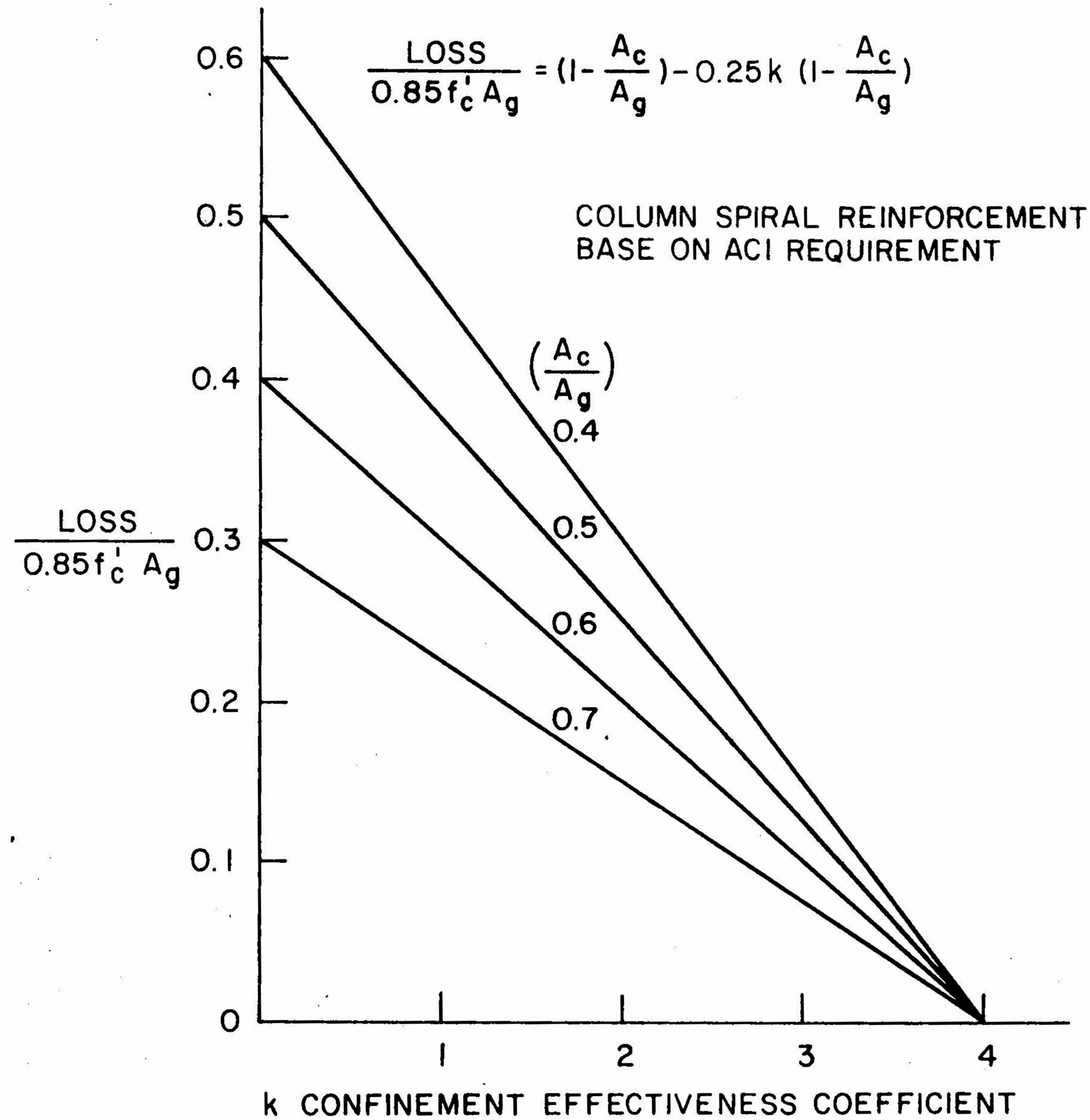

FIG. 13 LOSS OF COMPRESSIVE STRENGTH DUE TO SPALLING VS. CONFINEMENT EFFECTIVENESS COEFFICIENT