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EFFECT OF IMPACT LOADING ON TENSILE STRENGTH OF CONCRETES

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ABSTRACT

The tensile strength and strain rate sensitivity of concretes under impact loadings were examined by means of the method of reflected tensile stress waves. The experimental method is conducted by the Hopkinson bar technique and it is based on the superposition and concentration of tensile stress waves reflected both from the free ends of a striking bar and a specimen bar. The impact tensile experiment for concretes was carried out and the tensile strength of concretes under impact loadings was discussed as well as the effect of strain rates. This study focused on the estimation and measurement of strain rates using crack gages. As a result, the impact tensile strength of concrete at the strain rate of 10^0 sec^{-1} was found to be approximately twice of the static tensile strength, and it was remarkably influenced by strain rates ranging from 10^0 to 10^1sec^{-1}.

KEYWORDS

Impact tensile strength, Concentration of tensile stress waves, Cumulative fracture probability, Strain rate, Crack gage, Concrete.

INTRODUCTION

The investigation of the mechanical characteristics and the fracture strength of concrete under high loading rate is increasingly important for the safe assessment of most engineering structures against impact loadings such as impingement of projectiles, explosions and enormous earthquakes [1-3]. Since concrete is inherently weak in tension, it is commonly used as a compressive member material in civil engineering structures. On the other hand, concrete is also used in protective structures designed to resist impulsive loads. Although impulsive loads are originally compressive, they may produce tensile stress waves in structural members developed at the free boundary and so on. It is difficult to isolate concrete structures from impact tensile stresses, even though static tensile loads on concrete members are avoided. Even in static tests, precise measurement of the tensile strength of concrete is known to be difficult as well as rocks and ceramics. For determining the static tensile strength of concrete materials, the splitting-tensile test is commonly used to avoid some difficulties associated with the direct tension. Many investigations on impact tensile strength of concrete materials have been contributed by impact splitting-tensile test, together with impact direct tension test [4-7]. Recently an experimental method for dynamic tensile testing by spalling is reported [8,9]. However, it does not appear that there is a standard test method for measuring impact tensile strength of concrete materials [10].

This paper concerns with the measuring method for the impact tensile strength and strain rate sensitivity of concretes by means of the measuring method of reflected tensile stress waves. The experimental method has been proposed for brittle materials such as plaster, ceramics and concrete in our previous papers [11-15]. The impact tensile experiment is conducted by the Hopkinson bar technique and it is based on the superposition and concentration of tensile stress waves reflected both from the free ends of a striking bar and a specimen bar. The impact tensile experiment for concretes was carried out and the tensile strength of concretes under impact loadings was discussed as well as the effect of strain rates. This study focused on the estimation and measurement of strain rates using crack gages. Because the tensile stress region varies with time in this measuring method, it is necessary to find the beginning time when a specimen bar is broken after starting of tensile stress waves superposition, in other words, the gage length that the tensile stress waves have reached until the initiation of tensile break. Consequently, the impact tensile strength of concrete at the strain rate of 10^0 sec^{-1} was found to be approximately twice of the static tensile strength, and it was remarkably influenced by strain rates ranging from 10^0 to 10^1sec^{-1}.

STRESS WAVE PROPAGATION IN A CONCRETE BAR

The measuring theory had already been presented in the previous papers [11,13], but it is briefly explained here by means of a numerical simulation. Figure 1 (a) shows a concrete bar specimen with the length of l and an incident compressive stress σ_0 into the impact end of the bar. $T= t/t_0$ is the dimensionless time and $t_0= l/c_0$ is the time of the wavefront reaching at the free end of the bar. c_0 is the velocity of stress wave in the concrete specimen bar. Assuming that the pulse length of an incident compressive stress has the same length with a concrete specimen bar, the numerical simulation was carried out under the condition of two-dimensional axisymmetric model using a FEM code, MARC.

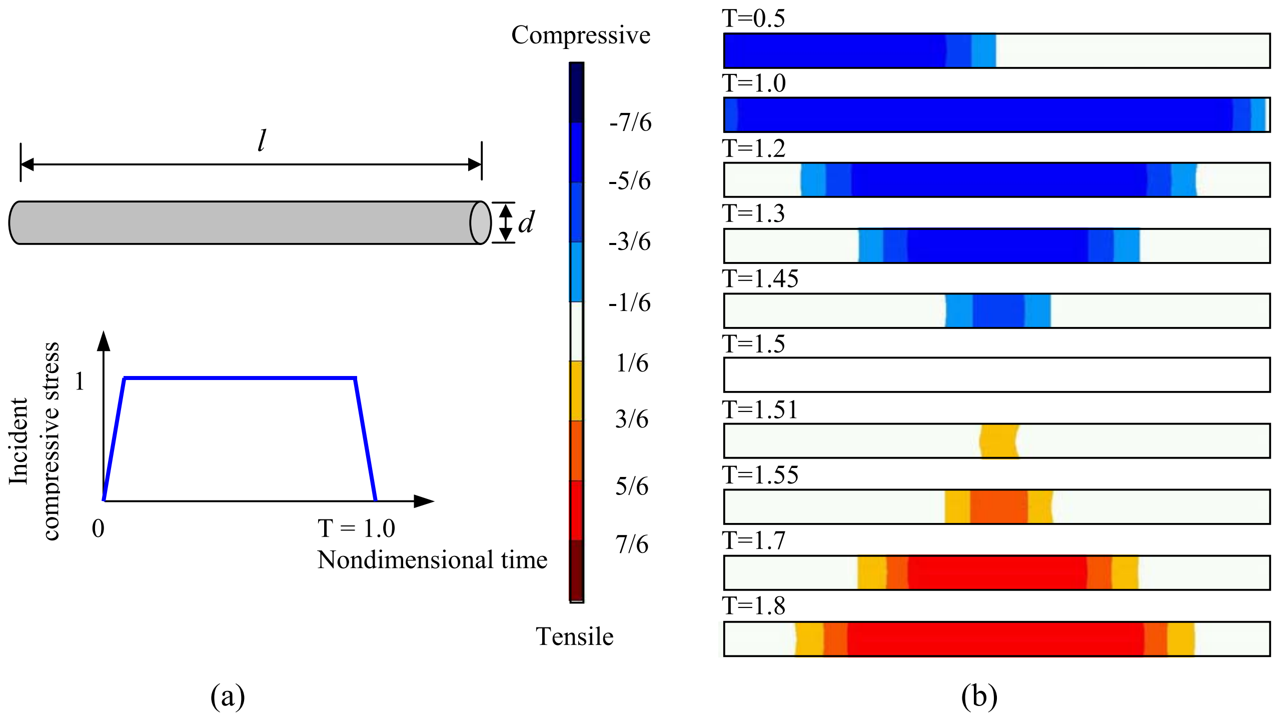

Figure 1: (a) Concrete specimen bar and an incident compressive stress in a numerical analysis.
(b) Propagation of incident compressive stress wave and development of tensile stress region produced by reflected tensile stress waves.

Figure 1 (b) shows the numerical results that illustrate the behavior of stress wave propagation in a concrete specimen bar. After the compressive stress wave propagation, the reflected tensile stress waves are superposed at the center of the specimen bar and the tensile stress region is developed. The blue denotes the compressive stress wave and region, and the red the tensile ones. By making use of this process of stress wave propagation, a simple measuring method for impact tensile strength of concrete materials was proposed. The impact tensile experiment is conducted by means of Hopkinson bar technique.

MECHANICAL PROPERTIES OF CONCRETE SPECIMEN

Concrete and mortar specimens were used for this study. In this paper, however, the results only concerning concrete specimens (with coarse aggregate) are presented. The concrete mix proportions are shown in Table 1. An ordinary Portland cement with fine and coarse aggregates was employed for the fabrication of concrete specimens. The maximum size of coarse aggregate was 10 mm. Concrete specimens cured for 10 months were used for this study. In the impact tensile strength experiment, cylindrical bar specimens of concrete with 750 mm length and 50 mm diameter were used. Static tests of splitting tension (Brazilian), 3-point bending and compression were also carried out to examine the static mechanical properties of the concrete specimen.

TABLE 1

MIX PROPORTIONS OF CONCRETE FOR A CUBIC METER

Material	Quantity
Water/cement ratio	0.5
Portland cement	370 kgf
Water	185 kgf
Fine aggregate	874 kgf
Coarse aggregate	874 kgf
Water-reducing admixture	0.74 kgf
Total weight per cubic meter	2303 kgf

TABLE 2

MECHANICAL PROPERTIES OF CONCRETE

Mechanical Properties	Value
Splitting tensile strength (σ_{ts})	2.9 MPa
Bending strength (σ_b)	5.4 MPa
Compressive strength (σ_c)	27.8 MPa
Elastic modulus (E)	35.1 GPa
Mass density (ρ)	2315 kg/m^3
Poisson ratio (ν)	0.2
Velocity of stress wave (c_0)	3894 m/s

In the static tests of splitting tension and compression, pieces of specimens with a length of 100 mm were cut from the long cylindrical bar specimens. To avoid some difficulties associated with the direct tension test such as specimen holing and proper alignment, the splitting tension test was carried out. The static splitting tensile test is an acceptable indirect method for determining tensile strength of concrete materials [6,10]. In the static bending test, the span was set to be 700 mm. All the static tests were conducted using an INSTRON (model 5586) material test machine at loading rates of 0.05 - 0.5 mm/min.

Table 2 shows the static mechanical properties of the mortar specimens obtained by the static tests. Each strength is the mean value of cumulative fracture probability, which is discussed later. Here, c_0 is the velocity of stress waves, given by $c_0^2 = E/\rho$, which almost corresponded to the experimental observation of elastic waves through the concrete specimen bar.

EXPERIMENTAL TECHNIQUE AND ARRANGEMENT

The Hopkinson bar technique is a widely used technique to determine the mechanical properties of materials at high loading rates. In this experiment, the setup consists of an air gun, a stainless-steel striking bar (SUS306), an aluminum alloy input bar (JISH4040), and a set of recording devices. The striking bar with 500 mm length and 20 mm diameter is chosen in order to initiate concentration of tensile stress at the center, C, of a specimen bar, shown in Fig. 2. The input bar is of length 1500 mm and 50 mm diameter. It is adjusted to be collinearly impacted by the striking bar shot out from the air gun. Two sets of semiconductor strain gages, *a* and *b* , are cemented diametrically at a distance of 6*d* and 12*d* from the contact end the input bar with a specimen bar for measuring incident stress waves into the specimen bar [11]. One end of the concrete specimen bar is arranged in tight contact with one end of the input bar, while the other end of the specimen bar is released from stresses. The factors of reflection and transmission at the interface between the input bar and the specimen bar can be calculated using both the material properties of the input bar and the concrete specimen. In the present combination, α = - 0.25 and β = 0.75, where $1+\alpha = \beta$ on the assumption that all the incident stress, reflection stress and transmitted stress are taken to be compressive [2]. All specimens are equipped with two strain gages pasted diametrically at two locations 1 and 2, respectively, to measure directly stress waves propagated in a specimen bar. In order to specify the tensile break time, four crack gages (KYOWA, KV-5C) are also mounted at the center position of the specimens. The response signals trapped at those locations are passed through bridge boxes to a four-channel digital oscilloscope (Nicolet, Model 400).

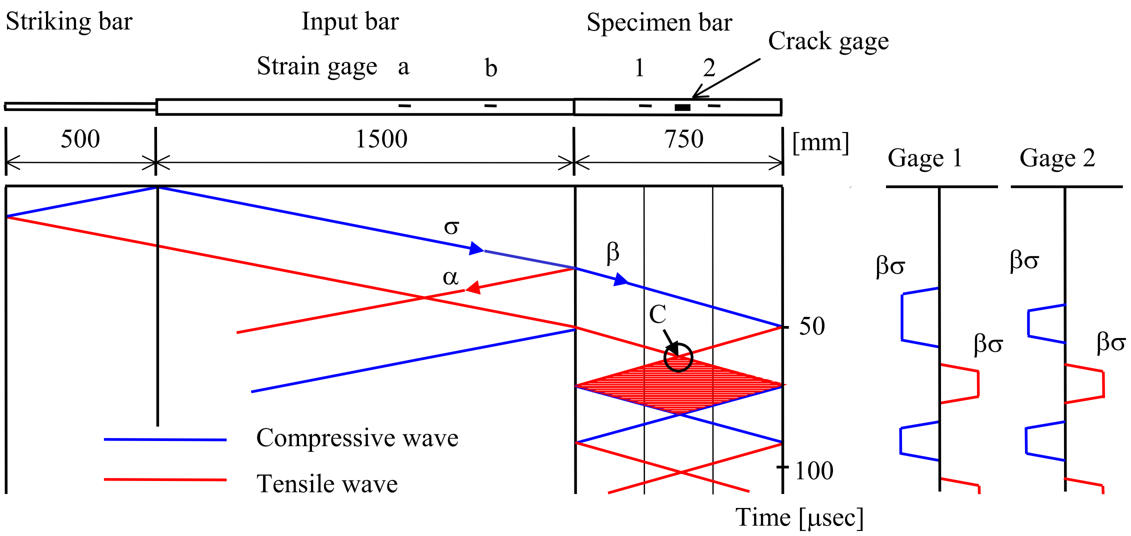

Figure 2: Experimental arrangement and superposition of tensile stress waves in concrete specimen.

IMPACT TENSILE STRENGTH AND STRAIN RATES

Cumulative Fracture Probability

The impact tensile strength is determined from reading off the intensity of the tensile stress waves measured by the strain gages cemented on the concrete specimen bar. Suitable statistical analyses may be required to treat the dispersion of the experimental data in relation to the concrete strengths. A Weibull distribution was applied to not only the impact tensile strength but also the static strengths of the concrete specimen, as shown in Figure 3. To plot the *i*-th ranked sample from a total of *n* number of fractured specimens, a median-rank position was adopted, which is the distribution function *Fi* expressed approximately in terms of $Fi = (i-0.3)/(n+0.4)$. The data plotted on the Weibull probability paper, i.e., $ln ln[1/(1-Fi)]$ versus $ln(\sigma)$ lay on straight lines. The regression lines were drawn by means of the method of least squares. The Weibull modulus (shape parameter) *m* of each plot and the scale parameter ξ (fracture probability 63.2%) can be found from the Weibull distribution. The mean stress μ and the standard deviation *s.d.* can be calculated based on such data. The statistical results of the concrete used for this study are shown in Table 3. Comparing the impact tensile strength with the static tensile strength, it is worth noting that the tensile strength of the concrete is significantly influenced and increased by loading rates. Here the impact tensile strength, σ_{it} , in Table 3 denotes the minimum tensile stress to break the concrete specimen under impact loading in this experimental method. The impact splitting-tension test was also performed, but the detail is omitted.

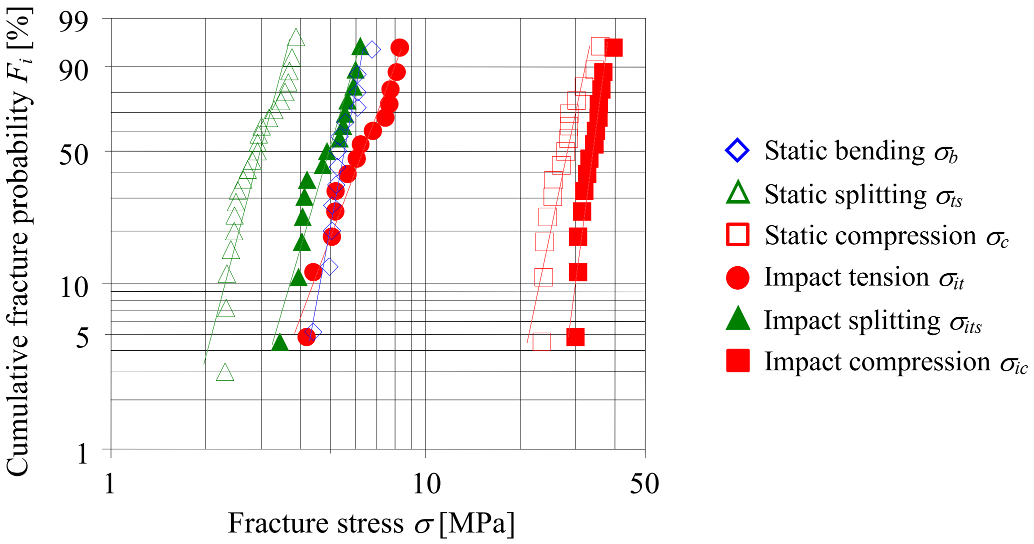

Figure 3: Cumulative fracture probability of concrete strengths.

TABLE 3
EXPERIMENTAL RESULTS OF STATISTICAL ANALYSIS BY WEIBULL PLOTS

Test		σ_b	σ_{ts}	σ_c	σ_{it}	σ_{its}	σ_{ic}
Number of samples	n	13	23	15	14	15	14
Shape parameter	m	10.6	6.3	9.8	5.2	6.5	14.6
Scale parameter [MPa]	ξ	5.7	3.1	29.3	6.8	5.2	36.9
Mean [MPa]	μ	5.4	2.9	27.8	6.2	4.9	33.7
Standard deviation [MPa]	*s.d.*	0.5	0.6	3.4	0.9	0.9	2.8

Strain Rate Sensitivity of Concrete

In this measuring method the tensile stress region developed in the axial direction of a specimen bar varies with time. Therefore it is necessary to find the beginning time when a specimen bar is broken after starting of tensile stress waves superposition, in other words, the gage length that the tensile stress waves have reached until the initiation of tensile break. The broken time of a specimen was measured using crack gages pasted on it, while the starting time of superposition of tensile stress waves was done by strain gages. A typical example of response signals measured by the strain and crack gages is presented in Figure 4. The solid blue line denotes the stress response at the broken position of a specimen bar, estimated from the stress response of the strain gage 2, while the red line denotes the response from crack gages. It can be found that the beginning time of tensile stress generation and tensile break is 431 μsec and 548 μsec, respectively, after an incident compressive stress is transmitted into the specimen bar. Then the gage length of tensile stress region is calculated as $l = 2c_0\Delta t = 0.85$ m, considering that the tensile stress region is initiated at the center of a specimen bar and progresses on both sides. Subsequently the strain rate can be found as, $\dot{\varepsilon} = v/l = 1.35$ sec^{-1} by making use of the relation between impact stress σ and particle velocity v, $v = \sigma / \rho c_0$. The corresponding impact tensile strength is about 9.2 MPa. Repeating the same procedure to each measuring result shown in Figure 3 and a series of experimental results on higher impact tensile stresses applied to concrete specimens, the relation of the impact tensile stress and the strain rate of the concrete used for the present test was obtained in Figure 5. The impact splitting tensile (Brazilian) results are also depicted in addition. The impact tensile strength of concrete at the strain rate of about 10^0 sec^{-1} may be found to be approximately twice of the static tensile strength, and it is remarkably influenced by strain rates ranging from 10^0 to $10^1 sec^{-1}$. In addition, it is recognized that there are some differences between the results obtained by the present measuring method using reflected tensile stress waves and by the impact splitting-tension test.

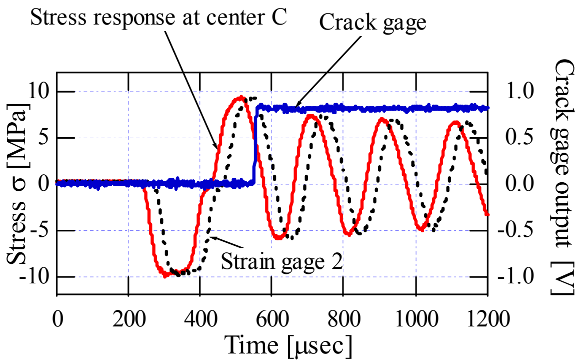

Figure 4: Responses of strain and crack gages.

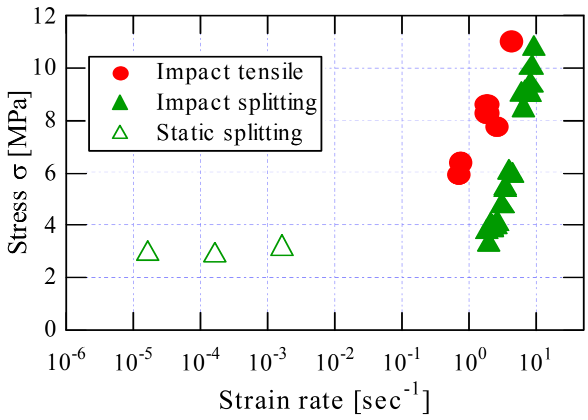

Figure 5: Strain rate effects on concrete strength.

CONCLUDING REMARKS

(1) In this paper the impact tensile strength and strain rate sensitivity of concrete was discussed by means of the measuring method using reflected tensile stress waves. The impact tensile experiment of concrete specimens was performed, together with the impact splitting-tension test. The experimental results were analyzed statistically by a Weibull distribution.

(2) The strain rates were estimated by specifying the gage length of the tensile stress region developed until the initiation of tensile break in a specimen bar, which was measured by using crack gages.

(3) The impact tensile strength of concrete used for the present study at the strain rate of $10^0 sec^{-1}$ was found to be approximately twice of the static tensile strength, and it was remarkably influenced by strain rates ranging from 10^0 to $10^1 sec^{-1}$.

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