A STUDY ON UNIAXIAL COMPRESSIVE STRENGTH OF PLAIN CONCRETE UNDER DYNAMIC CYCLIC LOADING

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SUMMARY

Learning from collapse patterns of building at the Hyogo-ken Nanbu earthquake (1995), the importance of vertical vibrations has pointed out to the benefit of having a low cycle fatigue test for plain concrete. In this paper, experimental investigations on the uniaxial compressive strength and the fracture behaviour of plain concrete under dynamic cyclic loading are presented and discussed.

All the plain concrete test samples had 100 mm diameter and 200 mm height. The total number of these test samples was 55. Input waves were chopping waves of 40cycles in 4Hz. The waves were applied to test samples by a hydraulic servo type of machine to generate dynamic loading.

In this test, an upper bound value of cyclic loading was an experimental parameter. A the lower bound value was fixed. When the upper bound value of cyclic loading was assigned as 110% of static ultimate compressive strength, no fracture occurred. When this value, however, was 130%, fracture occurred as soon as the loading was applied. When this value was 120%, fracture occurred in the first 20 cyclic load.

INTRODUCTION

When the collapse patterns of buildings at the Hyogo-ken Nanbu earthquake (1995) examined, it was clear that the pattern was not always the same that the story collapse (shown in Plate 1) occurred. That is to say, when buildings were damaged, all columns standing on the same floor did not always collapse at the same time and in the same direction. An example of those cases is shown in Plate 2. In this case, partial collapse of same level was observed. By investigating the reasons why the building collapsed partially by seismic waves, a more detailed knowledge of strength of structural materials under dynamic loading was necessary.

There is a considerable amount of research work on relationships between strain rate and axial compressive strength of structural materials [1][2][3]. This research showed that strength of structural materials was sensitive to the rate of loading. However, there are not many researches on material strength under dynamic cyclic loading, especially on strength of concrete material.

In this paper, experimental investigations of the uniaxial compressive strength and the fracture behaviour of plain concrete under dynamic cyclic loading are presented and discussed.

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Plate 1: The story collapse

Plate 2: Damage to the 4-story apartment building

LOADING METHODS AND EXPERIMENTAL RESULTS

A chopping (triangular) waves of 40 cycles in 4 Hz (shown as Fig.1-1) was subjected to test samples by a hydraulic servo type of machine (Plate 3) to generate dynamic loading. Because the frequency of about 4Hz represents the natural frequency of lower residential buildings, and because about first 10 seconds might be very important for the effects of vertical ground motions, load curves can be divided into two parts. One is adjusting loading time and another is steady loading time in which the upper and the lower bound values of cyclic loads are coincident with the assigned values.

Here, assigned values of the upper bound were experimental parameters, and assigned values of the lower bound were fixed in dynamic splitting tests and dynamic compressive experiments.

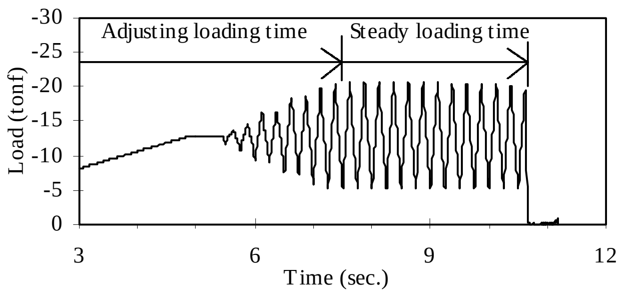

Figure 1-1: A chopping waves of 40 cycles in 4Hz

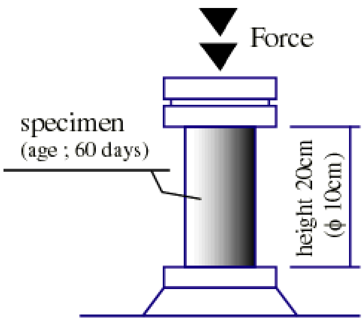

Figure 1-2: Compressive test

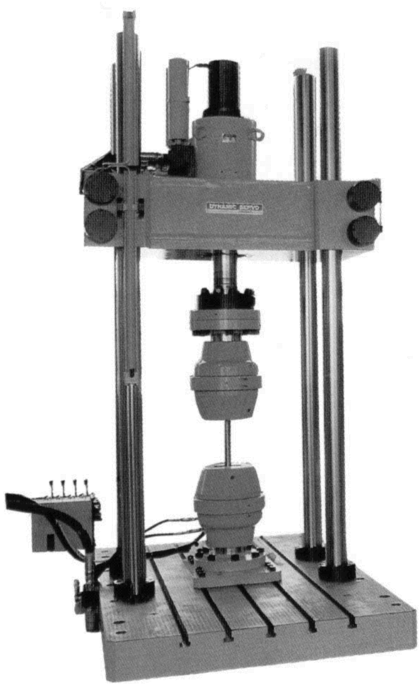

Plate 3: hydraulic servo type of loading machine

Table 1-1: Proportion of specimens (Per 1 m^3, A-G series)

W/C %	W kg	C kg	S kg	G kg	air %	S/a %	Admixture agent (AE water reducing) cc
65	200	308	743	983	4	44	250

Table 1-2: Proportion of specimens (Per 1 m^3, H-L series)

W/C %	W kg	C kg	S kg	G kg	air %	S/a %	Admixture agent (HP11) cc
70	192	274	863	933	3	49	1370

The plain concrete test pieces were 100 mm in diameter, 200 mm in height (Fig.1-2). The total number of these test samples was 55. Test pieces of A to G series were made up as in Table 1-1, H to L series, which were additional test, as in Table 1-2.

The flow chart of the experiment (A to G series) is shown in Fig.2. Five test samples were examined for every series. At first, static ultimate compressive strength σ_c and static ultimate tensile strength σ_t estimated by splitting test were calculated as shown in Table 2-1. The upper bound values of forces of each experiment written below were decided on the basis of these values.

Preliminary to dynamic compressive tests, dynamic splitting tests were examined by introducing the chopping waves of 20 cycles in 4 Hz. In C series the upper bound of the force of the input wave was set to 5 tonf (equal to 0.66 σ_t) and the lower bound of force 2 tonf. All the test samples did not fracture. In D series the upper bound of the force was 10 tonf (1.32 σ_t), four test samples fractured in adjusting loading time and the other was in steady loading time. In this case, each collapse load was near 1.3 σ_t. Therefore if the upper bound of the force had been a little smaller than 1.3 σ_t, these test samples could have fractured in steady loading time of 4 Hz chopping waves in the dynamic splitting test.

Dynamic compressive tests by the chopping waves of 40 cycles in 4 Hz were based on the above splitting tests. In E series that the upper bound of the force of the input wave was set to 25.0 tonf (equal to 1.10 σ_c) and the lower bound of force 5 tonf, test samples did not fracture except only one test sample. After this dynamic test, those unbroken test samples were loaded again but statically. No reduction of strength was observed. The mean value of those ultimate compressive strengths was 24.03 tonf (1.06 σ_c) as shown in Table 2-2. In E series, the upper bound of the force of the input wave was set to 30.0 tonf (equal to 1.32 σ_c). If these test samples fractured, the upper bound of the force of next F series would be set smaller value to fracture in steady loading time. And if not, the upper bound of the force would be larger. In fact, test samples all fractured in adjusting loading time. Then, the mean value of maximum compressive strength was 28.85 tonf (1.27 σ_c). Hence, it was quite obvious that concrete test samples used here would fracture in steady loading time when the upper bound of the force was some value from 25.0 to 28.85 tonf. Lastly, in E series that the upper bound of the force of the input wave was decided to 27.5 tonf (equal to 1.21 σ_c), test samples all fractured in steady loading time. (Shown in Table 2-3)

Table 2-1: Results of static tests

Series	Day	Test type	Max. load (tonf)	Tensile strength (kgf/cm^2)	Compressive strength (kgf/cm^2)	Standard deviation (kgf/cm^2)
A	1997 9.26	Static splitting	7.58	24.1	-	1.62
B	1997 9.26	Static compress.	22.7	-	289.0	4.08

Table 2-2: Strength after loaded dynamically

Series	Day	Test type	Max. load (tonf)	Tensile strength (kgf/cm^2)	Compressive strength (kgf/cm^2)	Standard deviation (kgf/cm^2)
C	1997 9.26	Static splitting	7.78	24.8	-	1.28
E	1997 9.27	Static compress.	24.0	-	305	15

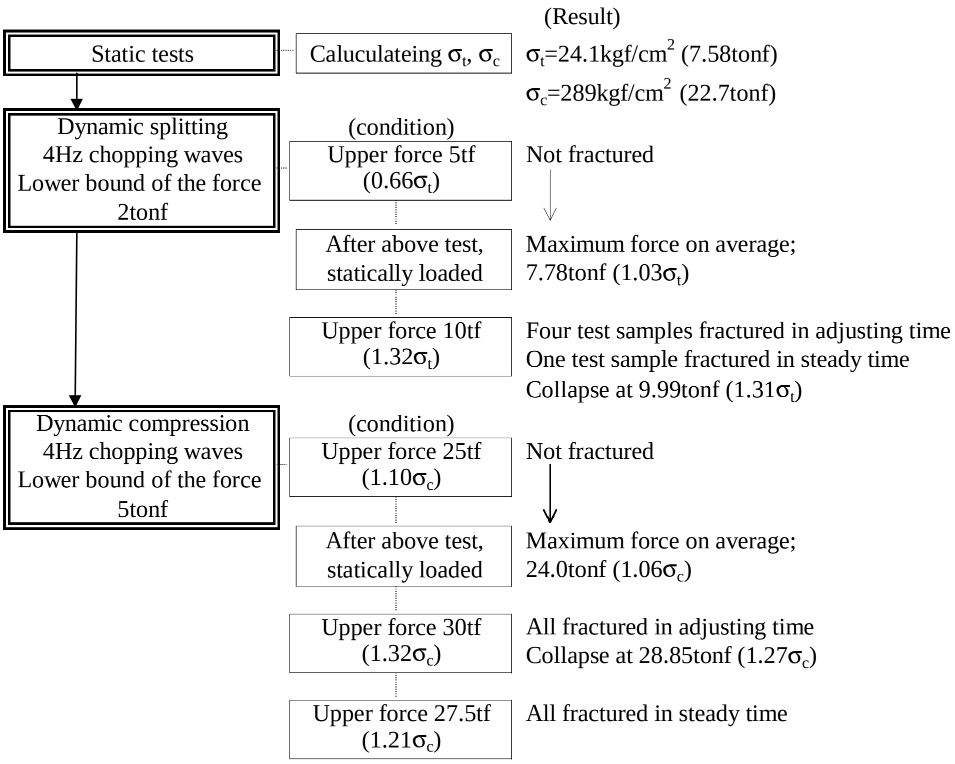

Figure 2: The flow chart of tests (A-G series)

Table 2-3: Results of dynamic loading (4Hz, A-G series)

Series	Test type Upper force (day)	Lower force (tonf)	Upper force (tonf)	Limit cycle	Cycle	Fractured load (tonf)	Fractured period	Comment
C-1	Dynamic splitting 0.66σ_t (97.9.26)	-2	-5	20	20	-	-	σ_t=24.1kgf/cm^2 (7.58tonf)
C-2		-2	-5	20	20	-	-	
C-3		-2	-5	20	20	-	-	Loading statically after this test
C-4		-2	-5	20	20	-	-	
C-5		-2	-5	20	20	-	-	
D-1	Dynamic splitting 1.32σ_t (97.9.26)	-2	-10	20	0	-10.00	adjusting	
D-2		-2	-10	20	0	-9.80	adjusting	
D-3		-2	-10	20	0	-9.98	adjusting	
D-4		-2	-10	20	0	-9.98	adjusting	
D-5		-2	-10	20	19	-10.00	steady	
E-1	Dynamic compression 1.1σ_c (97.9.27)	-5	-25	40	0	-12.60	steady	σ_c=289.3kgf/cm^2 (22.72tonf)
E-2		-5	-25	40	40	-	-	
E-3		-5	-25	40	40	-	-	Loading statically after this test
E-4		-5	-25	40	40	-	-	
E-5		-5	-25	40	40	-	-	
F-1	Dynamic compression 1.21σ_c (97.9.27)	-5	-27.5	40	14	-27.25	steady	
F-2		-5	-27.5	40	3	-27.55	steady	
F-3		-5	-27.5	40	4	-27.35	steady	
F-4		-5	-27.5	40	1	-27.55	steady	
F-5		-5	-27.5	40	8	-27.60	steady	
G-1	Dynamic compression 1.32σ_c (97.9.27)	-5	-30	40	0	-28.85	adjusting	
G-2		-5	-30	40	0	-28.85	adjusting	
G-3		-5	-30	40	0	-28.40	adjusting	
G-4		-5	-30	40	0	-29.10	adjusting	
G-5		-5	-30	40	0	-29.05	adjusting	

Test samples of H to L series, which were additional test, were made up as in Table 1-2. The aim of these series is to assure that a difference in proportion of test samples does affect the above results. They differed from test samples of A to G series in W/C, S, and so on. The flow of the experiment (H to L series) is shown in Fig.3.
With five test samples, at first, static ultimate compressive strength σ_c' was calculated as shown in Table 3-1. Then, dynamic compressive tests by the chopping waves of 100 cycles in 4 Hz were performed. These were named I, J, and K series. (Shown in Table 2-2) Three test samples were examined for every loading case. In I series, the upper bound of the force of the input wave was set to 22.48 tonf (equal to 1.2 σ_c') and the lower bound of the force 5 tonf. Two samples fractured in adjusting loading time and the other immediately fractured in steady loading time in this test. In J series, the upper bound of the force of the input wave was set to 20.60 tonf (equal to 1.1 σ_c'). Test samples all fractured in steady loading time in this test. In K series, the upper bound of the force of the input wave was set to 18.74 tonf (equal to 1.0 σ_c'). Two test samples fractured in steady loading time and the other did not fracture in this test.
With only one test sample left, dynamic compressive tests by the chopping waves of 1000 cycles in 4 Hz were performed. In the L series the upper bound of the force of the input wave was set to 16.87 tonf (equal to 0.9 σ_c') and the lower bound of the force 5 tonf, the test sample did not fracture. (Shown in Table 3-2)

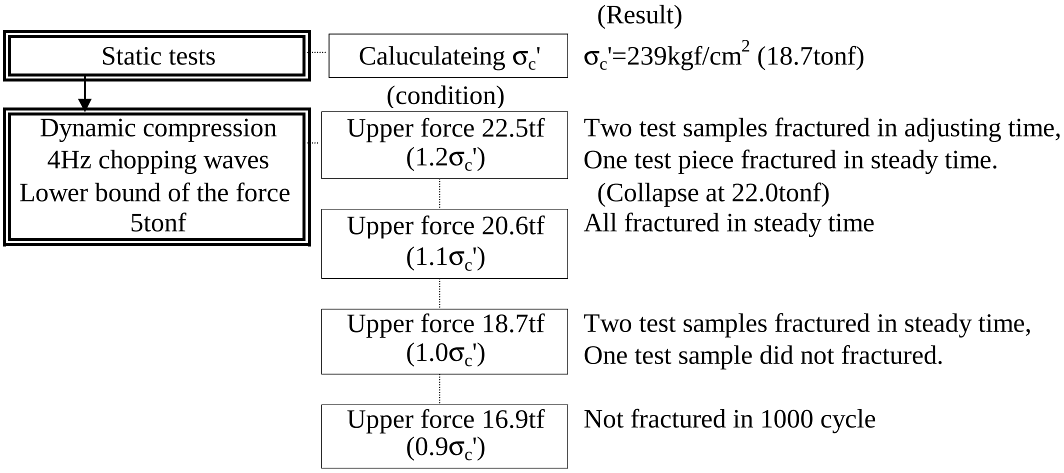

Fig. 3: The flow of tests (H-L series)

Table 3-1: Results of static tests

Series	Day	Test type	Max. load (tonf)	Tensile strength (kgf/cm^2)	Compressive strength (kgf/cm^2)	Standard deviation (kgf/cm^2)
H	1998 1.12	Static compress.	18.7	-	239.0	6.62

Table 3-2: Results of dynamic loading (4Hz, H-L series)

Series	Test type Upper force (1998.1.12)	Lower force (tonf)	Upper force (tonf)	Limit cycle	Cycle	Fractured load (tonf)	Fractured period	Comment
I-1	Dynamic compression 1.2σ_c'	-5	-22.5	100	1	-22.40	steady	σ_c'=238.6kgf/cm^2 (18.74tonf)
I-2		-5	-22.5	100	0	-22.15	adjusting	
I-3		-5	-22.5	100	0	-21.45	adjusting	
J-1	Dynamic compression 1.1σ_c'	-5	-20.6	100	3	-20.33	steady	
J-2		-5	-20.6	100	17	-20.60	steady	
J-3		-5	-20.6	100	11	-20.60	steady	
K-1	Dynamic compression 1.0σ_c'	-5	-18.7	100	100	-	-	
K-2		-5	-18.7	100	57	-18.70	steady	
K-3		-5	-18.7	100	27	-18.78	steady	
L	0.9σ_c'	-5	-16.9	1000	1000	-	-	

LOAD HISTORY, DISPLACEMENT HISTORY AND LOAD-DISPLACEMENT CURVE

As typical behaviours of each series, test samples E4, F2 and G5 were shown in Fig.4-1 to Fig.6-2. E4 was subjected dynamic compressive force of 4 Hz chopping waves, and did not fracture. Fig.4-1 shows the load and displacement history of E4. And, Fig.4-2 shows the load-displacement curve. F2 fractured at fourth cycle in steady loading time (Fig.5-1, Fig.5-2). G5 fractured in adjusting loading time (Fig.6-1, Fig.6-2). Compressive quantity is dealt with as a negative one. By that displacement history, it is shown that the test sample gradually got to fracture with progress of displacement.

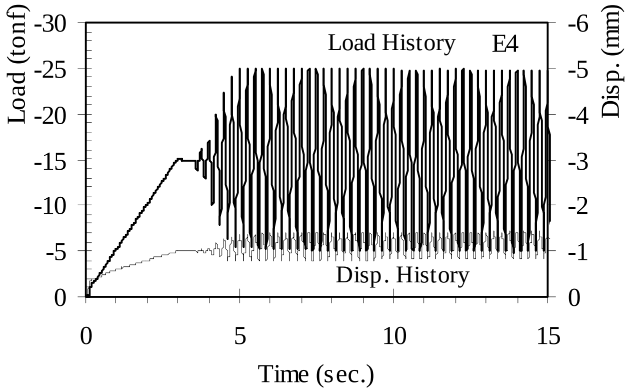

Fig. 4-1: Load history and Displacement history of E4 (E4: test sample not fractured)

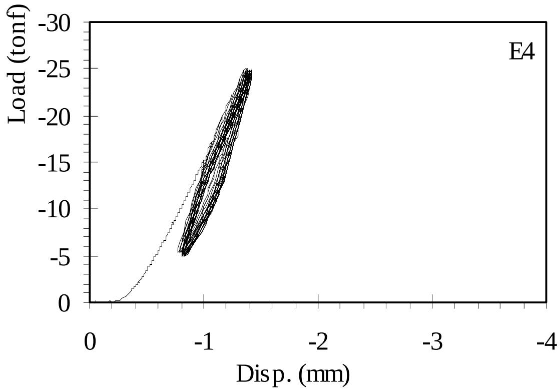

Fig. 4-2: Load and Displacement curve of E4

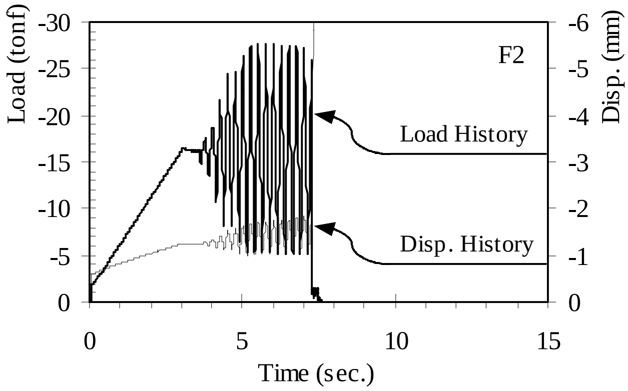

Fig. 5-1: Load history and Displacement history of F2 (F2: test sample fractured in steady loading time)

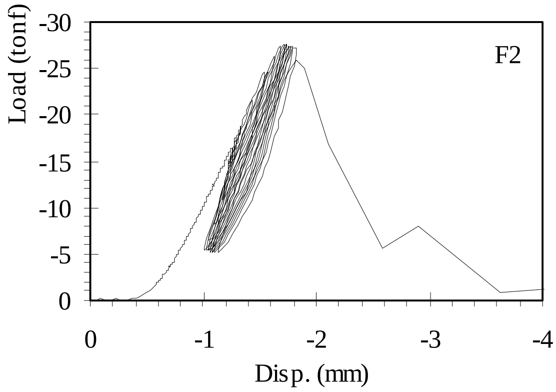

Fig. 5-2: Load and Displacement curve of F2

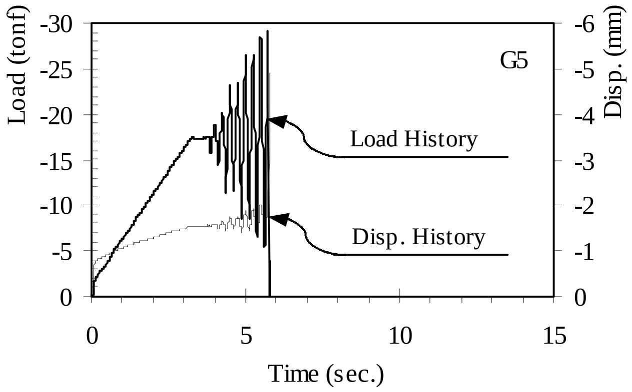

Fig. 6-1: Load history and Displacement history of G5 (G5: test sample fractured in adjusting loading time)

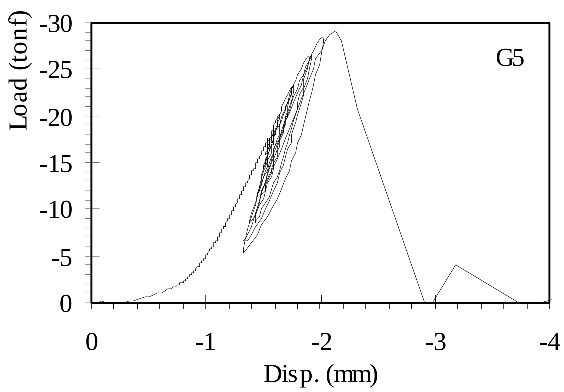

Fig. 6-2: Load and Displacement curve of G5

Fig. 7: Image of fracture in the dynamic test

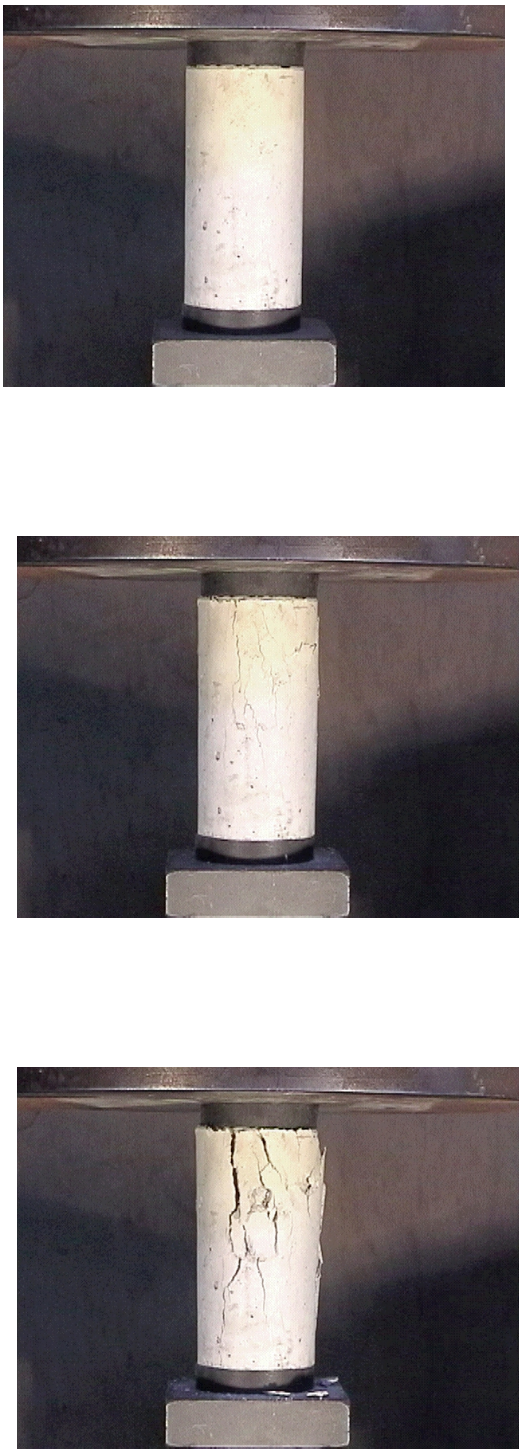

Fig. 8: Image of fracture in the static test

IMAGES OF FRACTURE

While the tests of I, J, K, and L series were carried out, an image of fracture was captured by a digital video. Hence, the process of concrete test samples was reviewed during fracturing. Fig.7 shows one frame of fracture in the dynamic test. When the static tests were carried out, an image of fracture was also taken as shown in Fig.8.

From these images, there was an obvious difference between the two regarding the way they fractured. The concrete test sample loaded dynamically fractured explosively. And, the concrete test sample loaded statically fractured with development of cracks gradually.

From these figures, it was observed that the ways cracks developed were different. In case of static test, surface cracks of the test sample developed from the upper part near the loading machine. In the case of the dynamic test, cracks developed from the central part.

CONCLUSIONS

In E to G series of dynamic compressive tests, that each chopping waves of 40 cycles in 4 Hz was subjected to test concrete test samples,

1. If the upper bound of the force of the input wave was about 110 % of static ultimate compressive strength, test samples would not fracture except one test sample.

2. If the upper bound of the force of the input wave was about 120 % of static ultimate compressive strength, test samples would all fracture by twentieth cycle in steady loading time.

3. If the upper bound of the force of the input wave was about 130 % of static ultimate compressive strength, test samples would all fracture in adjusting loading time.

In I to L series of dynamic compressive tests, that each chopping waves in 4 Hz was subjected to concrete test samples,

4. If the upper bound of the force of the input wave was nearly equal to static ultimate compressive strength, one test sample would not fracture and two would fracture at 28th, 58th cycle in steady loading time.

5. If the upper bound of the force of the input wave was about 110 % of static ultimate compressive strength, test samples would all fracture by 20th cycle in steady loading time.

6. If the upper bound of the force of the input wave was about 120 % of static ultimate compressive strength, two test samples would fracture in adjusting loading time and the other would immediately fracture in steady loading time.

7. If the upper bound of the force of the chopping waves of 1000 cycles in 4 Hz was 90 % of static ultimate compressive strength, test samples would not fracture.

8. By observation of Fig.7, Fig.8, it was realized that fracture of concrete test samples loaded dynamically did subtly differ from the fracture of test samples loaded statically in terms of the way cracks occurred.

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