Effects of strain rate on concrete strength subjected to impact load -Dynamic compressive strength test by Split Hopkinson Pressure Bar method

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Abstract

An impact test apparatus for concrete material was developed with both a hydraulic loading system and a Split Hopkinson Pressure Bar type loading system. In this apparatus, 100mm diameter bars were used taking account of the maximum aggregate size of the concrete. A data processing method to distinguish an incident wave and a reflected wave was developed to obtain stresses at both ends of the test specimen accurately by strain gauges on the pressure bars near the specimen. A shock absorbing material was used to mitigate the Pochhammer-Chree effect due to the stress wave dispersion, so that the specimen was deformed uniformly, and the estimated stress distribution was acceptable during the loading time to deform the specimen completely. According to the test results, the strain rate effect on the compressive concrete strength from $10^{-3}$/sec to $10^2$/sec was made clear. Moreover, the presence of moisture in the specimen was regarded as an important factor on the dynamic concrete strength.
1 Introduction

The strain rate of concrete is required in the design of reinforced concrete structures under impact force. Generally, it is well known that concrete strength becomes large with deformation speed of concrete. Those properties and several design formulae were proposed[1],[2],[3],[4]. However, there have been few experiments with the same test material over a wide range of strain rates.

The objective of this study is to clarify the concrete strength and the effect of strain rate on concrete strength. This paper presents an investigation on the application of the Split Hopkinson Pressure Bar (SHPB) method to impact tests with concrete test specimens of 100mm diameter. Test results, especially compressive concrete strength, are also discussed.

2 Test

2.1 Test Apparatus

An apparatus for conducting impact tests of concrete material is fabricated with both a hydraulic loading system and a SHPB type loading system. The hydraulic loading system is used for impact tests on strain rates from $10^{-5}$ to $10^{-1}$ /sec. Impact tests ranging from $10^{0}$ to $10^{2}$ /sec are carried out with the SHPB type loading system. The specifications of the hydraulic loading system are 490kN maximum load and 3m/sec maximum loading velocity. The SHPB type loading system has 20m/sec maximum velocity of the impact bar by an acceleration device using rubber spring force. This system consists of an impact bar (100mm in diameter and 1000mm in length), an incident bar (100mm in diameter and 3000mm in length) and a transmitter bar (100mm in diameter and 3000mm in length).

2.2 SHPB Test Method

2.2.1 Data Processing Method

Figure 1 shows the outline of the SHPB type test loading system for the impact test. The average stress, the average strain rate and the average strain are expressed by:

$$\bar{\sigma}(t) = \frac{E}{2} \left\{ \varepsilon_1(L_2, t) + \varepsilon_R(L_2, t) + \varepsilon_T(L_2 + L_S, t) \right\}$$  \hspace{1cm} (1)
where $E$ is Young's modulus of bars, and strains of the incident wave, the reflected wave and the transmitted wave are $\varepsilon_i$, $\varepsilon_R$ and $\varepsilon_T$, respectively. $c$ is the propagation velocity of stress wave, $t$ is time and the other symbols are shown in Figure 1.

Strains from the stress wave are measured by the strain gauges (2mm in gauge length) on the incident bar and the transmitter bar near the test specimen to increase the accuracy of the test. $\varepsilon_A(t), \varepsilon_B(t)$ and $\varepsilon_C(t)$ are the strains at the positions GA, GB, and GC. However, strain $\varepsilon_A(t)$ and $\varepsilon_B(t)$ are superposed by both the incident wave and the reflected one. Moreover, the measured strain is separated into the strain from the incident wave and that from the reflected wave as follows:

\begin{align}
\varepsilon_i(l_B, t) &= \varepsilon_A(t - \eta / c) - \varepsilon_B(t - 2\eta / c) + \varepsilon_i(l_B, t - 2\eta / c) \\ 
\varepsilon_R(l_B, t) &= \varepsilon_B(t) - \varepsilon_i(l_B, t)
\end{align}

As a result, each strain value expressed by eqns. (1)-(3) is obtained from eqns. (6)-(8) as follows:

\begin{align}
\varepsilon_i(L_2, t) &= \varepsilon_i(l_B, t - \zeta / c) \\ 
\varepsilon_R(L_2, t) &= \varepsilon_R(l_B, t + \zeta / c) \\ 
\varepsilon_T(L_2 + L_S, t) &= \varepsilon_C(l_C, t + l_C / c)
\end{align}

Figure 1: Schematic of SHPB type test
2.2.2 Investigation of Incident Waveform

Test specimens over some dimension are required since concrete is a mixture of cement and aggregate. The stress wave dispersion must be considered if the length of the test specimen does not exceed its diameter[5]. Therefore, the effects of the stress wave dispersion for the SHPB test method were investigated. In this study, the fundamental mode (mode 1 for the solution of the stress wave dispersion equation) was

![Figure 2: Strain distribution in the incident bar without absorbing material](image1)

![Figure 3: Strain distribution in the incident bar with absorbing material](image2)
considered because of the limit of measuring ability of the tests.

The incident waveform may be excited by mode 1. Figure 2 shows the longitudinal strain in the in-plane section calculated with the strains on the surface. A large oscillation on the wave is shown in Figure 2. To mitigate this effect, a shock absorbing material (3mm thick polypropylene plastic plate) is used between the impact bar and the incident bar. Figure 3 shows the longitudinal strain with the absorbing material. As a result, oscillations trailing the leading edge of the wave were decreased, and the waveform is almost uniform for the period of 200\mu s. The deviation in the radial direction is within 3\% for the above period.

![Figure 4: Effects of the absorbing material](image-url)

(a) Measured strain in the incident bar

(b) Stress in the specimen
Figure 4 shows the time history of the stress in the concrete test specimen. It is found that the proposed SHPB test condition is desirable using this absorbing material.

2.3 Test Specimen

The concrete test specimen is designed to have a compressive strength of 24MPa after 28 days. The diameter of specimens is 100mm, and length is 100mm and 200mm. Wet concrete specimens and completely dry ones are used to determine the effects of moisture on concrete strength.

3 Results

3.1 Strength

Several dynamic tests are conducted with strain rate varying from $10^{-1}$ to $10^2$ /sec for wet specimens and dry ones.

Figure 5 shows the dynamic strength factor which is defined as the ratio of the dynamic compressive strength to the static compressive strength in the same condition. The static value is represented for 200mm long specimens.

![Figure 5: Relation between dynamic strength and strain rate](image)
The dynamic strength factor in the wet concrete specimens increases rapidly over the strain rate of $10^0$ to $10^1$ /sec. On the other hand, a rapid increase of the factor was not observed for less than $10^1$/sec for the dry specimens. It is found that the compressive concrete strength depends on the moisture in the concrete.

A regression equation based on the test data can be expressed as follows:

$$\frac{f_{\text{CD}}}{f_{\text{CS}}} = 0.9783 + 0.0217 \times \left(\frac{\varepsilon_c}{\varepsilon_{c0}}\right)^{0.277} \quad (9)$$

where $f_{\text{CD}}$ is the dynamic compressive strength, $f_{\text{CS}}$ is the static compressive strength and $\varepsilon_{c0}$ is a standard strain rate equal to $3 \times 10^{-6}$/sec. In Figure 5, eqn. (9) and the strength equation recommended in CEB/FIP[3] are also plotted. The equation in the CEB/FIP code increases highly at the strain rate at 30 /sec. The obtained strength factor of wet concrete specimens begins to increase at the strain rate around $10^0$ /sec.

### 3.2 Collapse Mode

Figure 6 shows the collapse mode of the specimens. That of the 200mm long specimen was shear collapse, but that of the 100mm long specimen was compressive collapse.

![Figure 6: Collapse of specimens](image-url)
4 Discussion

The compressive concrete strength for compressive collapse mode and shear collapse mode is estimated by using of the theory proposed by Chen[6].

The model of each mode is shown in Figure 7. It is assumed that the model of the compressive collapse mode consists of two corned parts with a cylinder at both ends and innumerable side parts. In the model of the shear collapse mode, two parts distinguished with the angle $2\alpha$ from the cylindrical side are assumed.

Using the upper-bound theorem, upper-bound loads ($Q_u$) of each collapse mode are expressed as follows:

\[
\frac{Q_u}{\pi a^2} = f_c \left\{ 1.0 + \frac{f_c}{f_t} \tan^2 \left( \frac{\pi}{4} + \frac{\phi}{2} \right) \right\} \quad (10)
\]

\[
\frac{Q_u}{\pi a^2} = 1.0 \cdot f_c \quad (11)
\]

$f_c$ is the compressive strength, $f_t$ is the tensile strength and $\phi$ is the internal-friction angle. It is obvious that the apparent compressive strength ($Q_u/\pi a^2$) in the compressive collapse mode in eqn. (10) is

![Figure 7: Schematic of collapse mode](image-url)

(a) Compressive collapse mode  
(b) Shear collapse mode

Figure 7: Schematic of collapse mode
measured larger than the true one. The apparent compressive strength in
the shear collapse mode in eqn. (11) becomes the same as the true one.

5 Conclusion

Dynamic compressive tests in concrete specimens were conducted using
impact test apparatus to clarify the effects of strain rate on concrete
strength. The results are summarized below.

• An impact test apparatus was developed to measure the concrete
  strength of strain rates from $10^{-3}$ to $10^{2}$ /sec. There are both the
  hydraulic loading system to strain rate $10^{-3}$-$10^{-1}$ /sec and the SHPB
  method type loading system to strain rate $10^{0}$-$10^{2}$ /sec.
• A method of measuring an incident wave and a reflected wave near the
  specimens was proposed in the compressive test using the SHPB
  method.
• The effects of the stress wave dispersion were mitigated by use of the
  absorbing plate between the impact bar and the incident bar, and the
  amount of strain scatter inside the incident bar became within 3%.
• The ratio of the dynamic compressive strength to the static one in the
  wet specimens becomes large with the increase of strain rate. This
  ratio increases rapidly in the region of $10^{0}$-$10^{1}$ /sec strain rate.
• The dynamic strength in concrete is largely dependent upon of
  moisture content.

6 Acknowledgments

The authors wish to thank Mr. Miyano of Maekawa Testing Machine
Mfg. Co., Ltd. for the design and production of the impact test apparatus.
They are also indebted to Mr. Kato and Mr. Iizuka for help with the
preparation and measurement of tests, and with compiling the
experimental data.

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