Stress Waves and Dynamic Characteristics of Rocks under Detonator's Attack

By

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The experiments have been carried out to investigate the characteristics of the stress waves induced in rocks when they are attacked by an explosion of a detonator and also to study some mechanical properties of rocks under such an impulsive load.

To obtain the shape of a stress wave which is induced in a cylindrical bar specimen by an impulsive load, a method utilizing the displacement of the free end face of the specimen was used in this study and it was recognized that this method was simpler and more convenient than the pellet method developed by J.S. Rinehart.

The change in the propagation velocity of the stress wave with distance from the shot point was studied in detail and it was found that even in the case of detonator's attack a plastic wave or a shock wave seemed to be generated in the limited region near the shot point.

The dynamic stress-strain relationship and the dynamic strengths for compression and tension were determined for three kinds of rock specimens and these results were compared with those obtained by the conventional static test.

1. Introduction

In the present study measurements have been made of the stress waves and strains in the cylindrical rock specimen caused by the detonator's attack and thence some mechanical properties of rocks under such an impulsive load have been analysed and discussed.

To obtain a stress wave shape which is induced in a cylindrical bar specimen by an impulsive load, the method developed by J.S. Rinehart has generally been used[1),2)]. However, in the present experiment, using a cylindrical specimen with parallel ends perpendicular to the axis of the cylinder, the displacement of one end due to the stress wave propagated through the specimen from the other end was measured by using a capacitance gauge. The measurement was repeated with specimens of various thicknesses. Thus, the particle displacement, u, and the particle velocity, v, at the measuring point in the stress wave can be calculated by

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using following Equations (1) and (2):

$$u = \frac{1}{2} u_1 , \tag{1}$$

$$v = \frac{du}{dt} = \frac{1}{2}\frac{du_1}{dt} , \tag{2}$$

where u_1 is the displacement measured at the free end. Therefore, if the propagation velocity of the stress wave, c, and the density of the specimen, ρ, are known, the stress wave shape can be derived from Equation (3):

$$\sigma = \rho c v , \tag{3}$$

where σ is the stress.

2. Experimental Arrangement

The experimental arrangement is shown in Figure 1. At first, all the rock

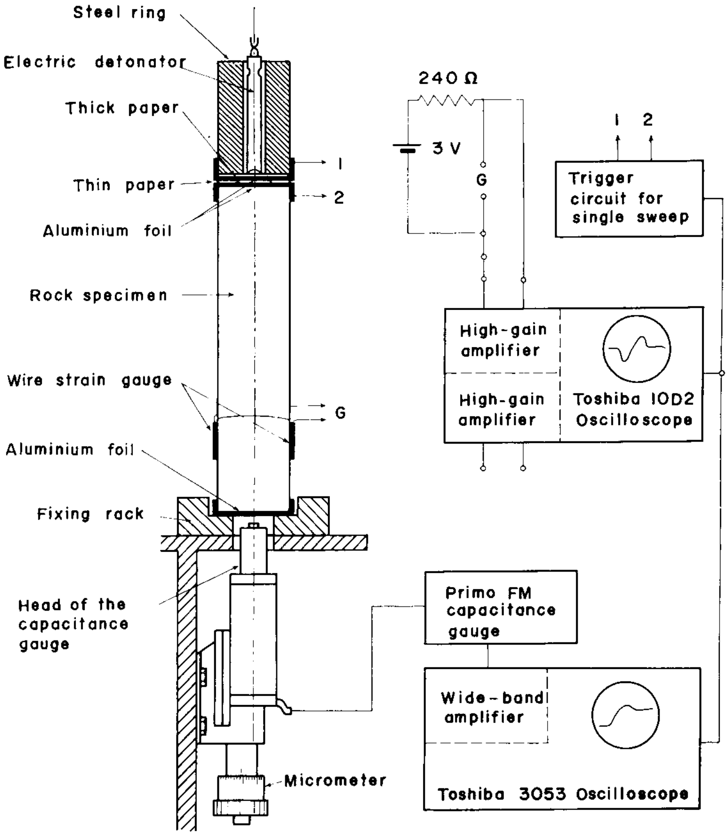


Fig. 1. Schematic diagram showing the arrangement of the experimental apparatus.

specimens were made into a cylinder with smooth ends perpendicular to the axis and an aluminium foil was cemented on each end to form a piece of electric contacts. An electric detonator was inserted in a steel ring, on the bottom of which an aluminium foil was cemented, and then the steel ring was tightly fixed on the upper end of the specimen by means of Scotch tape, keeping the electric insulation between the steel ring and the specimen by using a piece of thin paper. Thus, a set of electric contacts between 1 and 2 gave a means of triggering the oscilloscope.

Then, this set of specimen was placed on a fixing rack which had a circular hole at its lower surface to fit the insertion of the head of the capacitance gauge. The aluminium foil at the lower end of the rock specimen was used as a capacitance plate on the ground side of the capacitance gauge and the head of the capacitance gauge itself was used as the other capacitance plate.

The output signal from the capacitance gauge was fed to a single beam oscilloscope (Toshiba 3053) through a wide-band amplifier and the oscilloscope trace was recorded by using an oscilloscope camera.

To prepare a calibration curve, in advance, a micrometer was used to adjust the gap between the capacitance plates and the output signal from the capacitance gauge was measured for each gap.

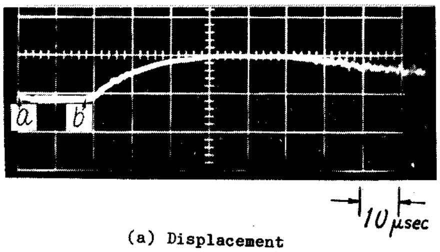
On the other hand, the strains in the rock specimen associated with these impulsive loads were measured by using wire strain gauges, amplifiers and a dual beam oscilloscope (Toshiba 10D2). A rosette type of wire strain gauge (Shinkoh SV-108) was used to measure the axial and radial strains. Two of these strain gauges were always cemented on the cylindrical surface at the lower end of the specimen so as to face each other and the element of each direction was connected in series.

All oscilloscopes were used in the single sweep mode. They were triggered at the instant when the upper end of the rock specimen was struck by the explosion of a detonator.

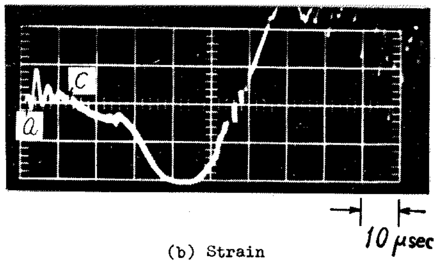
The rock specimens used were made of Mine marble from Yamaguchi prefecture, Izumi sandstone from Osaka prefecture and Tako sandstone from Gunma prefecture.

3. Experimental Results and Considerations

Examples of the displacement and strain oscillograms are shown in Figure 2. The left end point (a) on each trace represents the instant at which the specimen was struck by the explosion of a detonator; in other words, the time when the stress wave was first induced at the impacted end of the specimen by the explosion.



(a) Displacement



(b) Strain

Fig. 2. Examples of oscillograms.

The point (b) on the displacement trace represents the instant at which the stress wave front arrived at the free end of the specimen. The duration between (a) and (b) is the time required for the stress wave to propagate along the length of the specimen. Therefore, the mean propagation velocity of the stress wave in the specimen can be calculated from this time duration and the length of the specimen. The particle displacement versus time relationship at the free end can be obtained from the trace beyond the point (b) of the displacement oscillogram by using both calibration curve and Equation (1). The particle velocity versus time relationship can be obtained by differentiating graphically the displacement versus time curve with respect to time. On the other hand, the point (c) on the strain oscillogram represents the instant at which the stress wave arrived at the points where the strain gauges were cemented on the specimen. Therefore, the relationship between the dynamic stress and strain can be obtained by associating the point (b) on the displacement trace with the point (c) on the strain trace, ignoring the attenuation of the stress wave in short distance.

Now, by using No. 3 electric detonators and three kinds of rock specimens, the lengths of which were from 2 cm to 30 cm, stress wave shapes under the same intensity of impulsive load were observed. The results obtained are shown in Figure 3. Then, to study the phenomena under various intensities of explosion, three classes of electric detonators, No. 3, No. 6 and No. 8, were used separately and the same experiments were carried out with specimens of 5 cm long and 10 cm long. Stress wave shapes obtained in these experiments are shown in Figure 4. As shown in these figures, stress waves were characterized by an instantaneous rapid rise of the stress level and a comparatively slower fall of the stress level according to the length of the specimen, although they took somewhat different shapes in accordance with the kind of the rock.

Based on the relation between the mean propagation velocity measured and the distance from the shot point, the distribution of the instantaneous propagation velocity of the stress wave in these rock specimens can be deduced. Results cal-

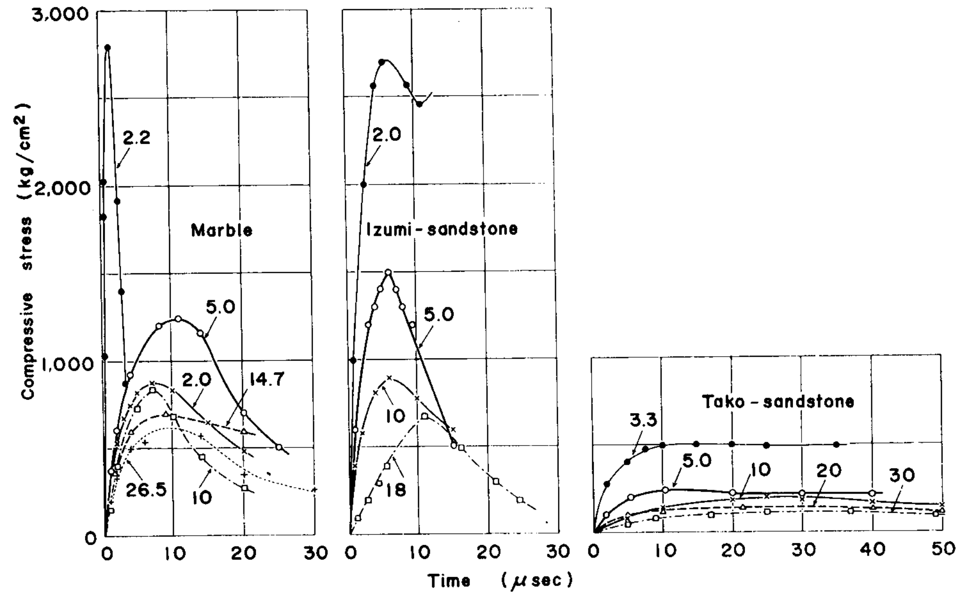


Fig. 3. Stress wave shapes obtained for No. 3 detonator's attack. Figures put on respective curves designate the length of the rock specimen in cm.

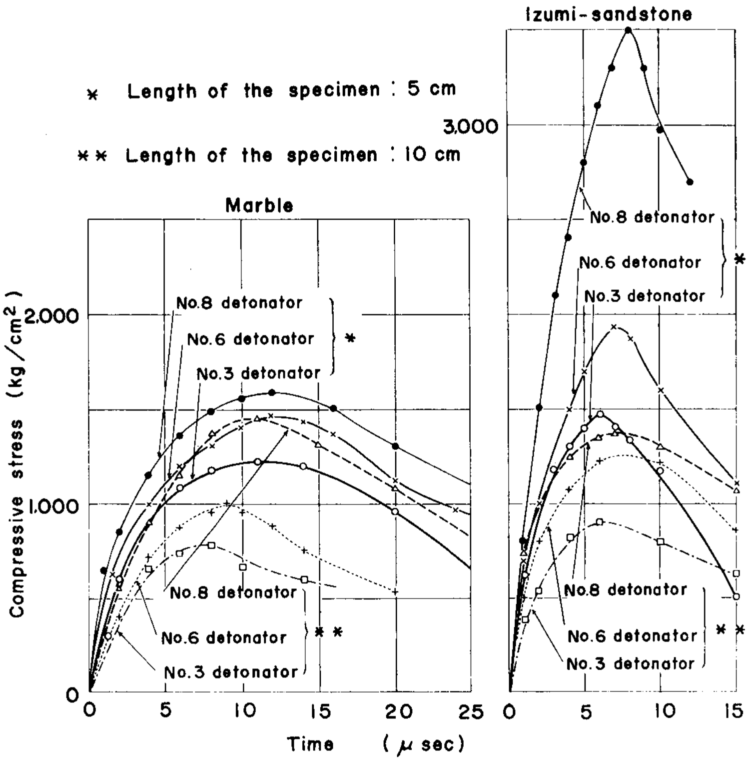


Fig. 4. Stress wave shapes obtained for various intensities of the detonator.

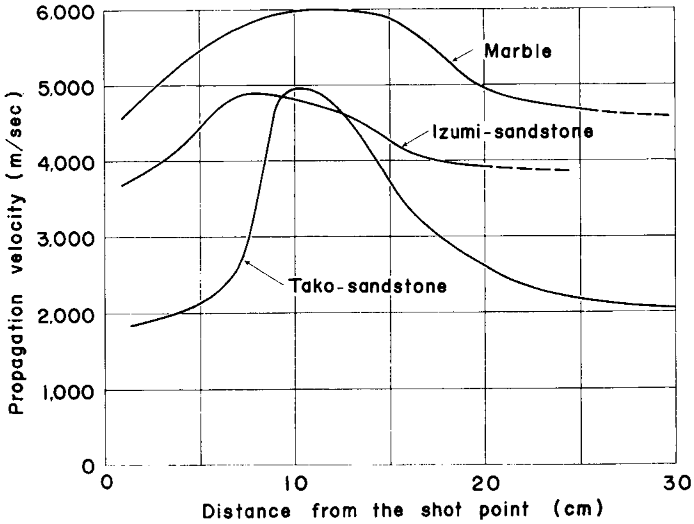


Fig. 5. Relation between the propagation velocity of the stress wave and the distance from the shot point.

culated are shown in Figure 5 for the case of experiments in which the stress wave shapes shown in Figure 3 were obtained. It is obvious that three distinct regions exist for the propagation velocity in the rock and it is considered that a plastic wave is initially generated involving relatively low speed in the rock near the shot point. As the plastic wave progresses away from the interface between the detonator and the rock, the velocity increases rapidly. At some distance, the plastic wave changes to the shock wave with its propagation. After the velocity of the shock wave has reached a maximum, it gradually decreases and approaches to the elastic wave velocity. Hereupon, the authors define the terms "plastic, shock and elastic wave zones" in terms of the instantaneous propagation velocity of the stress wave. As shown in the figure, although the plastic wave zone is limited to a narrow region near the shot point, it is found that the lengths of the plastic and shock wave zones under the same intensity of explosion are different due to the characteristics of the rock used. These phenomena already have been recognized in the results of similar experiments using explosives' attack[3].

The relationship between the dynamic stress and strain can be deduced assuming that the maximum dynamic stress corresponds approximately to the maximum dynamic strain in the specimen observed simultaneously in each case of measurements. The results obtained were compared with the static stress-strain relationship in Figure 6, where the static values were determined by conventional test for the static compression and were plotted in the dotted lines. From this

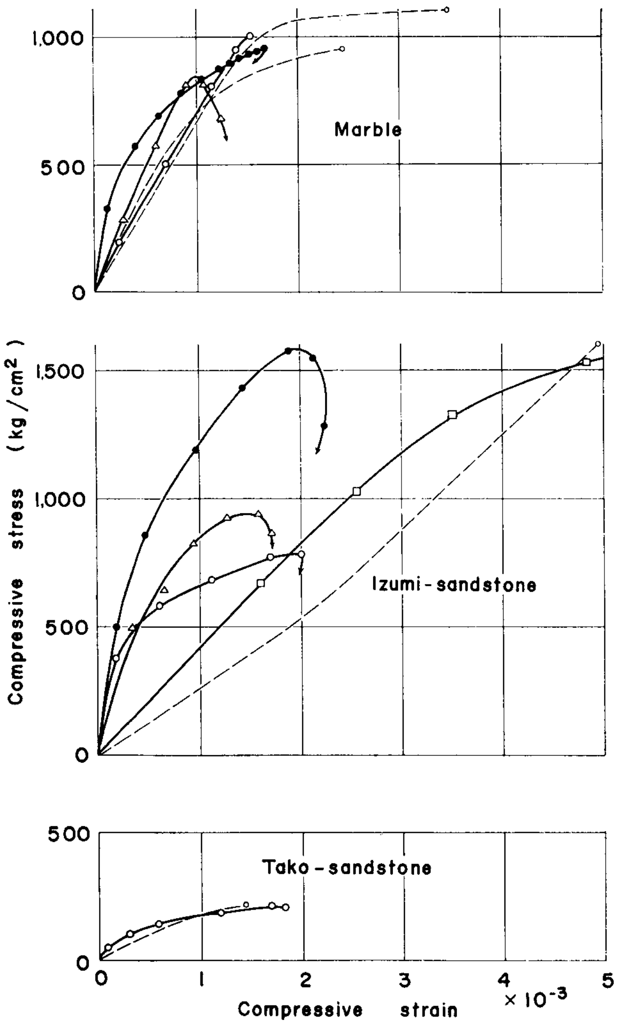


Fig. 6. Dynamic and static stress-strain relationships for three kinds of rocks.

figure, it is clear that the dynamic Young's modulus of the rock in the region of lower stress is somewhat greater than the static one. Moreover, these dynamic situations of rocks are fairly different from those reported in the case of metals[4]. In the case of rock specimens, the so-called plastic flow phenomenon could not always be observed and most of the rock appeared to undergo brittle fractures when the dynamic stresses in them exceeded certain values above their own elastic limits.

The dynamic compressive strength of the rock was obtained by applying the length of the crushed zone produced in the rock specimen to the attenuation curve of the maximum stress from the shot point (Figure 7). On the other hand, the

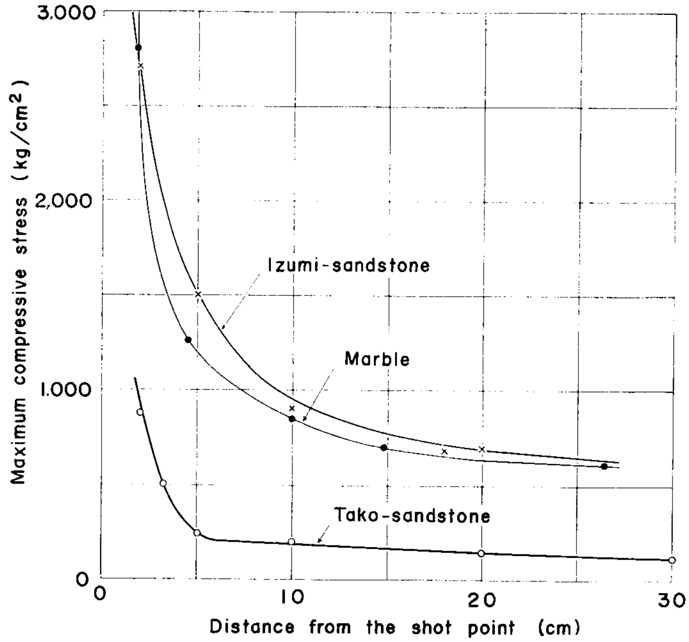


Fig. 7. Relation between the value of the maximum compressive stress and the distance from the shot point.

dynamic tensile strength of the rock was obtained by utilizing the well-known phenomenon of spalling which was found near the free end of the specimen. Thus, the results obtained are shown in Table 1. As shown in the table, the dynamic strengths are generally greater than the static ones and the difference between them

Table I. Summarized experimental results.

Kind of rock (Locality)		Marble (Mine-shi, Yamaguchi)	Izumi-sandstone (Sennan-gun, Osaka)	Tako-sandstone (Tano-gun, Gunma)
Density (g/cm³)		2.7	2.6	2.0
Mean propagation velocity of the stress wave (m/sec)		4500～6000	3700～4300	1800～3500
Compressive strength (kg/cm²)	Dynamic	1200～2000	1200～2000	200～500
	Static	900～1100	1000～1400	150～250
Tensile strength (kg/cm²)	Dynamic	200～400	500～ 700	100～200
	Static	50～ 90	80 ～ 90	20～ 30

seems to be greater in the case of tensile strength than in the case of compressive strength.

4. Conclusions

The results obtained in this investigation have been summarized as follows.

1) To obtain the stress wave shape, it has been recognized that a method utilizing the displacement of the free end face of the rock specimen is simpler and more convenient than the method developed by J.S. Rinehart.

2) It has been found from the change in the propagation velocity of the stress wave with distance from the shot point that even in the case of detonator's attack a plastic wave or a shock wave seems to be generated in the rock near the shot point.

3) The dynamic compressive and tensile strengths of the rock obtained in this study are generally greater than the static ones and the difference between them seems to be greater in the case of tensile strength than in the case of compressive strength.

References

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