BEHAVIOUR OF PLAIN CONCRETE UNDER DYNAMIC LOADING WITH STRAINING RATE COMPARABLE TO EARTHQUAKE LOADING

by S. Ban* and H. Muguruma**

Introduction

In designing a structure subject to violent earthquake load, the engineer faces the twofold problem in determining the peak loads on the structure. At present, there are many analytical researches on the vibration of structures under the action of violent earthquakes. However, these results cannot be applied reasonably to the practical design of the actual structures because of their assumptions. Among those, there is a misunderstanding regarding with the restoration force-displacement relations actually shown by structure under dynamic load, i.e., the ideal elasto-plastic or the rigid-plastic assumption.

Although the analysis of the structures based on such ideal bodies is, of course, necessary to clarify the fundamental behaviours of structure under the action of seismic waves, it is also required to improve the assumptions on the restoration force-displacement relations in the actual structures, because they will be necessary to extend the analytical results obtained on the ideal body to the more reasonable design of actual structures.

Since the restoration force-displacement relations of structures is depending on their composing members or materials, the behaviour of members or materials under the dynamic load should be studied precisely in advance. While a number of investigators has studied the properties of structural members, i.e., beams and columns, under the impact or repeated loading, the test results obtained did not agree so well with the analysis as were expected. It will be evident that the behaviour of members under the dynamic load is decided by the stress-strain relations of structural materials under similar dynamic loading. From this concept, it can be concluded that the fundamental problem is to study the behaviour of structural materials, especially their stress-strain relationships and the strength, under the dynamic load.

In this study, it was the purpose to investigate the behaviours of plain concrete under the impact or repeated loading with loading rate comparable to the earthquake forces.

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Scope of the Tests

A number of investigators has studied the properties of plain concrete under impact or repeated loading. D. A. Abrams (1), P. G. Jones and F. E. Richart (2) employed relatively low loading speeds, because the aim of their studies was to designate the standard method of compression tests for concrete. D. Watstein (3), C. Katsuta (4), J. Takeda (5), D. McHenry and J. J. Shiderer (6) had tested a plain concrete in compression at the rates of strain varying from 10^{-6} to 10 in./in. sec.. Considering the vibration of the ordinary reinforced concrete structures, its frequency is expected to be 0.5 to 10 cycle per sec. at the time of earthquake. Therefore it is desirable to consider the impact whose duration is about 1 to 0.05 sec.. The corresponding average rate of strain can be predicted as 3×10^{-3} to 6×10^{-2} in./in.sec.. Therefore, in this study the average duration of impact load was selected as 1 sec. throughout the impact loading tests.

The repeated loading tests were also undertaken in this study. On the fatigue behaviour of plain concrete many test results were already presented (7). However, almost of them were to investigate the physical properties of concrete for the permanent use of structures under the usual design loads, and therefore, the main object was to determine the fatigue limits of concrete as a basis of safety design for reinforced concrete structures under the stress of several millions repetition. From the standpoint of the analysis of structure against the violent earthquake forces, it is consequently important to confirm the stress-strain relationship of plain concrete under the violently repeated stress, where a high speed repetition and a large number of cycles are not necessary but the upper limit of stress should be taken higher than that of usual repeated tests. Therefore, in this report the dynamic stress-strain relations were investigated under the repeated stress, the upper limit being 60 to 90 % of static strength.

Program of the Experiments

(1) Test specimens

The study included the concretes having the different mix proportions as listed in Table 1. Both static and dynamic (impact or repeated) loading specimens were prepared in each mix of concrete.

The materials used in the concrete specimens were normal portland cement and river aggregates under 15 m.m..

The test specimens used in Dynamic and companion static tests were 7.5 x 15 cm cylinders. The concrete was mixed by hand and cast into the steel molds by the method of tapping with 6 m.m. dia. steel bar. At the age of 3 days, the mold was removed and then the specimens were partly moist-cured and partly cured in air. Prior to testing the moist-cured specimens were air-dryed for 3 days to get the surface of concrete dry enough for application of bonded type wire strain gages.

(2) Test procedure and apparatus

(a) Static tests ----- The 7.5 x 15 cm companion cylinders were tested in a 100 ton capacity hydraulic machine. The load was applied to the specimen at a loading rate of about 20 kg/cm^2 sec.. The loading speed was adjusted by controlling the valve in oil pipe at the initial stage of loading and no further adjustments were made until the specimen began to yield before the maximum load was reached.

The bonded type wire strain gauges were used for the compressive strain measurement. A pair of gauges mounted on opposite sides at mid-height of each specimen were connected in parallel and the average of the output of each gauge was recorded directly.

(b) Impact loading tests ----- Tests were made in a loading apparatus composed of two levers shown in Fig. 1. The 7.5 x 15 cm concrete specimen was placed on a 25 ton capacity load cell fixed on the lower joist. The impact load was applied on the specimen by slowly dropping a 500kg dead weight on extreme end of upper lever. The strain was measured in the similar method as described before. The outputs of the gauges mounted on the specimen and the load cell were fed into the dynamic strain indicator with wide band strain amplifier and self-recording oscillograph as shown in Fig. 2. A block diagram of equipment is shown in Fig. 3.

(c) Repeated loading tests ----- The fatigue testing machine specially prepared for the fatigue tests under the low speed loading cycles was used. The speed of loading cycles was 1.2 cycle per sec., and was kept constant throughout the tests. The upper limit of loading cycles was selected in the range from 60 to 90 % of the static breaking load of the same concrete cylinder. This adjustment was done by mechanical cams which move the base plate up and down. The compressive strain of concrete specimens as well as the corresponding load were recorded by the same system as that in the impact loading tests. The fatigue testing machine and measuring equipments used for the tests are shown in Fig. 4.

Results of Impact Loading Tests and Discussions

(1) Stress and strain of concrete

Typical records of stress or strain versus time duration are illustrated in Fig. 5. In Fig. 5, it will be noted that the rate of loading was gradually increased at the first stage of loading (see the portion AB in Fig. 5) and was contrarily decreased at the last stage (see the portion CD in Fig. 5). At the intermediate stage the rate of loading was kept almost unvaried (see the portion BC in Fig. 5). It has been verified by the many past investigations that these gradual changes of loading rate have no influence upon the properties of concrete under impact loading.

Typical stress-strain relations obtained from the stress-time and strain-time records are shown in Fig. 6. From those the initial tangent modulus and the secant modulus corresponding to the stress level of one-third of dynamic compressive strength were calculated.

(2) Comparison between the static and impact loading test results

The properties of concrete under the static and impact loadings are compared in Table 2, in which the average values obtained for each concrete mix are listed. The ratios of the dynamic (impact loading) to static compressive strengths, secant moduli of elasticity, maximum compressive strains and strains corresponding to the maximum stress are given in Table 2 and are shown in Fig. 7 (a), (b) and (c).

From Fig. 7 (a) it will be seen that the effect of the dynamic loading upon the compressive strength is more remarkable for the weaker concrete than the stronger concrete. However, no significant difference in strength is recognized in the concrete having the static strength more than 260 kg/cm^2 . Similar properties were found out in the comparison between dynamic and static secant modulus of elasticity (see Fig. 7 (b)). On the contrary, the maximum compressive strain was observed smaller in the impact loading tests than those in the static tests. The decrease in the maximum compressive strain was also found out larger with the decrease in static strength, provided that the static strength is less than 260 kg/cm^2 .

(3) Assumption of stress-strain curve of concrete under impact loading

As mentioned above, the impact loading with the loading rate from 200 to 400 kg/cm^2 sec. had considerable influences upon the properties of concrete having the static compressive strength less than 260 kg/cm^2 The variation of secant modulus of elasticity as well as maximum compressive strain will not be neglected in the theoretical analysis of the elastic and plastic behaviours of reinforced concrete members under seismic action (8).

Under the assumption of ideal stress-strain curve shown in Fig. 8 The dynamic stress-strain relation will be predicted through the static one, provided the ratios of dynamic to static compressive strength, secant modulus of elasticity and maximum strain are given as follows:

For concrete having the static strength less than 260 kg/cm^2

$$\frac{E_{dc}}{E_{sc}} = 1.975 - 0.00375\,\sigma_{sc} \qquad (1)$$

$$\frac{\sigma_{dc}}{\sigma_{sc}} = 2.3 - 0.005\,\sigma_{sc} \qquad (2)$$

$$\frac{\varepsilon_{dc}}{\varepsilon_{sc}} = -0.3 + 0.005\,\sigma_{sc} \qquad (3)$$

For concrete having the static strength more than 260 kg/cm^2

$$\frac{E_{dc}}{E_{sc}} = \frac{\sigma_{dc}}{\sigma_{sc}} = \frac{\varepsilon_{dc}}{\varepsilon_{sc}} = 1 \qquad (4)$$

Results of Repeated Loading Tests and Discussions

(1) Static test results

The compressive strength obtained from the static tests of conpanion cylinders are summarized in Table 1 (b).

(2) Stress-strain curves under repeated loading

Typical stress-strain relations measured by the dynamic strain indicator durihg the repeated loading are shown in Fig. 9 with commentary on the initial strain and upper limit stress ratio. This illustrates that the stress-strain curve varies with the number of load repetitions. Whatever the ratio of upper limit to static strength may be large or small, the convex upward curve straightens under the loading cycles and finally become concave upward prior to the failure. And this shows that concrete possesses a property similar to strain hardening in metals. The degree of concavity is expected to warn the failure. As the upper limit of loading cycles becomes larger, the rapid transition in curves from convex upward to concave upward was recognized in the tests. These transitions had been also observed in the fatigue tests under the high speed loading cycles with relatively small stress intensity less than 60 % of the compressive strength (7).

Such property as strain hardening in stress-strain relations of plain concrete is of particular importance to discuss theoretically the elastic and plastic behaviours of actual reinforced concrete members or structures subject to a high repeated load. However, the curves obtained are too complicated to be expressed in simple formula. Therefore, in this study, several basic terms on stress-strain curve were representatively investigated, i.e., the increase of compressive strain at upper limit, the increase of permanent strain and the decrease of initial tangent or secant modulus of elasticity at each loading or unloading.

(3) Maximum or permanent strain versus number of loading cycles

Fig. 10 and Fig. 11 shows the maximum and permanent strains of concrete in relation to the number of loading cycles. From those, it is evident that the maximum strain as well as the permanent strain increased gradually with the loading cycles. The amount of such increases had no obvious relations to the concrete mixes or the static strength in compression, but was evidently related to the maximum compressive strain observed by the first loading. This strain will be defined as " original strain " and the total number of loading cycles before the failure occurs will be defined as " endurance number " hereafter. The larger the original strain , the endurance number became less, and on the contrary the maximum strain as well as the permanent strain at the fatigue failure became larger. Especially, when the original strain exceeded a limited value of about 0.1 %, the rate of strain increase became excessively larger, and the endurance number was about 30 or less. This can be exactly seen in Fig. 12 giving the relation between the original strain and the endurance number.

Consequently, it can be predicted that when a reinforced concrete members are subjected to the repetitive load such as the compressive fiber strain of concrete exceeds 0.1 %, the maximum and permanent displacements of the members will continue to increase rapidly and the members will result in fatigue after further loading cycles.

Additionally, a curve giving the maximum or permanent strain can be decided in relation to the endurance number and it is plotted in Fig. 10 and Fig. 11, respectively. Using Fig. 12 and Fig. 10 or Fig. 11, it is possible to predict the number of loading cycles which can be withstood by concrete, when the intensity of loading cycles as well as the maximum or permanent strain at the fatigue failure are previously assumed.

(4) Relationship between modulus of elasticity and number of loading cycles

As it can be seen in Fig. 9, the modulus of elasticity of concrete varied gradually with the increase in number of loading cycles. Simplifying the stress-strain curves at each loading cycles as shown in Fig. 13, the initial tangent moduli E_A and E_C as well as the tangent moduli E_B and E_D were calculated for each loading cycle. In fig. 14 the variations of a initial tangent modulus E_A are plotted against the number of loading cycles as an example. It can be seen from Fig. 14 that almost of the variations in the elastic modulus took place during the first 20 - 30 loading cycles and thereafter the obvious variations were not recognized. Especially, the variations were remarkable in the first 2 or 3 loading cycles. Consequently, we can conclude that the dynamic behaviour of a reinforced concrete member will change remarkably under the first 2 or 3 loading, when the member is subjected to high loading repetition.

Conclusions

From the test results following conclusions were derived.

Impact loading tests

(1) From the comparison with the static tests on plain concrete, it was found that under the impact loading with the loading rate from 200 to 400 kg/cm^2 sec. the compressive strength of plain concrete as well as the secant modulus were observed larger than those obtained from the static tests.

(2) The maximum compressive strain and the strain corresponding to the maximum stress of strain-stress relation were measured remarkably smaller by impact loading than by static loading.

(3) These differences became more distinctly when the concrete tested showed lower strength, but were not recognized at all for the concrete having the static strength more than 260 kg/cm^2

Repeated loading tests

(1) Under the repetition of high load (60 to 90 % of static crushing load) and the constant loading speed of 1.2 cycle per sec.remarkable transitions from convex upward to concave upward were recognized in the stress-strain curves. This shows that concrete possesses a property

similar to strain hardening in metals.

(2) The maximum strain increase and permanent strain increase took place in contact with the number of loading cycles. This phenomena was very remarkable when the maximum strain by the first loading exceeded 0.1 %.

(3) The initial as well as the secant modulus of elasticity varied in various ways depending on the intensity of load. However, most of these variations took place in the early stage of loading cycles, usually during the first 20 to 30 cycles.

(4) Number of cycles withstood by concrete before failure occurred was found very small under the loading cycles with the original strain exceeding 0.1 %.

References

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(3) D. Watstein, J. of the ACI, Vol. 24 No. 8, April 1953.

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Nomenclature

E_{dc} and E_{sc} = Dynamic and static secant moduli of elasticity (in kg/cm^2)

σ_{dc} and σ_{sc} = Dynamic and static compressive strengths (in kg/cm^2)

ε_{dc} and ε_{sc} = Dynamic and static maximum strains

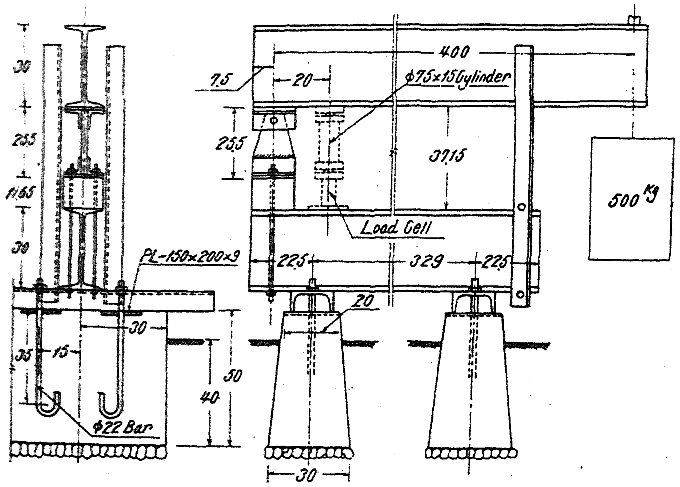

Fig. 1 Impact loading apparatus.

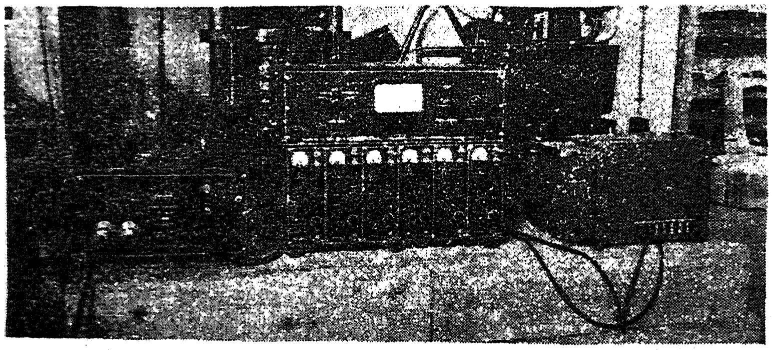

Fig. 2 Dynamic strain measuring apparatus.

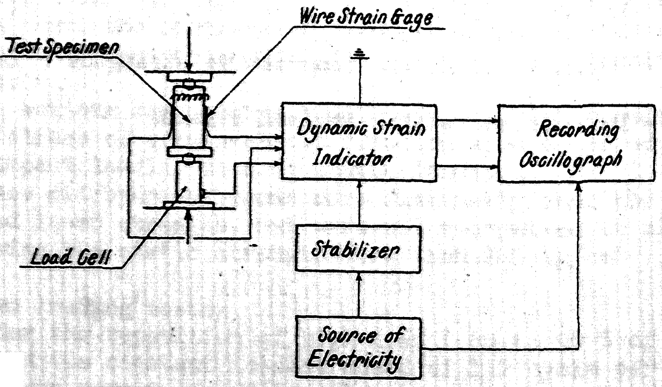

Fig. 3 Block diagram of equipment for stress and strain measurings.

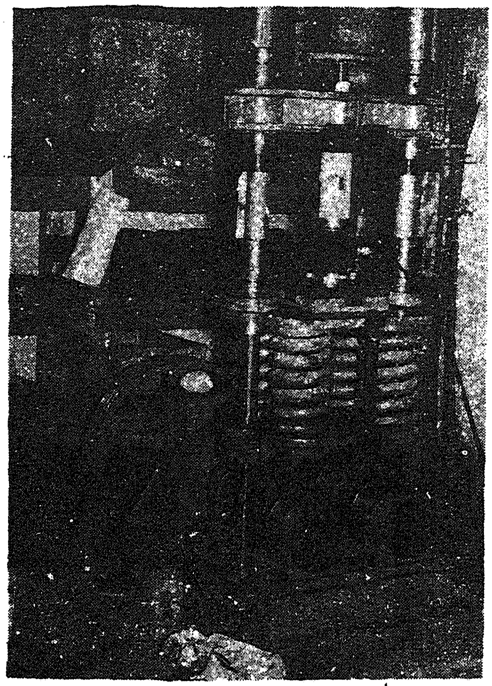

Fig. 4 Fatigue testing machine.

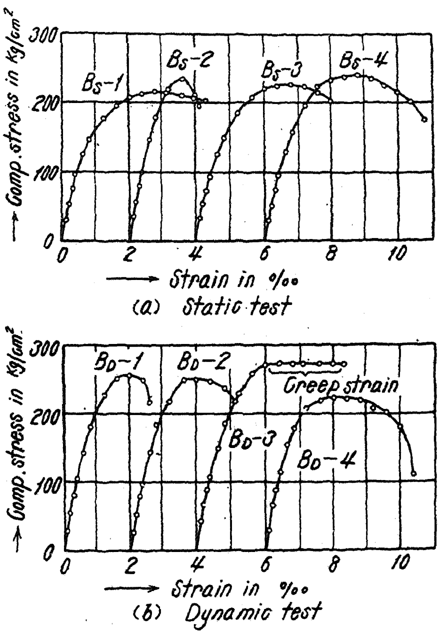

Fig. 6 Typical static and dynamic stress-strain curves obtained from the impact tests of B - Mix concrete.

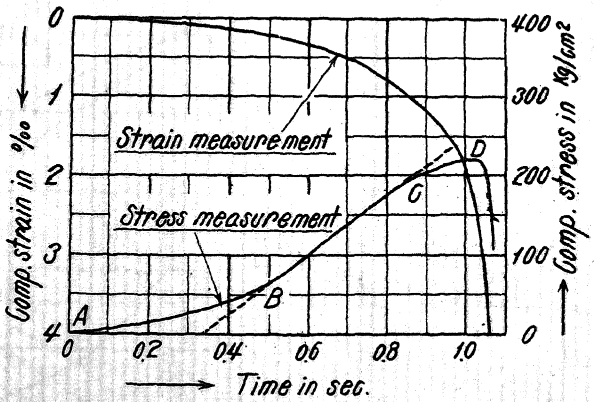

Fig. 5 Typical stress-time and strain-time records of concrete under impact loading (Specimen Bd - 4).

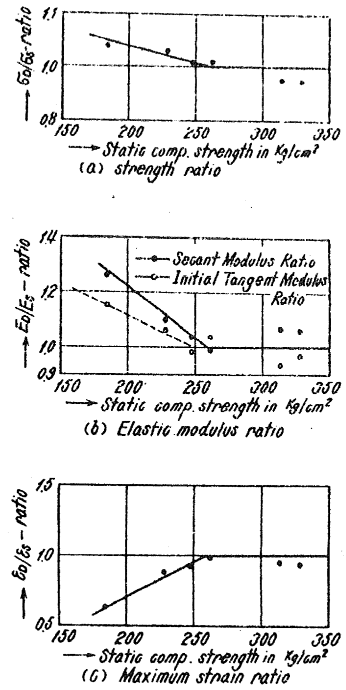

Fig. 7 Comparision between impact loading and static test results.

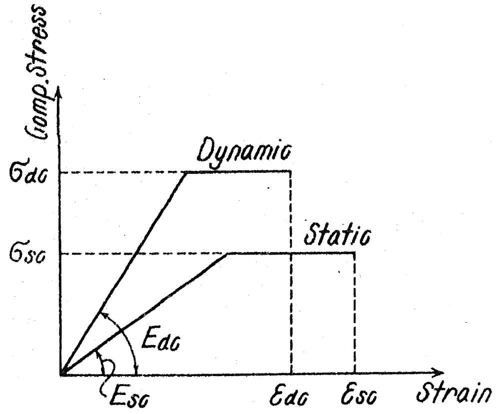

Fig. 8 Ideal stress-strain curves.

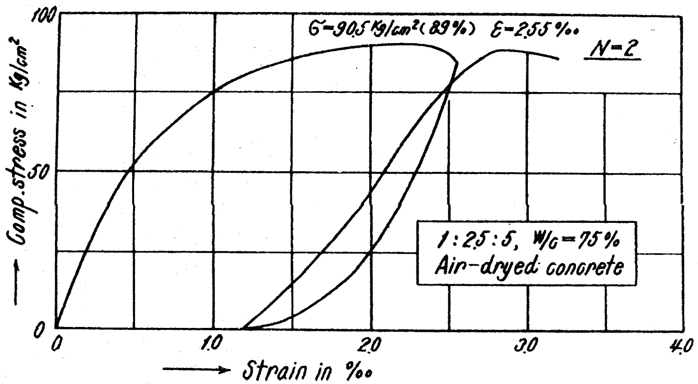

Fig. 9 Typical stress-strain curves under repetitive load.

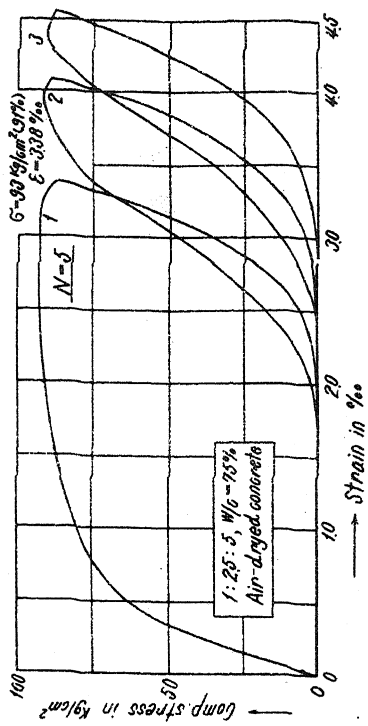

Fig. 9(b)

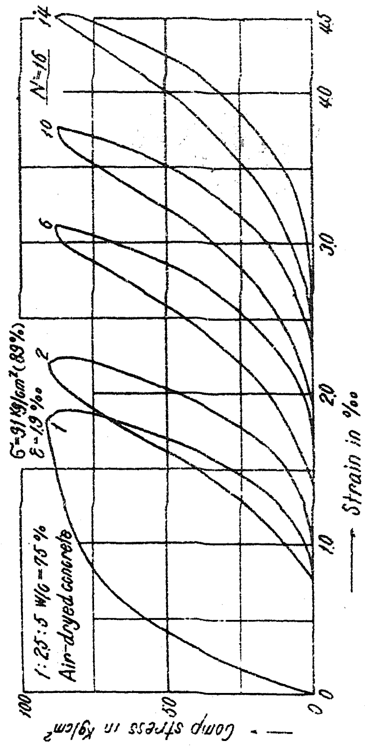

Fig. 9(c)

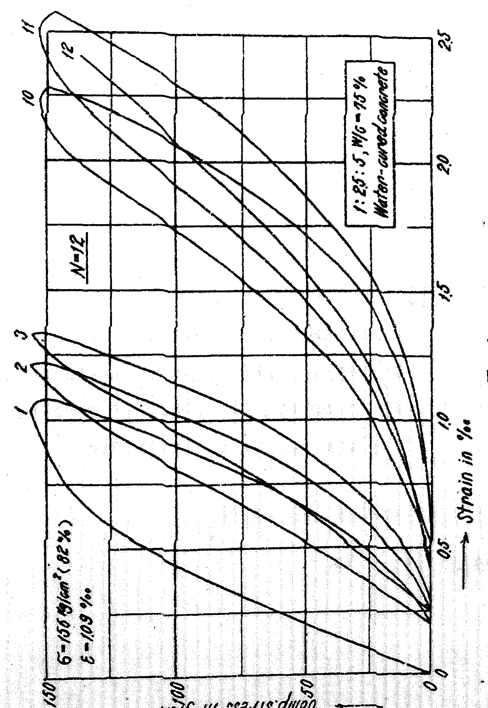

Fig. 9(d)

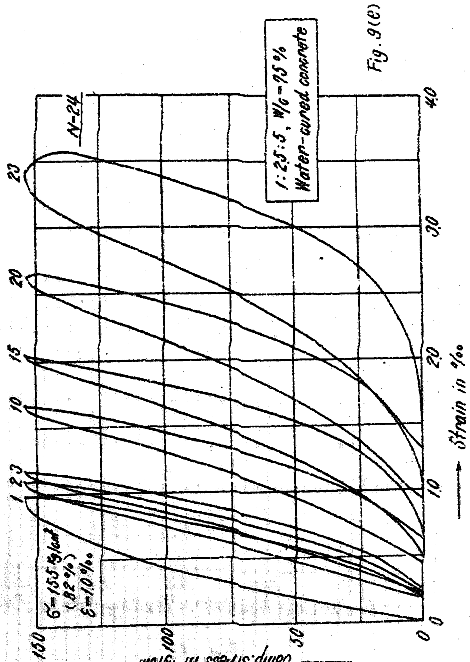

Fig. 9(e)

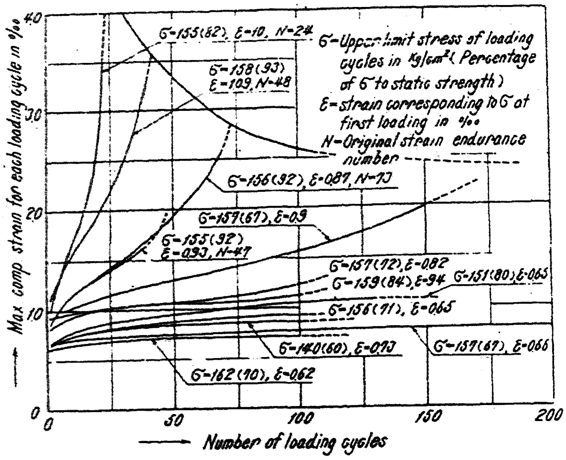

Fig. 10

Fig. 10

Relations between maximum compressive strain for each loading cycle and number of loading cycles.

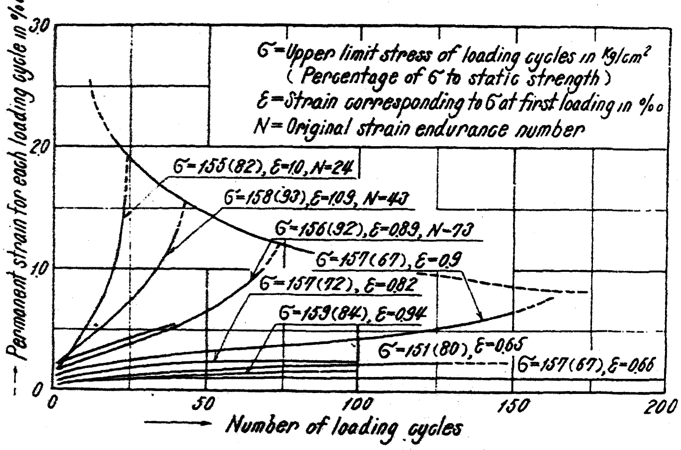

Fig. 11

Fig. 11

Relations between permanent strain for each loading cycle and number of loading cycles.

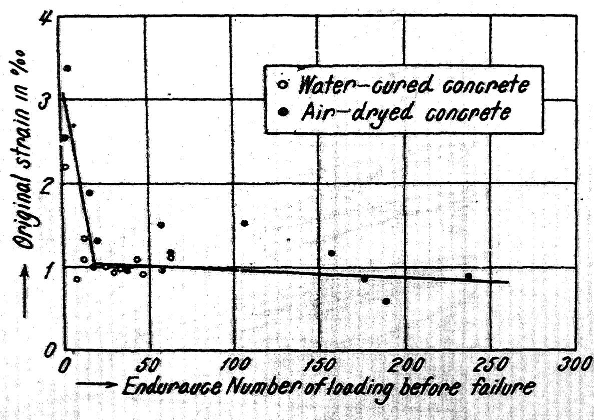

Fig. 12

Fig. 12

Relations between maximum strain at the first loading and number of loading cycles before failure occurred.

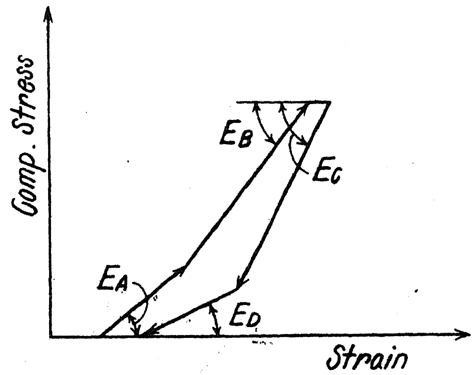

Fig. 13 Simplified stress-strain curve under repetitive load.

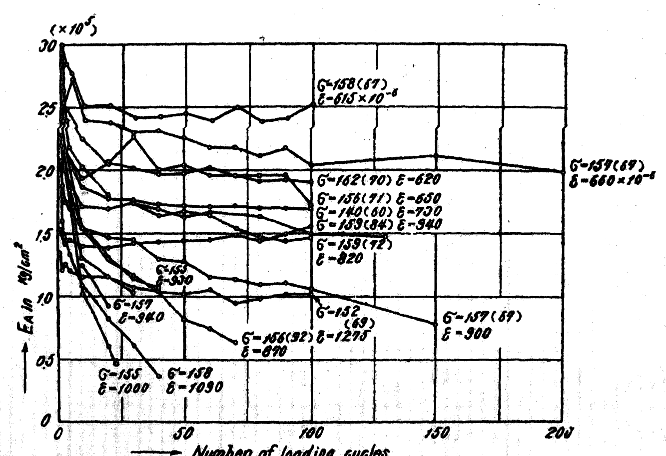

Fig. 14 Relations between E_A and number of loading cycles.

Table 1 (a) Test Schedules for Impact Loading

Test Series	Mix Proportion by Weight	W/C-Ratio in %	Test Age in Days	Number of Test Specimens Static Test	Impact Loading Test
A	1 : 2.5 : 5	75	28	3	4
B	1 : 2.5 : 5	70	28	4	4
C	1 : 2 : 4	65	28	5	5
D	1 : 2 : 4	60	28	4	5
E	1 : 1.5 : 3	55	28	4	5
F	1 : 1.5 : 3	50	28	4	5

Table 1 (b) Test Schedules for Repeated Loading

Test Series	Mix Proportion by Weight	W/C-Ratio in %	Test Age in Days	Static Comp. Strength in kg/cm^2	Number of Test Specimens Static Test	Repeated Loading Test
AD*	1 : 2.5 : 5	75	28	116	5	11
BD*	1 : 2.5 : 5	70	28	108	5	10
CD*	1 : 2 : 4	65	28	178	3	3
AW**	1 : 2.5 : 5	75	28	179	6	10
BW**	1 : 2.5 : 5	70	28	234	6	5
CW**	1 : 2 : 4	65	28	220	4	5

* Air-dryed concrete, ** Water-cured concrete.

Table 2 Summary of Impact Loading Test Results

Test * Series		Secant Modulus in kg/cm^2	Initial Tangent Modulus in kg/cm^2	Time Duration of Loading in sec.	Comp. Strain Corresponding to Breaking Stress in %	Maximum Strain in %	Comp. Strength in kg/cm^2	Average Rate of Loading in $kg/cm^2.sec.$	Average Rate of Strain in 1/sec.
A	As	$2.26x10^5$	$2.99x10^5$	40.0	0.310	0.392	185	6.21	$62.3x10^{-6}$
	Ad	$2.28x10^5$	$3.44x10^5$	1.09	0.247	0.247	200	308	$1606x10^{-6}$
	Ad/As	1.26	1.15	----	0.56	0.63	1.08	----	-------
B	Bs	$2.51x10^5$	$3.17x10^5$	32.2	0.250	0.382	229	7.15	$50.5x10^{-6}$
	Bd	$2.77x10^5$	$3.39x10^5$	0.61	0.200	0.335	243	418	$2490x10^{-6}$
	Bd/Bs	1.10	1.07	----	0.80	0.88	1.06	----	-------
C	Cs	$2.68x10^5$	$3.39x10^5$	23.8	0.220	0.309	248	11.3	$60.6x10^{-6}$
	Cd	$2.80x10^5$	$3.34x10^5$	1.38	0.178	0.283	254	201	$1334x10^{-6}$
	Cd/Cs	1.04	0.985	----	0.81	0.92	1.02	----	-------
D	Ds	$2.54x10^5$	$2.86x10^5$	26.2	0.232	0.321	262	11.0	$68.5x10^{-6}$
	Dd	$2.52x10^5$	$2.97x10^5$	1.00	0.220	0.315	267	444	$1818x10^{-6}$
	Dd/Ds	0.99	1.04	----	0.95	0.98	1.02	----	--------
E	Es	$2.85x10^5$	$3.77x10^5$	25.4	0.172	0.242	329	11.2	$56.5x10^{-6}$
	Ed	$3.04x10^5$	$3.66x10^5$	0.94	0.180	0.227	312	494	$1812x10^{-6}$
	Ed/Es	1.07	0.97	----	1.05	0.94	0.95	----	-------
F	Fs	$2.93x10^5$	$3.36x10^5$	38.2	0.193	0.257	314	8.75	$37.5x10^{-6}$
	Fd	$3.15x10^5$	$3.14x10^5$	0.92	0.180	0.243	300	309	$1476x10^{-6}$
	Fd/Fs	1.07	0.94	----	0.93	0.95	0.96	----	-------

* Suffix " d " = Impact loading test, Suffix " s " = Static test.