BEARING CAPACITY OF BUILDING MATERIALS UNDER DYNAMIC REPEATED LOADINGS

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The paper deals with the investigations carried out by the Central Research Institute for Building Structures of Gosstroy of the USSR in order to study the strengths of building materials (steel, aluminium, heavy and lightweight concretes) under various dynamic effects.

The paper provides the results of the investigation of the stability of steel and reinforced concrete struts under a repeated dynamic load.

The material tests under dynamic repeated loadings were affected by some specific features of seismic loads characterized by a low number of load repetitions (about 1000 cycles), high values of the upper limit of stress and certain load change rate.

The regularities observed in the variation of the bearing capacity of different materials under repeated loadings permited a summarized analytical relationship to be derived.

The experiments carried out enabled the possibility of employment of different materials in earthquake engineering to be established, the values of coefficients of working conditions required for the design of earthquake-resistant structures for strength and stability on the basis of the USSR Code to be recommended.

Notations

R_{ult} = ultimate strength of steel under static tension;

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σ_{yield} = yield point of steel under static tension;

ε = complete static elongation related to the effective length of the metal test specimen;

ψ = relative narrowing of the cross-sectional area of the metal specimen;

σ_{max} = stress at the moment of the sample failure corresponding to n -cycles of the load repetition with the stress ratio ρ and frequency ω ;

σ_z = endurance limit at the same ρ and ω ;

R = ultimate strength for a once applied loading with the velocity corresponding to the frequency of the cyclic load;

z = the number of cycles corresponding to the endurance limit;

R_{pr} = the ultimate prismatic strength of concrete under static loading;

R_{sh} = ultimate strength of concrete samples in shear loaded statically;

P^{cr}_{st} = critical load under a static once-applied loading at which the strut loses its stability;

P^{cr}_{max} = the critical load under repeated loading at which the strut loses its stability.

Endurance of different building materials under large numbers of load repetitions was the objective of many investigations. Much less attention was paid to the problem of strengths of building materials under not numerous repeated loadings or the so-called "low-cycled endurance". Evidently, this may be attributed, to some degree, to the fact that on high frequency pulsators, where fatigue tests are usually accomplished, it is fairly difficult to produce not numerous repeated loading (1 to 1000 cycles) under stresses close to the ultimate strength of the material as the speeding up duty of the pulsator often exceeds considerably the range of the number of cycles of interest. In some cases, measures should, therefore, be undertaken to reduce or eliminate the number of speeding up cycles. At the same time the data on "low-cycled endurance" of materials for solution of the problems of earthquake resistance are of considerable interest as they reflect the performance of the material during earthquakes better than customary static tests. The scarcity of test data on low number of loadings makes it difficult to determine general regularities appropriate for the entire range of load repetitions.

In reference / 9 / F. Stüssi has proposed the relationship $\sigma_{max} - n$, the equation of which has the form:

$$\sigma_{max} = \sigma_z + (R_{ult} - \sigma_z)\frac{1}{1 + C_w n^p} \qquad (1)$$

where C_w and p are test coefficients, e.g. for iron $C_w = 0.00282$, $p = 0.59$.

For repeatedly applied loadings (about 10^3 to 6.10^6) the curve in steeper, and for low numbers of repeated loadings the slope is almost gentle, close to horizontal. According to F. Stüssi, as follows from (1) the strength of steel under low number of repeated loadings does not exceed its static ultimate strength R_{ult} and with the increase of the number of repetitions from 1 to 1000 it changes insignificantly.

According to Prof. I. L. Korchinsky / 3 / for the speed of loading corresponding to the speed of natural vibrations of building structures (within 0.5 to 10 hertz) the relationship $\sigma_{max} - \lg n$ in the range of 1 to 10^6 may be described by a general straight line. If to take into consideration that the rate of loading exerts an appreciable influence on the bearing capacity of the material in the range of low values (less than 100), the strength may even exceed its static equivalent R_{ult} The equation of the general straight line may be written as:

$$\sigma_{max} = \sigma_z + (R - \sigma_z)\left(1 - \frac{\lg n}{\lg z}\right) \qquad (2)$$

The discrepancy in the opinions is accounted for, to a certain extent, by the fact that the assumptions given above did not pay sufficient attention to the problem of the influence of the loading rate in the repeated test. Provided the influence of the rate of loading is taken into account, then the above discrepancy will, probably, be smoothed away, somehow. For high rates of loading the relationship $\sigma_{max} - \lg n$ in the range of low numbers of loadings is likely to be closer to an inclined line, for low-rate loadings, corresponding to customary static loadings, this relationship will, however, have a distinctly curvilinear pattern. Regularities of course, depend upon the characteristics of plastic properties of materials and other factors.

The Central Research Institute for Building Structures carries out systematic research in the strength and deformability of building materials and structures under dynamic single and repeated loadings. The range of repeated loading covers both small (1 to 1000) and large numbers of loading (up to 5×10^6).

The investigations have been done with metals and concretes under different conditions of loading. When processing the test results it was, at first, assumed that the relationship $\sigma_{max} - \lg n$ in the whole investigated range of repetitions n may be linear according to (2). As the test results have shown, this assumption had proved to be in agreement with the test data. For some materials an increase in the strength was observed at low numbers of loading in comparison with R_{ult} (R_{pr}) / 3 /. It is a corollary of a more detailed analysis of numerous test results on different materials (steel, aluminium, heavy, silicate, lightweight and cellular concretes, etc.) that for, some materials the assumption of a linear relationship $\sigma_{max} - \lg n$ within the entire range of repetitions (from a once-applied loading to large numbers of repetitions corresponding to the endurance zone) may lead to some inaccuracy, particularly in the range of small n . Thus, assuming the linear relationship $\sigma_{max} - \lg n$ for this or that material one should mention the limits of its application.

For evaluation of the bearing capacity of the material in the range of repetitions n and for any rates of loading the following empiric relationship seems to be more appropriate:

$$\sigma_{max} = \sigma_z + (R - \sigma_z)\, e^{-(\alpha \lg n)^m} \qquad (3)$$

here α and m are coefficients, reflecting the regularity of variation of the bearing capacity of each material under repeated loading. Formula (3), well reflecting the test data for the entire range of n being usually of interest for the investigator allows also to take into consideration the fact that at $n = 1$ the dynamic ultimate strength may differ from the static one. Below are given briefly test results on each material. The diagrams show ratios of the cyclis strength σ_{max} to the static ultimate strength R_{ult} and, in respective cases, to R_{pr} . For comparison two relationships are plotted in the diagrams in the system of coordinates $\sigma_{max}/R_{ult} - \lg n$ or $\sigma_{max}/R_{pr} - \lg n$ viz. straight line found by formula (2) and the curve found by formula (3).

Metals.

Steel St 3 ($R_{ult} = 43$ kg/mm^2; $\sigma_{yield} = 32$ kg/mm^2; $\varepsilon = 31\%$; $\psi = 41\%$). Aluminium alloy AM g/k - 61 ($R_{ult} = 34$ kg/mm^2; $\sigma_{yield} = 24$ kg/mm^2; $\varepsilon = 16\%$; $\psi = 65{,}5\%$).

Steel and aluminium specimens with the effective area 82 mm long and 10 mm dia were tested under low-cycled repeated loading (1 to about 1000 cycles). The stressed state corresponded to central tension with the stress ratio ρ equal to zero. The repeated loading was produced on a pulsator of one-sided action which provided the velocity of testing about 300 cycles per minute. The stress in testing was controlled by a dynamometer specially developed and placed in succession with the test specimen. To assess the carrying capacity of the materials some specimens (of steel and aluminium) were tested statically. The results of cyclic tests are plotted in Fig. 1 and 2. As can be seen from the figures, the strength of steel and aluminium alloy under low numbers of repetitions exceeds its static equivalent. A line according to formula (2) and a curve according to formula (3) are drawn on these figures. As is seen from the diagrams, in a comparatively small range of n - values ($n = 100$ to $n = 1000$), for which test data were available, design relationships (2) and (3) are in good agreement with each other and with the experimental results.

It has been found out that under a low-cycled repeated loading the value of the full permanent elongation is larger than that under a static loading. With the reduction of the number of loadings (or with the increase of stress) the value of the permanent elongation for steel and aluminium specimens increases. The results of testing steel under a single rapid loading have shown that its strength under the loading duration from 0.4 to 2 seconds increases up to 20 per cent as compared with the static strength. This is in agreement with the calculations done by formula (3).

Tests of steel and aluminium specimens under a cyclic loading have shown that the appearance of fracture is similar to that of specimens failed under a static loading, i.e. "throat" formation (though the "throat" in aluminium specimens was scarcely visible) is typical of specimens tested under a dynamic loading as well as of those tested statically.

Concretes (cellular, lightweight and heavy).

1. Specimens (prisms made of different concretes) were tested under a repeated loading by means of transportable jacks being connected up to the pulsation arrangements. The stressed state in testing all kinds of concrete corresponded to the central compression. Some specimens of dense silicate concrete were tested under repeated loading in shear.

When specimens were tested under small numbers of cycles of repeated loadings (about 1000 cycles) a pulsator was used which provided loading directly with the amplitude required without the speeding-up duty. The load was controlled by a specially developed dynamometer.

2. Table 1 gives basic characteristics of tested concrete specimens, covering the type of concrete, grade, size of specimens, stress ratio of a cycle and frequency of application of repeated load. Some specimens of heavy cement concrete have been subjected (before testing) to a long-term (1 to 3 years) centrally applied compressive load equal to 40 per cent of the static crushing load of reference specimens.

The results from testing specimens of various concretes in repeated compression are given in Fig. 3 to 11. Processing of the test data of Fig. 3 to 9 have indicated that it is inexpedient to use a common relationship (2) for all n -values, the relationships (2) have therefore been established separately for the ranges of large and small n . It also follows from the graphs on Fig. 3 to 9 that the curves plotted with the use of relationship (3) are in fairly good agreement with the test points in the entire range of n - loadings.

3. Fig. 10 presents relationships (3) plotted on the basis of the test data obtained in testing heavy cement concrete, perlite concrete and gas silicate. Comparison of the curves of the figure shows that under the same relative stress σ_{max}/R_{pr} specimens of gas silicate resist a smaller number of loading cycles than heavy cement concrete and perlite concrete, and the relative cyclic strengths of perlite concrete and heavy cement concrete are about the same. In the range of low numbers of load repetitions the curve for gas silicate appears to be lower than the value $\sigma_{max}/R_{pr} = 1$, but as the tests on perlite concrete, heavy cement concrete and dense silicate concrete have shown (Fig. 6) in the same range of numbers of repetitions some increase of the relative cyclic strength is observed as compared with a single static loading.

As it has been stated by tests failure of gas silicate is of fragile pattern, without preliminary development of deformations typical of heavy cement concrete. By way of illustration Fig. 13 presents oscillograms recorded in testing heavy cement concrete and gas silicate under repeated dynamic loads at the same relative stress $\sigma_{max}/R_{pr} = 0.97$.

4. Testing up to crushing of prisms of heavy cement concrete under a single static compressive load carried out on specimens preliminarily subjected to a long-term action of a compressive longitudinal force $N < N_{cr}$ (where N_{cr} is the longitudinal force at the occurrence of the ist crack) and then unloaded (main specimens) has shown that the strength of these specimens is by 8-14 per cent higher than the strength of specimens not subjected to preliminary compression (control specimens). The creep of that concrete was, according to the test results on the main specimens, from $8 \cdot 10^{-6}$ cm^2/kg to $11 \cdot 10^{-6}$ cm^2/kg.

Comparison of the results of cyclic tests on the main and control specimens (Fig. 11) allows the conclusion to be made that the relative cyclic strength of concrete preliminarily subjected to a long-term action of a compressive longitudinal force (main specimens) is somewhat lower than that of the same concrete but not subjected preliminarily to compression (control specimens).

5. Specimens of heavy cement concrete and dense silicate concrete were tested under rapid single centrally-applied compressive loadings. The duration of loading t was chosen within the limits observed under earthquake effects. For the values $t = 0.4$ to $t = 4$ sec. the strength of heavy cement concrete of grade 75 has increased by about 22 per cent as compared with that under a single static loading. For the duration from $t = 0.2$ to $t = 5$ sec. the strength of dense silicate concrete of Grade 250 and 600 has increased by 24 to 12% respectively as compared with that under static loading.

6. To that dense silicate concrete under pulsating shear special specimens were prepared. The bearing capacity of dense silicate concrete of Grade 200-300 in shear depending on the number of load cycles at two values of the stress ratio $\rho = 0.33$ and $\rho = 0.5$ were studied. Pulsation frequency in tests was taken equal to 600 cycles/min. The tests have shown that under shear as well, with the increase of the stress ratio the number of cycles required for crushing the specimen (Fig. 12) grows. The value of the relative endurance limit under shear for $\rho = 0.33$ is equal to $0.4\ R_{sh} \div 0.45\ R_{sh}$ with the number of

repetitions $5 \cdot 10^6$ cycles, and for $\rho = 0.5$ it varies within $0.5\, R_{sh}$ to $0.55\, R_{sh}$ under the same number of loadings.

Stability of Steel and Reinforced Concrete Struts under Dynamic Loading

In some cases the bearing capacity of working members is determined by the stability of elements in compression but not by the strength of the material. To study this problem under a cycle effect of the load experiments with slender steel and reinforced concrete struts posts were carried out under small number of cycles (up to 1000 loadings) of repeated loading with the stress ratio of a cycle $\rho \approx 0.1$ to 0.2 and the velocity of loading of about 50 cycles per minute. The repeated loading was produced by means of a low frequency exciter.

All steel and reinforced concrete bars failed as a result of loss of stability under dynamic load.

The experimental results are shown in Fig. 14a and b, where in the coordinates of the relative load $P^{cr}_{max} / P^{cr}_{st}$ against the logarithm of the number of loadings n test data are plotted, respectively for steel (Fig. 14a) and reinforced concrete specimens (Fig. 14b).

The tests have indicated that the relation between the bearing capacity and the logarithm of the loading numbers in the range of 1 to 1000 loadings can be characterized by a linear law (2)[x]. The value of the bearing capacity of slender struts in compression under repeated dynamic loading has appeared almost not to exceed the static critical force of the test struts, and with the increase of the number of loadings the intensity of the reduction of the ultimate load is insignificant.

Conclusions

1. The tests show that within the entire range of n - numbers of load repetitions under consideration a linear relationship by formula (2) commonly used cannot

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[x] Since no test data have been available for large numbers of n so far, relationship (3) have not been used for processing the results obtained.

be recommended for the description of the relative cycle strength of concretes. At the same time formula (3) gives fairly good agreement with the experimental data: this formula may be used for evaluation of the cyclic strength of building materials.

2. The tests have shown that when the perlite concrete of Grade 100 is subjected to pulsating compression the variation of its strength with the number of load repetitions is close to that established for heavy cement concrete. In this connection the coefficient of performance conditions m_s for perlite concrete in compression taken into account in the USSR Code for Designing Earthquake Resistant Structures may be assumed the same as that for heavy cement concrete (in calculations for compression $m_s = 1.2$). This lightweight concrete with the volume weight 1100 kg/cu.m and higher may be recommended for load-carrying structural elements subjected to dynamic effects, seismic ones included. For these purposes dense silicate concrete may also be recommended.

3. The tests on gas silicate have indicated that their cyclic strength is less than that of heavy cement concrete and perlite concrete. For gas silicate in calculations for compression $m_s = 1$. A clearly expressed fragile pattern of failure of gas silicate is an unfavourable factor for the performance of this material under dynamic loads. Thus gas silicate cannot be recommended for bearing structures working under conditions of intensive dynamic loads including seismic ones. The employment of gas silicate for earthquake-resistant buildings may be recommended only in complex members where a larger portion of the load is taken on by, for instance, heavy concrete.

4. As is shown by tests, the preliminary subjection of heavy cement concrete to a long-term loading equal to 0.4 of the short-term crushing load, increases the fragility of concrete and may diminish (Fig. 11) its resistability to cyclic loads (in the range of cycles $n < 200\,000$).

Since all structures before earthquake are exposed to a prolonged compression, the study of the problem is of great practical importance.

5. Tests on dense silicate concrete under pulsating shear have shown that the value of relative endurance limit under shear for $\rho = 0.33$ is equal to $0.4 \div 0.45\, R_{sh}$ at the number of repetitions 5×10^6 cycles and for $\rho = 0.5$ it varies from 0.5 to $0.55\, R_{sh}$

6. The results of the investigation of stability of steel and reinforced concrete bars show that the value of the critical load under a repeated loading does not exceed its static equivalent and changes but only slightly under the number of loadings from 1 to 1000. No corrections should, therefore, be introduced to the design resistances determined for a static loading, i.e. m_s should be assumed equal to unity, when designing steel and reinforced concrete members for stability under earthquake forces.

Table 1.

S.N.	Type of concrete	Size of prisms in cm	Concrete Grade	Number of cycles per minute	Stress ratio of a cycle $\rho = \frac{\sigma_{min}}{\sigma_{max}}$
1a	Heavy cement concrete				
	I series	10x10x30	200 & 300	300	0.05
	II series	10x10x30	200	100	0.05+0.1
1b	Heavy cement concrete subjected to a long-term loading				
	I series	10x10x30	200 & 300	100 & 300	0.05
	II series	10x10x30	200	100	0.05+0.1
2	Heavy cement concrete	7x7x21	200	300	0
3	Dense silicate concrete	10x10x30	250 + 300	335	0.1
4	Perlite concrete	10x10x30	100	300	0.05+0.1
5	Gas silicate with loess as main aggregate	10x10x30	50	300	0.04+0.1
6	Gas silicate on wind-blown sand				
	I series	10x10x30	75	300	0.05+0.1
	II series	10x10x30	75	90	0.02+0.06

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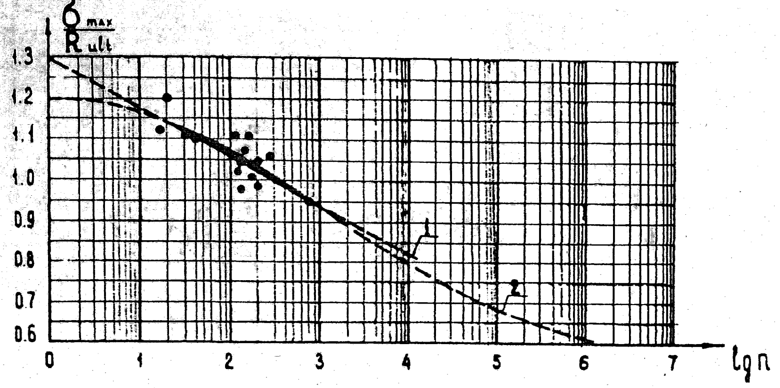

Fig. I. Cyclic Strength of Steel Specimens in Tension

$\omega = 300$ cycles/min; $\rho = 0$

I. $\sigma_{max} = R_{ult}\,(I,3-0,12\,\lg n)$ 2. $\sigma_{max} = 0,5+(I,2-0,5)e^{-(0,23\,\lg n)^2}$

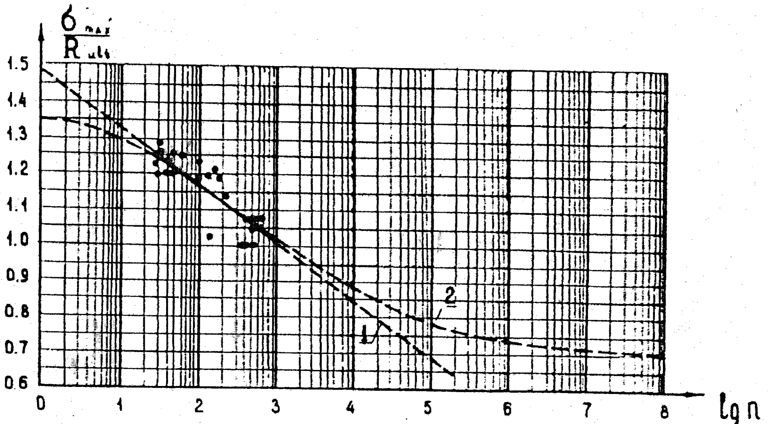

Fig. 2. Cyclic Strength of Aluminium Alloy in Tension

$\omega = 300$ cycles/min; $\rho = 0$

I. $\sigma_{max} = R_{ult}\,(I,49-0,16\,\lg n)$ 2. $\sigma_{max} = 0,7+(I,35-0,7)e^{-(0,28\,\lg n)^2}$

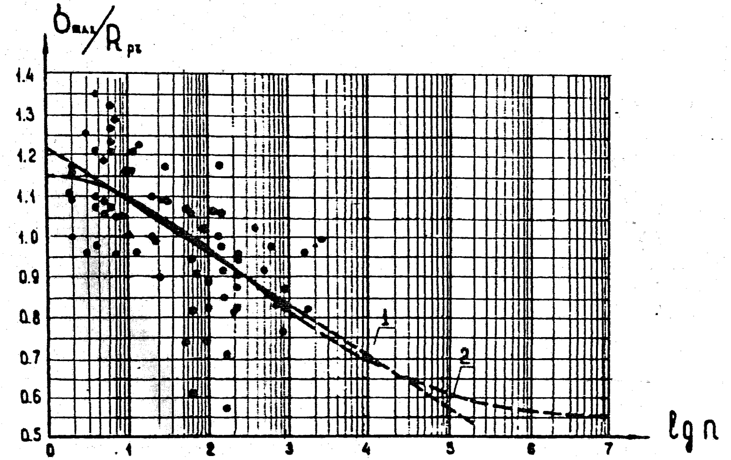

Fig. 3. Cyclic Strength of Heavy Cement Concrete (prisms of size 7x7x2I cm) in Compression.

$\omega = 300$ cycles/min; $\rho = 0$

I. $\sigma_{max} = R_{pr}\,(I,22-0,13\,\lg n)$ 2. $\sigma_{max} = 0,55+(I,15-0,55)e^{-(0,3\,\lg n)^2}$

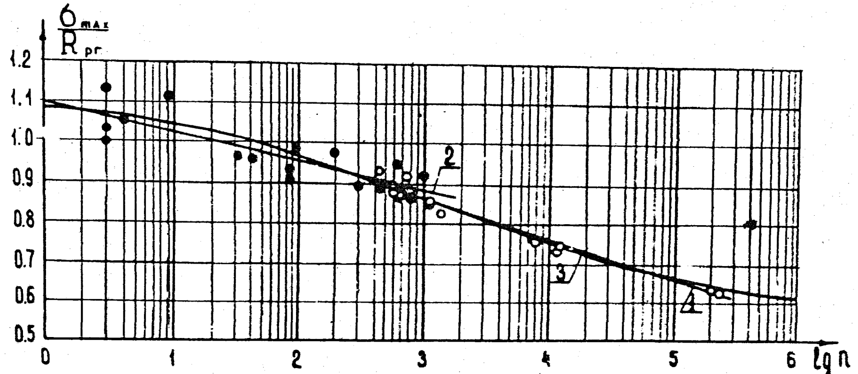

Fig. 4. Cyclic Strength of Heavy Cement Concrete (Prisms of size I0xI0x30 cm) in Compression

I, ○ specimens of the Ist series
2, ● specimens of the 2nd series

I. $\sigma_{max} = R_{pr}\,(I,18-0,1\,\lg n)$ $\omega = 300$ cycles/min. $\rho = 0,05$
2. $\sigma_{max} = R_{pr}\,(I,I-0,07\,\lg n)$ $\omega = 100$ cycles/min; $\rho = 0,05 \div 0,1$
3. $\sigma_{max} = 0,54\left[I + e^{-(0,24\,\lg n)^2}\right]$

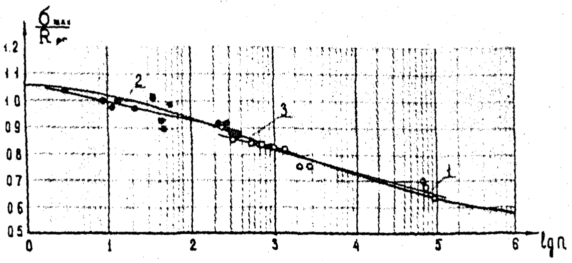

Fig. 5. Cyclic Strength of Precompressed Heavy Cement Concrete (main specimens)

I, ○ specimens of the Ist series

2, ● specimens of the 2nd series

1. $\sigma_{max} = R_{pr}\,(I{,}084 - 0{,}085\,\lg n)$ ω = I00 & 300 cycles/min; $\rho = 0{,}05$
2. $\sigma_{max} = R_{pr}\,(I{,}075 - 0{,}069\,\lg n)$ ω = I00 cycles/min; $\rho = 0{,}05 \div 0{,}I$
3. $\sigma_{max} = 0{,}53\,\left[I + e^{-(0{,}25\,\lg n)^2}\right]$

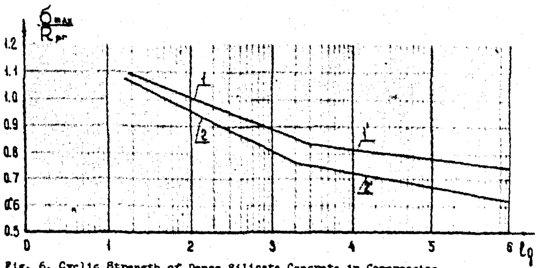

Fig. 6. Cyclic Strength of Dense Silicate Concrete in Compression

I. ω = 335 cycles/min; $\rho = 0{,}5$

2. ω = 335 cycles/min; $\rho = 0{,}I$

I. $\sigma_{max} = R_{pr}\,(I{,}26 - 0{,}15\,\lg n)$ I'. $\sigma_{max} = R_{pr}\,(0{,}95 - 0{,}055\,\lg n)$

2. $\sigma_{max} = R_{pr}\,(I{,}25 - 0{,}I2\,\lg n)$ 2'. $\sigma_{max} = R_{pr}\,(0{,}96 - 0{,}037\,\lg n)$

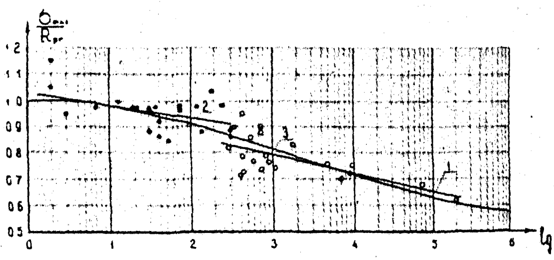

Fig. 7. Cyclic Strength of Gas Silicate with Wind-Blown Sand as Main Aggregate in Compression

I, ○ specimens of the Ist series 2, ● specimens of the 2nd series

1. $\sigma_{max} = R_{pr}\,(I{,}0 - 0{,}07\,\lg n)$ ω = 300 cycles/min; $\rho = 0{,}05 \div 0{,}I$
2. $\sigma_{max} = R_{pr}\,(I{,}02 - 0{,}046\,\lg n)$ ω = 90 cycles/min; $\rho = 0{,}02 \div 0{,}06$
3. $\sigma_{max} = 0{,}5\,\left[I + e^{-(0{,}23\,\lg n)^2}\right]$

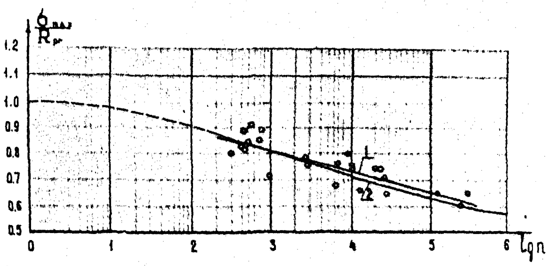

Fig. 8. Cyclic Strength of Gas Silicate With Loess as Main Aggregate in Compression

ω = 300 cycles/min $\rho = 0{,}04 \div 0{,}I$

I. $\sigma_{max} = R_{pr}\,(I{,}05 - 0{,}079\,\lg n)$

2. $\sigma_{max} = 0{,}5\,\left[I + e^{-(0{,}23\,\lg n)^2}\right]$

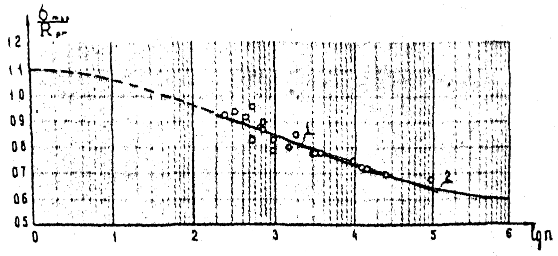

Fig. 9. Cyclic Strength of Perlite Concrete Under Compression

ω = [illegible] cycles/min; $\rho = 0{,}05 \div 0{,}I$

1. $\sigma_{max} = R_{pr}\,(I{,}I7 - 0{,}II\,\lg n)$

2. $\sigma_{max} = 0{,}55\,\left[I + e^{-(0{,}26\,\lg n)^2}\right]$

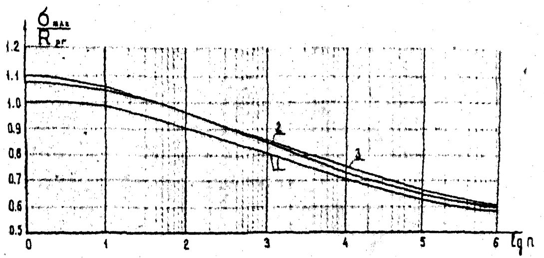

Fig. IO. Comparison of Cyclic Strengths of Different Concretes in Compression.

I.- on the basis of tests with gas silicate

2.- on the basis of tests with perlite concrete

3.- on the basis of tests with heavy cement concrete

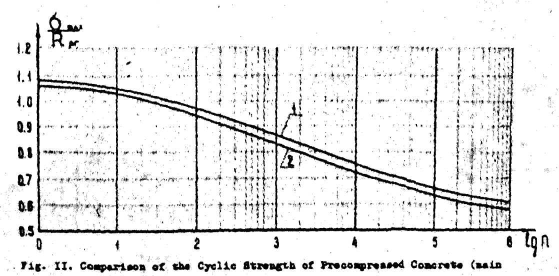

Fig. II. Comparison of the Cyclic Strength of Precompressed Concrete (main specimens) and Control Specimens in Compression

I - control specimens

2 - main specimens

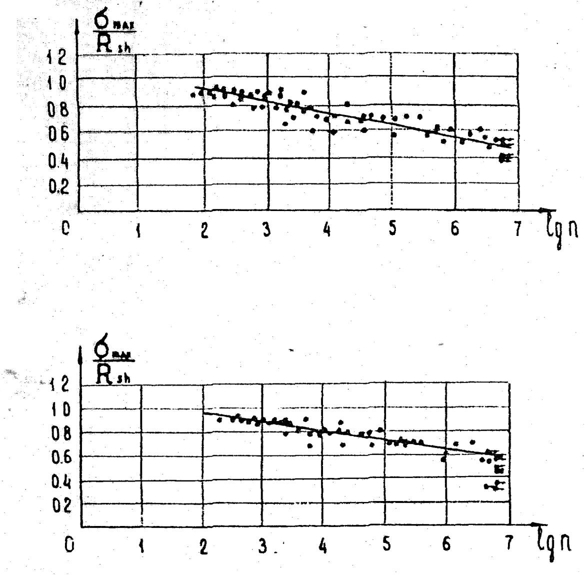

Fig. I2. Cyclic Strength of Dense Silicate Concrete of Grade 200 ÷ 300 in Shear

a) ω = 600 cycles/min; ρ = 0,33
I. $\sigma_{max} = R_{sh}$ (I,I3 - 0,094 lg n)

b) ω = 600 cycles/min; ρ = 0,5
I. $\sigma_{max} = R_{sh}$ (I,I29 - 0,08 lg n)

←• not failed specimens

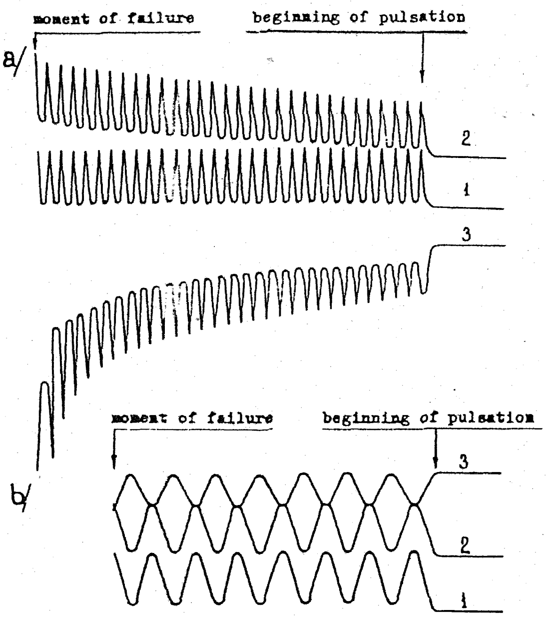

Fig. I3. Oscillograms obtained from Cyclic Tests With Gas Silicate and Heavy Cement Concrete

a) heavy cement concrete; the velocity of the tape run during the record was I cm/sec

b) gas silicate; the velocity of the tape run during the record was 4 cm/sec;

I - load, 2 - longitudinal deformations

3 - transverse deformations

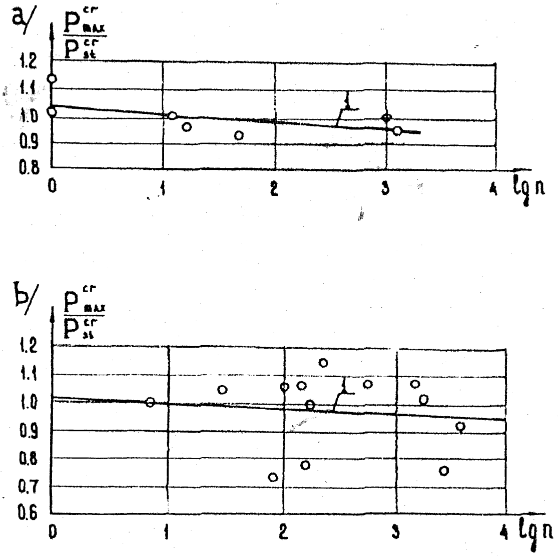

Fig. I4. Bearing Capacity of Slender Struts Under Not Numerous Repeated Loadings

a) for steel struts ω = 50 cycles/min; ρ = 0,I÷0,2
I. $P^{cr}_{max} = P^{cr}_{st}$ (I,042 - 0,012 lg n)

b) for reinforced concrete struts ω = 50 cycles/min;
ρ = 0,I ÷ 0,2
I. $R^{cr}_{max} = R^{cr}_{st}$ (I,022 - 0,0I9 lg n)