DYNAMICAL COMPRESSIVE DEFORMATION AND FAILURE OF CONCRETE UNDER EARTHQUAKE LOAD

T. Hatano*
H. Tsutsumi**

Introduction

Study on the earthquake proof of concrete dams has expanded its scope from dynamics of perfect rigid bodies to the analysis of elastic bodies and even to elastic vibrational approaches in which the damping of vibration, to be obtained through vibration tests of real dams, is supposed to be viscous damping[1)].

To advance such studies further, it seems highly important to make basic researches on dynamical properties of materials in the structure.

As the first step in this direction, we conducted experiments on the response of concrete when one stroke of compressive load, with the same load-velocity as earthquake load, is given, and attempted to look into the elasticity, viscosity and failure of concrete.

Such experiments were first attempted about 20 years ago by Professor Katsuta of Tokyo Industrial College[2)], but we carried out manifold experiments on various kinds of concrete and mortar with a simple high-speed compressive test machine, which we made, and handy strain and pressure meters, and tried to obtain general relations, and furthermore to explain the dynamical behaviors of concrete.

Methods of Experiments

Photo 1 shows arrangement of the high-speed compressive test machine and other measuring apparatuses. It is possible to carry out experiments on failure at varying speeds ranging from 15 r/min. to 300 r/min., which will be developed by turning the fly wheel with motor. The oil pressure pump is driven by the fly wheel. The oil in the cylindrical oil tank flows into the pump, and by pulling the lever, the globular valve comes off and the compressed oil runs beneath the ram of the 100-ton Amsler compressive test machine. The ram is impulsively pushed up by the oil, and the specimen is compressed. On the other hand, the cum, linked with the piston of the oil pressure pump, is set in motion, and pushes the globular valve back to its original position so that the oil can be sent beneath the ram only during one stroke of the pump. The ram is hoisted by 2 mm in one stroke, and the 20 cm high concrete specimen fails in about 0.03 sec. to 1 sec. according to the speeds of the fly wheel ranging from 15 r/min. to 300 r/min.

---

* Chief Research Engineer, Central Research Institute of Electric Power Industry, Tokyo.

** Assistant Research Engineer, ibid.

Photo 2 shows the positions of the strain and pressure meters for the specimen. As pressure meter, we used a short cylinder made of special steel, in which un-bonded type strain gauge was fixed. Its capacity is 100 tons, and sensitivity, 28 μ/ton. As the strain meter, we used π gauge, that is a thin phosphor-bronze plate, of the Ω shape on which a bonded type strain gauge is stuck. And the strain meters were fixed in the perpendicular direction on the pressure plates on the upper and lower sides of the specimen, and the deformations were recorded, together with pressure, in 20 cm between the bottom and the top of the specimen.

As it is difficult to expect parallel movements of the upper and lower sides of pressure plates, we used a total of four gauges in two diametrical directions and took the average of four strain values. The gauges could stand 3 mm of compressive deformation, and their degrees of sensitivity, though different to some degrees, were approximately 1,600 μ/mm. These measuring meters were carefully checked before and after each experiment (the pressure meter was examined by the Amsler test machine, and the strain meter, by a 1/1,000 mm dial gauge).

The properties of cement and aggregates used are given in Tables 1 and 2. Using these data, we carried out a total of 14 experiments on the Test No.1 - No.10 concrete and Test No.11 - No.14 mortar of the mix proportions and ages indicated in Table 3. The properties of not hardened concrete and mortar right after the making of the specimen are also appended in this thesis. In the meantime the specimen is a cylinder, 10 cm in diameter and 20 cm in height, which had been cured in the water at a temperature of 20 degrees C until right before each experiment.

Test Results

Each test was made on about 20 specimens, the first three of which were for ordinary statical tests. Although we designed to fail the specimens in about 100 sec., it was found difficult to adjust load velocity by hand. In dynamical tests, there arose cases where in two strokes of impulsive load acted on and failed the specimens or the records of the strain meter vibrated too much to read rightly. In the former cases, the test findings were discarded, and in the latter cases, only the readings of the pressure meter were adopted.

Failure, as is shown in Photo 3, typically gave conic dents on both top and bottom sides of the cylindrical specimen, but made no difference by failure time. But in the statical failure of a poor-mix specimen, just as shown in Photo 3, the specimen did not break up even after the failure. In the case of dynamical failure, it was found that the higher the age of the material was and the richer its mix was, the bigger sound was produced and the circumference of the conical dents was scattered in small pieces. It was also discovered that the larger the strength was, the more coarse aggregates were broken into pieces and the greater the deviation of strength was (See below).

Fig. 1 shows a few instances of test records. Since the load apparatuses made use of the rotation of the fly wheel, the relationship between load and time approximated to the (1 - cos at) form and near failure, the load velocity became low and the strain velocity high. In the case of statical failure, any type of specimen and in the case of dynamical failure, the specimen of poor mix and long failure time, after withstanding a load slightly smaller than the maximum one after load reached the maximum point, were seen broken up. This tendency was far more conspicuous in mortar than in concrete. At the instant of failure, the pressure reading bounced back to its original position, while the strain record was seen vibrating at about 60 cycles/sec. due to the sharp rise of the ram.

The stress-strain curves were drawn up on the basis of test records, and the representative of them were described in Fig. 2-1 to Fig. 2-14 for each Test No. As the strain velocity is not constant, the curve are given by failure time t which is the time from the beginning of load to the maximum of it. The stress-strain curve of the portion which withstood load even after it reached the maximum stress and whose pressure record was clearly visible is indicated by dotted line. The diagram proves that the smaller the failure time is, the steeper the stress-strain curve crawls, and that the poorer the mix is, the more convex the curve becomes. The gibbous curvature of mortar is far larger than that of concrete.

Fig. 3-1 to Fig. 3-14 show the relationships between the strength of failure σ_u and failure time t and between the strain at the maximum strength of failure ϵ_c (which is defined as "compressibility") and failure time t. For failure times here are natural logarithmic values used.

It could be observed that almost linear relations exist between σ_u and lnt, and ϵ_c is almost stable regardless of t. Table 4 indicates regression line values and standard deviations in case σ_u and ϵ_c were adjusted in the light of these relations. The coefficient of variation of σ_u, if it is taken as the base when failure time is equal to 1.0 sec., is 4.7 to 3.0 % for concrete as against 2.1 to 1.8 % for mortar, and the tendency is seen that the poorer the mix, the smaller the coefficient.

The coefficient of variation of ϵ_c is 6.8 to 4.0 % for concrete as compared with 3.9 to 3.3 % for mortar. Secant modulus Es at points of 0.25, 0.50, 0.75 and 1.00 times ϵ_c on the stress-strain curve are given in connection with in Fig. 4-1 to Fig. 4-14. As the decline of Es is likely to slow down along with the increase of t, we assumed that Es is equal to be^{-} c lnt, and the regression line values and standard deviations which were obtained on the basis of this relationship are given in Table 5-1 to Table 5-2.

The standard deviation of Es, though slightly larger than those of σ_u and ϵ_c, (t = 1.0 sec. is taken as the base) is 7.4 to 2.3 % for concrete 4.9 to 2.4 % for mortar. It is known here that the deviation of Es to a big strain value is rather smaller than the deviation of Es to a small strain value.

Consideration

When a concrete structure gives rise to compressive stress in its inside as a result of earthquake, its strain velocity or load velocity becomes unsteady and shows trigonometric functional changes. That is why we first deal herein with cases in which one stroke of trigonometric functional load velocity takes place. Hence it seems advisable to simply indicate strength and the coefficient of elasticity in relation to the period of earthquake motion. In this case, it will be possible to, on the simple assumption that failure time equals half of the period of earthquake motion, apply the foregoing various dynamical tests at 0.03 to 1.00 sec. to conditions when the period of earthquake motion is 0.06 to 2.00 seconds.

From Fig. 3.and Table 4 can it be said that σ_u is in inverse proportion to t, and that the following equation can be established - with the same degree of accuracy as the compressive strength of concrete and mortar in statical tests:

$$\sigma_u = -d + f \ln t \qquad (1)$$

$$0.03 \text{ sec.} < t < 100 \text{ sec.}$$

In this test, supposing that the strength of 100 second failure is 1, it augments to 1.17 to 1.30 at the time of 1 second failure; and 1.30 to 1.56 at the time of 0.03 second failure. It is witnessed that the poorer the mix, the higher the multiplication rate tends to be, and that the multiplication rate is somewhat larger for the 13-weeks material than that for the 4-weeks material.

Compressibility ε_c becomes almost constant by the kind and age of concrete and mortar and the following equation seems to be established regardless of failure time:

$$\varepsilon_c = \text{Constant} \qquad (2)$$

$$0.03 \text{ sec.} < t < 100 \text{ sec.}$$

In this test, the compressibility, is 19.1 to 28.1 x 10^{-4} for concrete and 26.2 to 38.2 x 10^{-4} for mortar. These values are inclined to become larger when the mix is richer, and to be in proportion to the age of material.

These results of tests on compressive strength and compressibility seem to give valuable suggestions to the theory on the failure of concrete and mortar. When the theory on failure is considered in the light of time elements, the energy theory, much less the stress theory, seems to lose the ground. In this respect, the authors intend to introduce their views and tests on some other occasion.

How the incline of the stress-strain curve increases along with the decrease of failure time, as mentioned previously, will be able to be signified by the following equation using Secant-Modulus Es:

$$E_s = b\, e^{-c} \ln t \qquad (3)$$

$$0.03 \text{ sec.} < t < 100 \text{ sec.}$$

If Es at 100 seconds of failure time should be represented by 1, in this test it increases to 1.15 to 1.25 at 1 second of failure time and further to 1.20 to 1.50 at 0.03 second. It was found that the poorer the mix, the greater multiplication rate, and that the multiplication rate tends to be high towards Es against ε_c from Es against 0.25 ε_c.

With these data, it is possible to push rheological analysis of concrete as material. But as it will take a considerable amount of time to make a model which will suffice to satisfactorily explain the responses of concrete and mortar in various tests, we will limit ourselves to citing a few examples of constant values for a simple model.

As the consideration of all behaviors up to failure will necessitate the introduction of non-linearity, we will confine ourselves to strain and stress up to $0.25\,\varepsilon_c$ on the stress-strain curve. As a model, we use a simple three-element model, that is, the Kelvin model to which a spring is connected directly.

Now, if

$$\sigma = K\,t \qquad (4)$$

should be acted on the model, strain ε will result, and the following equation will be established:

$$\varepsilon = K\left(\frac{t}{E_1} - \frac{\eta_1}{E_1^2} + \frac{\eta_1}{E_1^2} e^{-\frac{E_1}{\eta_1} t}\right) + K\frac{t}{E} \qquad (5)$$

in which

σ : Stress (kg/cm²) K : Constant (kg/cm²: 1/sec.)

E_1 : Coefficient of elasticity of Kelvin body (kg/cm²)

η_1 : Coefficient of viscosity of Kelvin body (kg/cm²: sec.)

E : Coefficient of elasticity of spring directly connected to Kelvin body (kg/cm²)

From the regression line of ε_c, σ_u, $E_{s,0.25\varepsilon_c}$ in the above diagrams will values at 0.03 sec., 0.2 sec., 1 sec. and 100 sec. be obtained; K will be obtained from the strength of failure against failure time; stress σ against $0.25\,\varepsilon_c$ will be obtained from $E_{s,0.25\varepsilon_c}$; and t for $0.25\,\varepsilon_c$ will be obtained from (4). The values obtained through application of these to (5) and curve fitting are given in Table 6.

Table 6

Test No.	1	5	11
Mix proportion w/c	1:2:4, w/c: 37%	1:4:7, w/c: 65%	1:3, w/c: 50%
Age	4 Ws	4 Ws	4 Ws
E kg/cm²	32.1×10^4	27.2×10^4	27.5×10^4
E_1 kg/cm²	3.1×10^4	7.8×10^4	4.4×10^4
η_1 kg/cm² sec.	31.0×10^4	110.7×10^4	64.0×10^4
Retardation time η_1/E_1 sec.	10	14.2	14.5

Naturally these values do not suffice to explain the behavior in statical tests, but are able to explain behaviors within low stress in dynamical tests to a certain extent. In other words, dynamical behaviors, such as both statical and dynamical elasticity, specifically changes in dynamical elasticity under periodical stress, and the absolute value of viscosity, will be explained to some extent.

Conclusion

Thus some of the dynamical behaviors of concrete and mortar under one stroke of compressive load with the same load-velocity as earthquake load have been analyzed. It has been found that the smaller the failure time, the greater the strength of failure, and that between these two exist (1) relations.

In respect to compressibility, it is almost steady according to the quality and age of material, and regardless of failure time, there exist (2) relations.

Relations between elasticity and failure time are signified by (3), in which the smaller failure time, the greater elasticity.

From these, the coefficient of elasticity and coefficient of viscosity of a simple three-element model can be obtained, and with them, dynamical behaviors within low stress can be explained to some extent.

REFERENCES

1) T. Hatano, T. Takahashi
"The Stability of an Arch Dam Against Earthquakes"

Technical Report C56-07, February 15, 1957
Central Research Institute of Electric Power Industry

T. Hatano, T. Takahashi, H. Tsutsumi
"Dynamical Study of Tsukabaru Gravity Dam"

Technical Report C5801, January 5, 1958
Central Research Institute of Electric Power Industry

2) T. Katsuta
"On the Elastic & Plastic Properties of Concrete in Compression Test with High Deformation-Velocity"

Transactions of the Institute of Japanese Architects
(Annual Conference Number 1943)

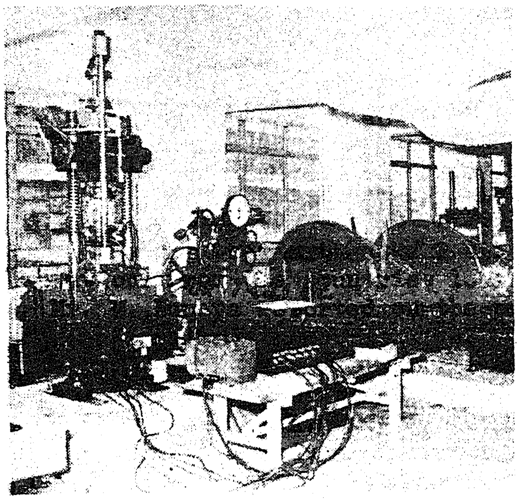


Photo. 1

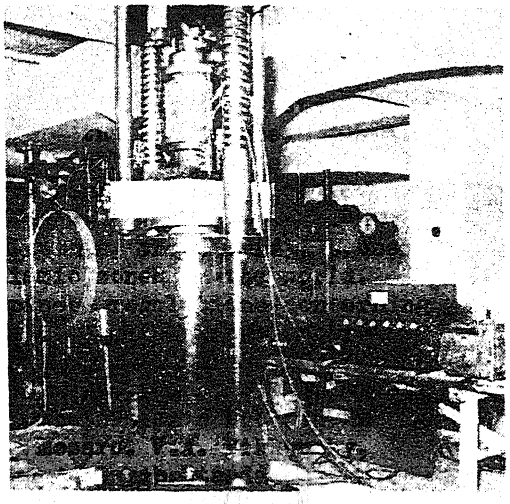


Photo. 2

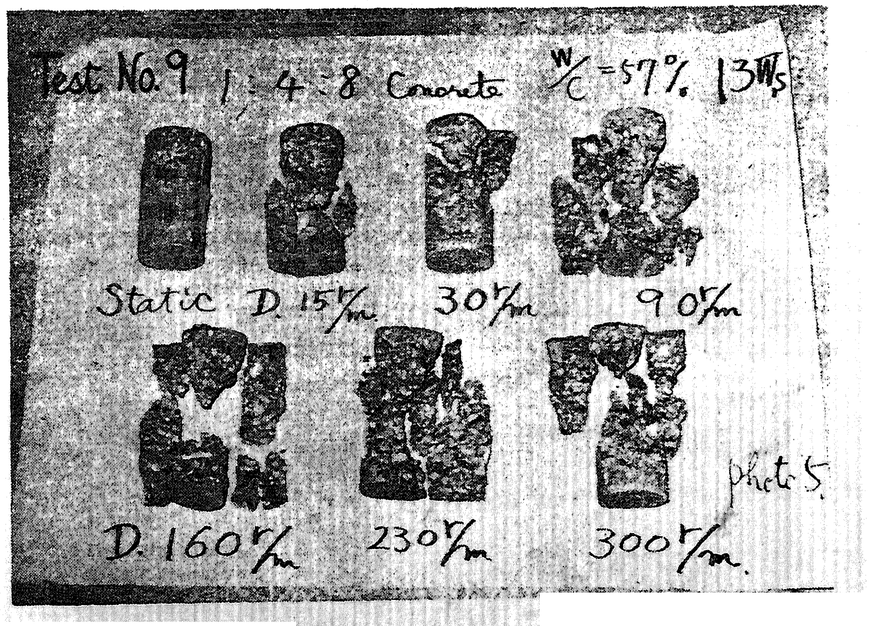
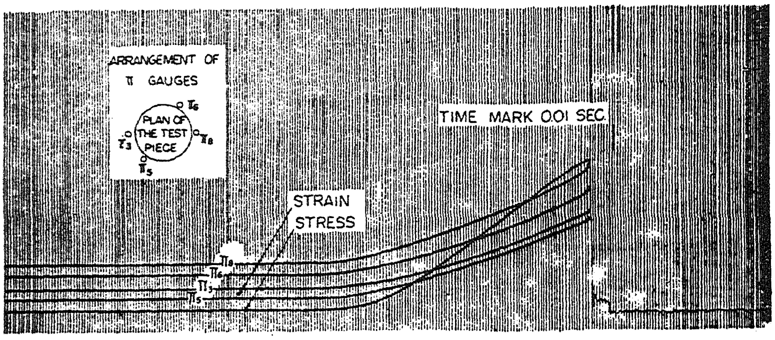


Photo. 3

FIG. 1-1 TEST RECORD TEST No.2-4



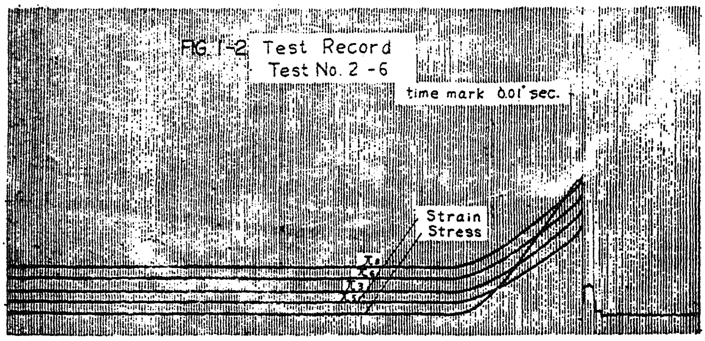


FIG. 1-2 Test Record Test No. 2-6

FIG. 1-3 TEST RECORD TEST No.2-9

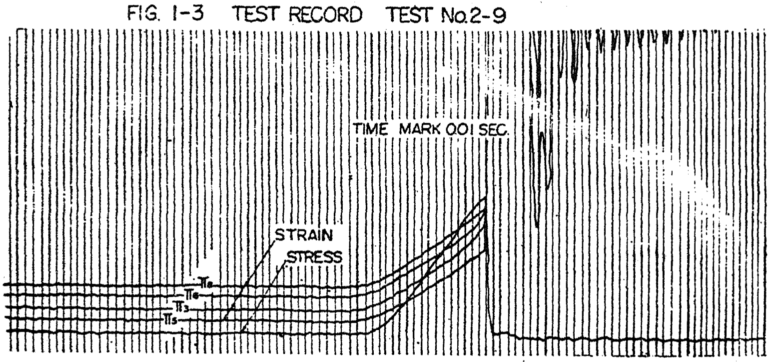


FIG. 1-4 TEST RECORD TEST No.2-14.

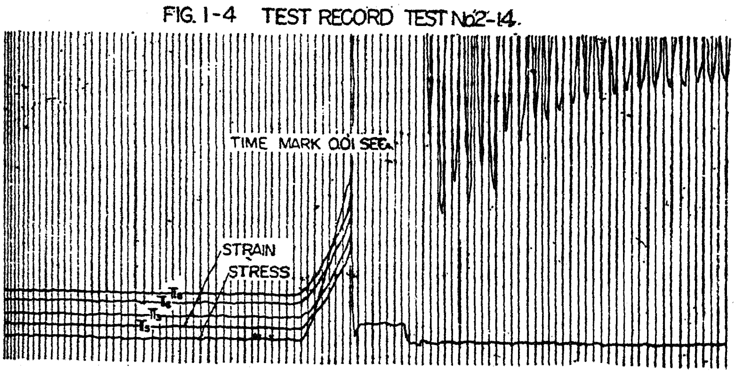


FIG. 2-1 STRESS-STRAIN TEST No.1

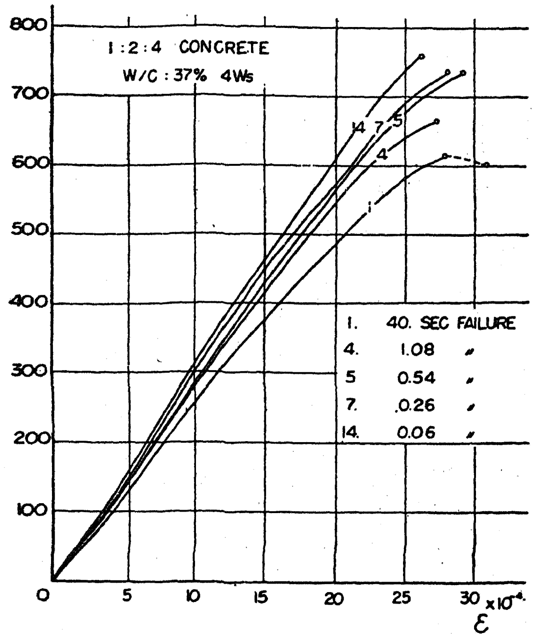


FIG. 2-5 STRESS-STRAIN TEST No.5

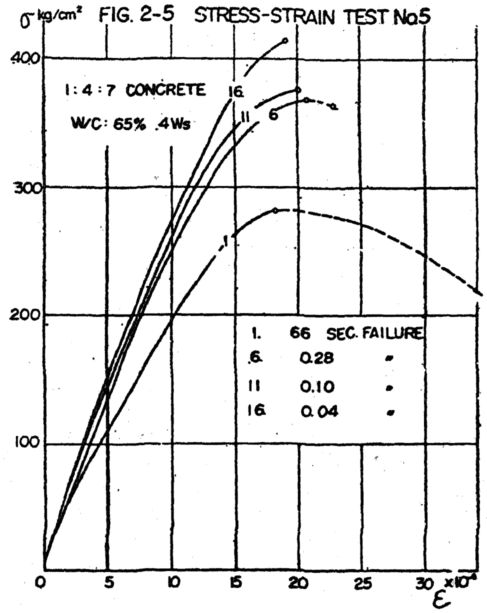


FIG 2-3 STRESS-STRAIN TEST No.3

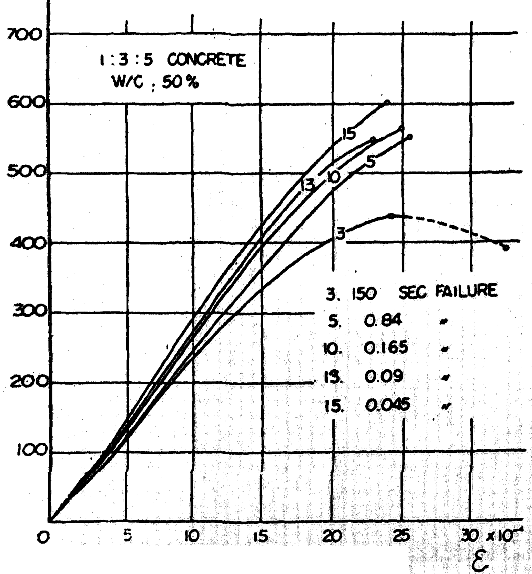
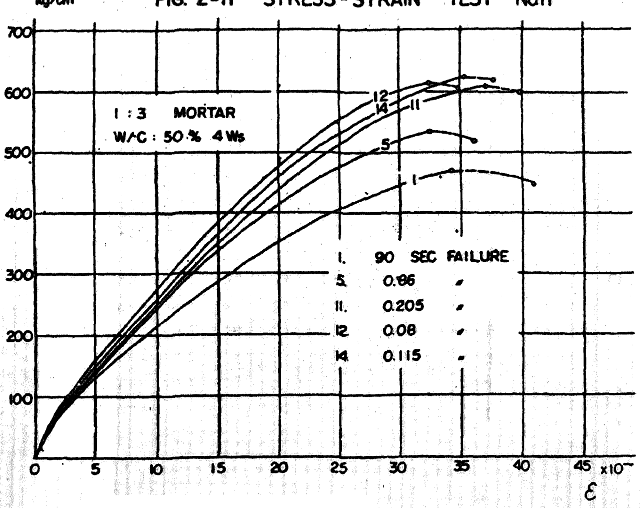


FIG. 2-11 STRESS-STRAIN TEST No11



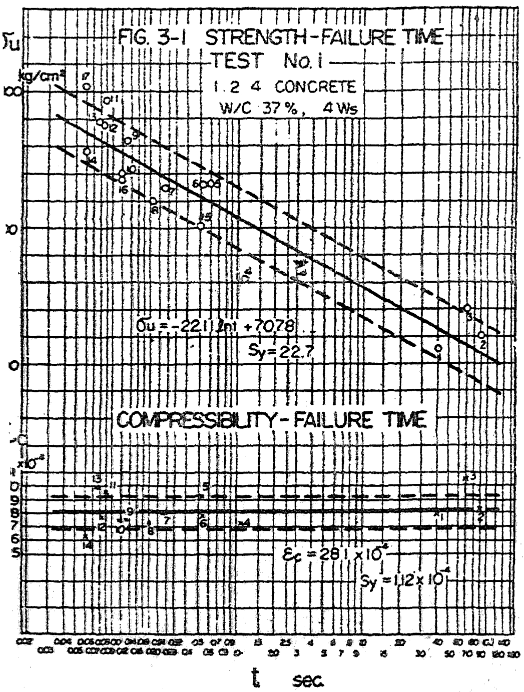


FIG. 3-1 STRENGTH-FAILURE TIME
TEST No.1
1:2:4 CONCRETE
W/C 37%, 4Ws
σu kg/cm²
σu = -22.11 ℓnt + 707.8
Sy = 22.7
COMPRESSIBILITY-FAILURE TIME
εc = 28.1 x 10⁻⁴
Sy = 1.12 x 10⁻⁴
t sec

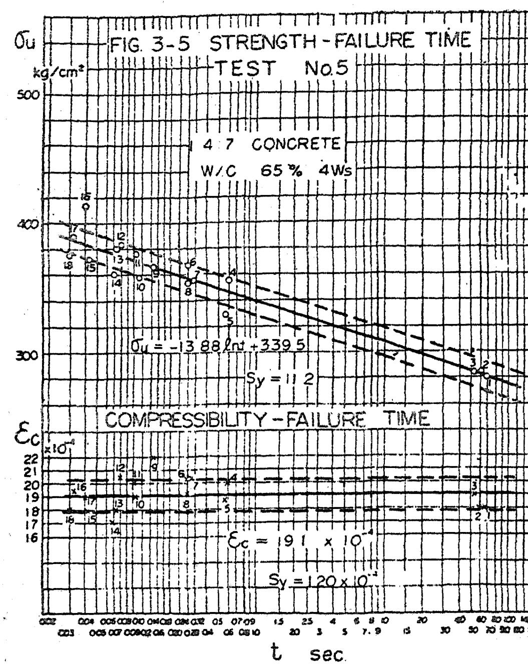


FIG. 3-5 STRENGTH-FAILURE TIME
TEST No.5
1:4:7 CONCRETE
W/C 65% 4Ws
σu kg/cm²
500
400
300
σu = -13.88 ℓnt + 339.5
Sy = 11.2
COMPRESSIBILITY-FAILURE TIME
εc x10⁻⁴
εc = 19.1 x 10⁻⁴
Sy = 1.20 x 10⁻⁴
t sec

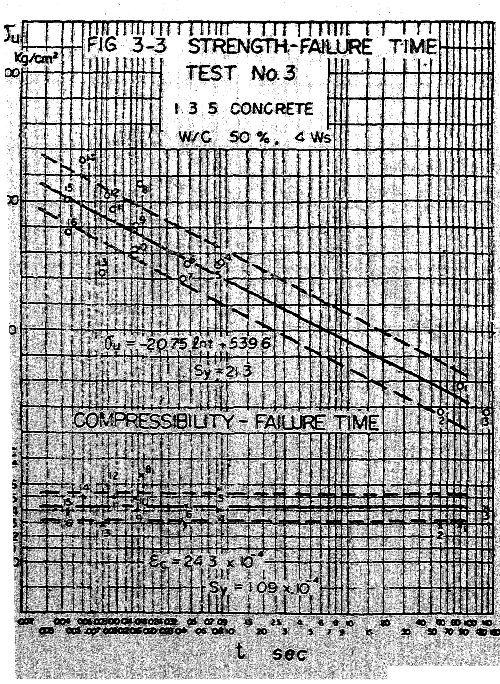


FIG 3-3 STRENGTH-FAILURE TIME
TEST No.3
1:3:5 CONCRETE
W/C 50%, 4Ws
σu kg/cm²
σu = -20.75 ℓnt + 539.6
Sy = 21.3
COMPRESSIBILITY-FAILURE TIME
εc = 24.3 x 10⁻⁴
Sy = 1.09 x 10⁻⁴
t sec

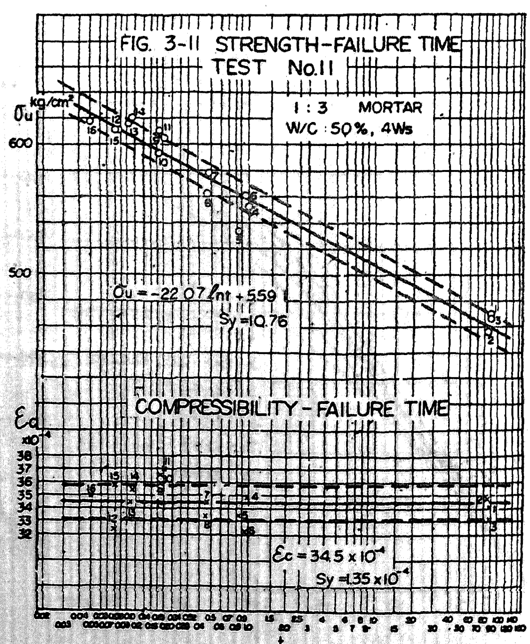


FIG. 3-11 STRENGTH-FAILURE TIME
TEST No.11
1:3 MORTAR
W/C 50%, 4Ws
σu kg/cm²
600
500
σu = -22.07 ℓnt + 559.1
Sy = 10.76
COMPRESSIBILITY-FAILURE TIME
εc x10⁻⁴
εc = 34.5 x 10⁻⁴
Sy = 1.35 x 10⁻⁴
t Sec.

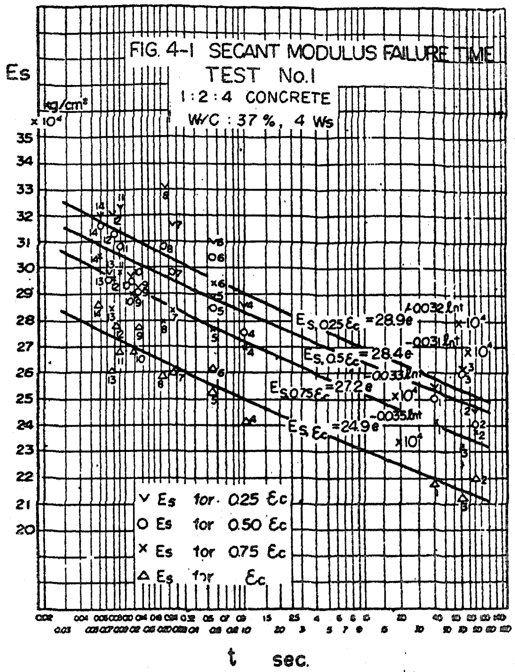


FIG. 4-1 SECANT MODULUS FAILURE TIME

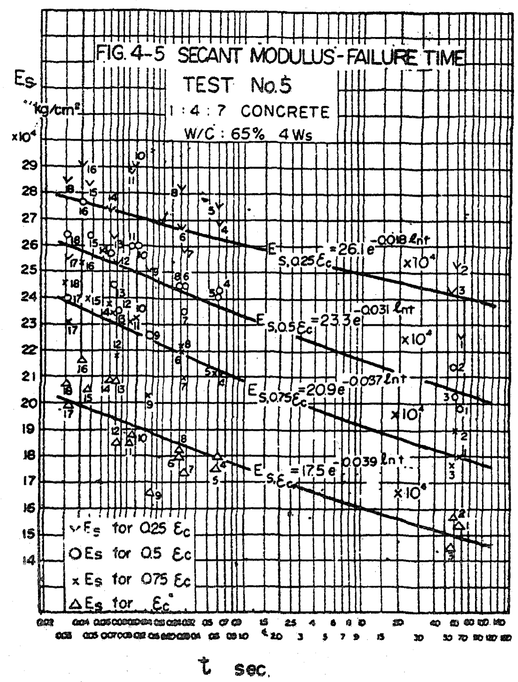


FIG. 4-5 SECANT MODULUS-FAILURE TIME

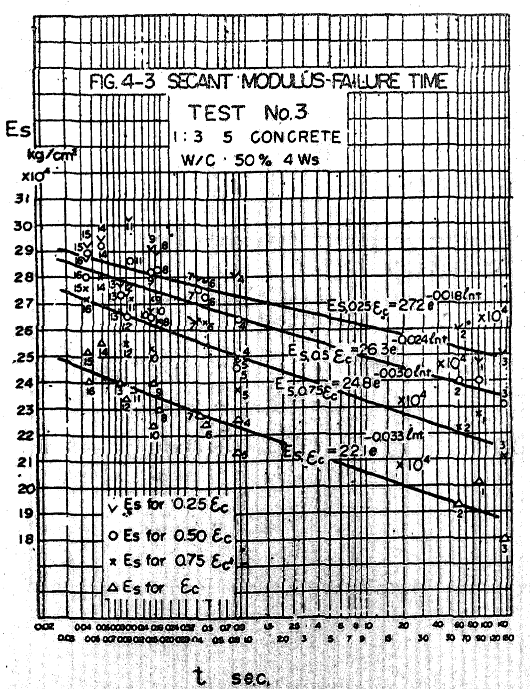


FIG. 4-3 SECANT MODULUS-FAILURE TIME

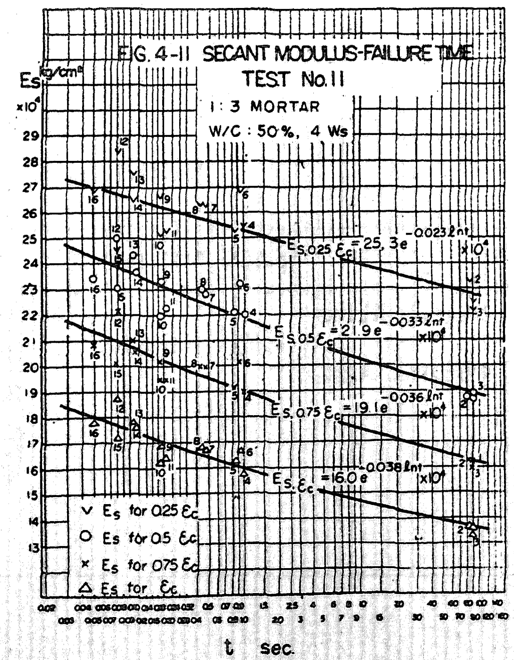


FIG. 4-11 SECANT MODULUS-FAILURE TIME

Table - 1

Properties of the Cement

1)

Ig. loss	Ins. R	SiO_2	Al_2O_3	Fe_2O_3	Cao	Mgo	SO_3
0.75	0.27	23.21	4.03	4.13	63.76	0.93	1.98

C_3S	C_2S	C_3A	C_4AF
44.4	33.1	3.7	12.6

2)

Sp. gr.	finess
3.20	3250 cm^2/g

3)

Strength of Standard Mortar			
flow	3 day	7 day	28 day
256 m.m.	127 kg/cm^2	170	405

Table - 2

Properties of the Aggregates

	Sp.gr.	Max size	Gradation			
			Gravel		Sand	
Sagami River Natural Agg.	2.75	25 m.m.	25 - 20 m.m.	25%	5 - 2.5 m.m	15%
			20 - 15	25	2.5 - 1.2	15
			15 - 10	25	1.2 - 0.6	25
			10 - 5	25	0.6 - 0.3	25
					0.3 - 0.15	15
					0.5 -	5

Table - 3

Tested Concrete & Mortar

Test No.	Age in Weeks	Mix proportion					Slump & air		
		Cement (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	W/c (%)	Slump (cm)	Air(%)	cement void ratio C/V
1	4	380	140	698	1296	37	0.6	1.69	0.757
2	4	380	160	658	1222	42	10.0	0.98	0.700
3	4	300	150	710	1264	50	10.3	1.18	0.580
4	4	220	125	800	1300	57	0.5	2.20	0.467
5	4	220	143	781	1276	65	3.5	1.64	0.431
6	13	380	160	658	1222	42	10.0	1.25	0.685
7	13	300	135	724	1288	45	1.5	1.68	0.618
8	13	300	150	710	1264	50	4.3	1.34	0.574
9	13	220	130	800	1300	57	0.5	2.80	0.435
10	13	220	143	781	1276	65	3.4	2.03	0.421
11	4	511	256	1533	-	50	flow 17.0	4.41	0.528
12	4	410	246	1640	-	60	16.2	5.81	0.421
13	13	511	256	1533	-	50	17.1	4.11	0.538
14	13	410	246	1640	-	60	15.3	5.79	0.422

Table 5 - 2

Secant Modulus (2)

Test No.	Relation between (sec. kg/cm²) Secant Modulus for 0.75 ε_c & failure time x10⁴	Standard deviation x10⁴ (kg/cm²)	Relation between (sec. kg/cm²) Secant Modulus for ε_c & failure time x10⁴	Standard deviation x10⁴ (kg/cm²)
1	$E_{s,0.75\varepsilon_c} = 27.2\ e^{-0.033\ \ln t}$	0.62	$E_{s,\varepsilon_c} = 24.9\ e^{-0.035\ \ln t}$	0.65
2	$E_{s,0.75\varepsilon_c} = 29.1\ e^{-0.037\ \ln t}$	1.25	$E_{s,\varepsilon_c} = 25.9\ e^{-0.039\ \ln t}$	1.13
3	$E_{s,0.75\varepsilon_c} = 24.8\ e^{-0.030\ \ln t}$	0.77	$E_{s,\varepsilon_c} = 22.1\ e^{-0.033\ \ln t}$	0.67
4	$E_{s,0.75\varepsilon_c} = 22.3\ e^{-0.039\ \ln t}$	1.06	$E_{s,\varepsilon_c} = 18.7\ e^{-0.054\ \ln t}$	1.04
5	$E_{s,0.75\varepsilon_c} = 20.9\ e^{-0.037\ \ln t}$	0.88	$E_{s,\varepsilon_c} = 17.5\ e^{-0.039\ \ln t}$	0.99
6	$E_{s,0.75\varepsilon_c} = 29.7\ e^{-0.040\ \ln t}$	1.89	$E_{s,\varepsilon_c} = 27.1\ e^{-0.041\ \ln t}$	1.79
7	$E_{s,0.75\varepsilon_c} = 26.7\ e^{-0.039\ \ln t}$	0.86	$E_{s,\varepsilon_c} = 24.1\ e^{-0.044\ \ln t}$	1.01
8	$E_{s,0.75\varepsilon_c} = 24.8\ e^{-0.045\ \ln t}$	1.06	$E_{s,\varepsilon_c} = 22.3\ e^{-0.046\ \ln t}$	1.00
9	$E_{s,0.75\varepsilon_c} = 22.5\ e^{-0.043\ \ln t}$	1.04	$E_{s,\varepsilon_c} = 19.0\ e^{-0.052\ \ln t}$	1.03
10	$E_{s,0.75\varepsilon_c} = 20.7\ e^{-0.040\ \ln t}$	0.72	$E_{s,\varepsilon_c} = 17.7\ e^{-0.044\ \ln t}$	0.85
11	$E_{s,0.75\varepsilon_c} = 19.1\ e^{-0.036\ \ln t}$	0.55	$E_{s,\varepsilon_c} = 16.0\ e^{-0.038\ \ln t}$	0.46
12	$E_{s,0.75\varepsilon_c} = 14.7\ e^{-0.035\ \ln t}$	0.44	$E_{s,\varepsilon_c} = 11.7\ e^{-0.038\ \ln t}$	0.35
13	$E_{s,0.75\varepsilon_c} = 22.4\ e^{-0.040\ \ln t}$	0.81	$E_{s,\varepsilon_c} = 19.4\ e^{-0.040\ \ln t}$	0.63
14	$E_{s,0.75\varepsilon_c} = 18.2\ e^{-0.034\ \ln t}$	0.44	$E_{s,\varepsilon_c} = 15.1\ e^{-0.041\ \ln t}$	0.48