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Mechanical behaviour and characteristics of rocks subjected to shock loads

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ABSTRACT: The dynamic mechanical behaviour and characteristics of rocks have been investigated using different techniques. One of the commonly used technique is the Split Hopkinson Pressure Bar technique. However, the measured responses are inferred from the strain gauges attached to intermittent and transmitting bars rather than directly from samples. The authors devised a new experimental apparatus to investigate the behaviour of rocks under shock waves. The device may be fundamentally categorized as the drop-weight apparatus and it is possible to evaluate the mechanical behaviour and characteristics of rocks subjected to shock waves during pre-failure as well as post-failure stages. The rocks tested are tuff, limetsone, granite, marble, gneiss, porphyrite, ranging from soft rocks to hard rocks. The testing conditions correspond to uniaxial compression test and Brazilian tensile test. The nominal impact velocity can be easily adjusted and it can be easily correlated with the measured responses and dynamic mechanical properties. The authors present the outcomes of this experimental study and discuss their implications in the field of rock dynamics.

1 INTRODUCTION

The dynamic mechanical behaviour and characteristics of rocks have been investigated using different techniques in relation to evaluate the engineering structures by dynamic loads such as those resulting from the impact of missiles or meteorites, One of the most commonly used techniques is the Split Hopkinson Pressure Bar technique, which was originally developed Hopkinson in 1914 to measure stress pulse propagation in a metal bar. Kolsky (1949) refined Hopkinson's technique by using two Hopkinson bars in series, now known as the Split-Hopkinson Pressure bar (SHPB), to measure stress and strain. However, the measured responses are inferred from the strain gauges attached to intermittent and transmitting bars. Furthemore, it is difficult to evaluate the post-failure characteristics of rocks.

The authors devised new experimental apparatuses to investigate the behavior of rocks under shock waves. The devices are fundamentally categorized as the drop-weight apparatus, it can be equipped with load-cell, non-contact type laser displacement transducers, accelerometers and infra-red thermo-graphic imaging. Therefore, it is possible to evaluate the mechanical behavior and characteristics of rocks subjected to shock waves during pre-failure as well as post-failure stages. The tested rocks are tuff, limestone, granite, marble, gneiss, porphyrite. In other words, rocks tested range from soft rocks to hard rocks. The testing conditions correspond to uniaxial compression test and Brazilian tensile test. Nevertheless, it is possible to do experiments such as punching tests, bending tests. The nominal impact velocity can also be easily adjusted and it can be easily correlated with the measured responses and dynamic mechanical properties. The authors explain the newly developed experimental apparatus and experiments on various rock under shock loads and present the outcomes of this experimental study and discuss their implications in rock dynamics field.

2 SHOCK TESTING DEVICES AND ROCKS

2.1 *Shock testing devices*

The authors first developed a special shock testing device. The device consist of a steel cylinder with a weight of 8300gf having a diameter of 97 mm, a load cell, an accelerometer (Fig. 1). The plastic pipe container, in which the cylinder was dropped, had an internal diameter of 100 mm and height of 500mm. The steel cylinder was dropped from certain heights and acceleration and force were measured simultaneously using YOKOGAWA WE7000 data-acquisition system at a sampling rate of 1ms. No digital filtering was imposed on measured force and accelerometer records. The initially designed device shown in Fig. 1 was not equipped with non-contact type laser displacement transducers.

The authors recently improved their initial device and equipped with non-contact type laser displacement transducers to measure the displacement of the loading platen. The load cell was also improved, which is now capable of measuring much higher dynamic loads. The device is shown in Fig. 2 and it also enables to take infra-red thermo-graphic images during the shock tests. The displacement of the loading platen is allowed to move downward

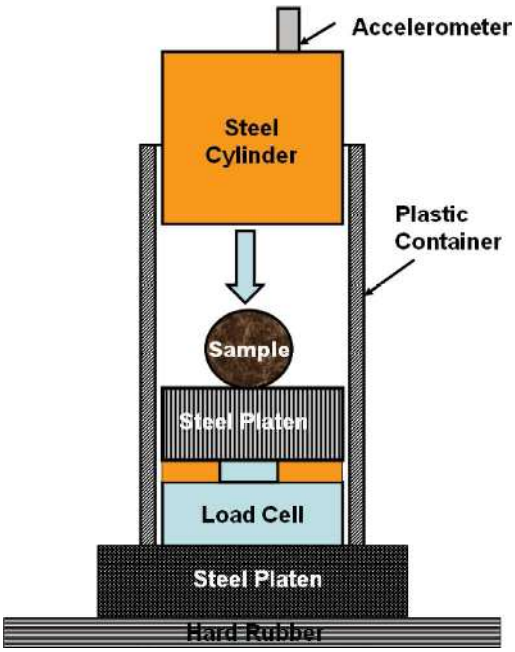

Figure 1. Schematic drawing of the initial shock testing device.

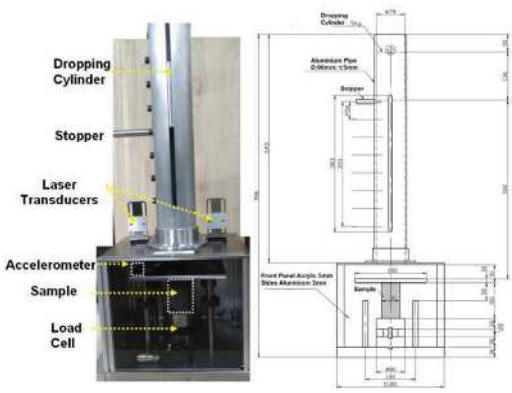

Figure 2. Schematic drawing of the new shock testing device.

up-to 20 mm in order to prevent the total destruction of samples upon failure. The cylindrical weight can be dropped from different heights up to 500 mm with an interval of 50 mm.

2.2 *Samples*

Samples of rocks are gathered from different locations in Japan and Turkey and the attention was given to those rocks with well-known mechanical properties. One of the main goal of this study is also to see the effect of velocity of shock load on the deformability and strength characteristics of rocks. The rocks were tuffs from Cappadocia, Oya and Fukui, limestone from Ryukyu limestone formation and Bazda in south-western Turkey, mudstone belonging Shimajiri formation and Seyitömer in Turkey, andesite from Sinop in Turkey, porphyrite from Atera fault zone in Japan. The experiments were carried out under uniaxial compression and Brazilian test conditions.

2.3 *Effect of velocity and location of impact*

Before tests on actual rock samples, some preliminary impact experiments were carried out on paraffin samples. Fig. 3 shows the state of paraffin sample tested under uniaxial compression shock test. It was quite interesting that the ends of the sample deformed while the center part of the sample was less deformed. This is quite different situation when the deformation state of samples is compared under static testing. Furthermore, the conical failure surface was observed at the impact side while there was no such a failure surface at the restrained side. This fact implies that the propagation of the stress wave through the sample is not uniform.

Figs. 4 and 5 show the responses during the shock tests on the paraffin sample numbered UCS2. If the shock load is sufficient enough to yield the sample, the shock load looks has a triangular shape. The larger plastic zone developed in the sample near the

Figure 3. The deformation and failure state of sample under uniaxial compression shock test.

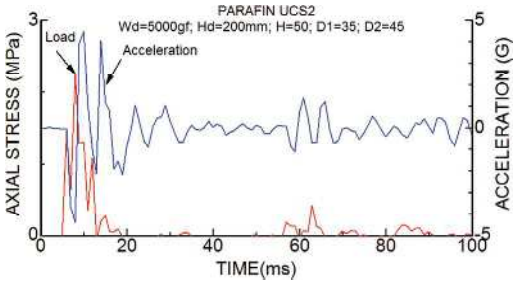

Figure 4. Time response of load and acceleration during shock test on Paraffin sample UCS2.

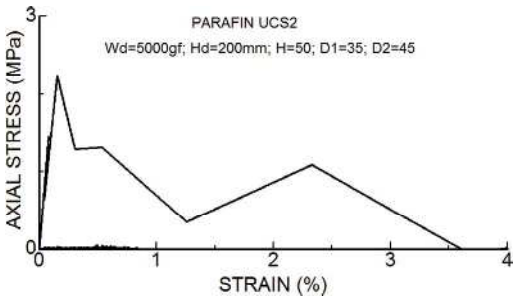

Figure 5. Strain-stress relation during shock test on Paraffin sample UCS2.

impact side. Furthermore, the post failure indicates strain softening behavior (Fig. 5).

Fig. 6 shows the deformed and failure state of two paraffin samples subjected to different impact velocity. The plastic deformation (whitened) zone is wider at the impact side than that at the restrained side, which also implies non-uniform stress wave propagation through the sample.

Another important feature is that the damage zone increase in size as the impact velocity increases. This observation has an important implication that the plastic deformation and fracturing would be much larger as the impact velocity increases. In other words, the failure zone or fractured volume is much larger in dynamic shock tests as compared with that under static condition. This may also imply that the plastic work done would be larger under dynamic conditions compared with that under static condition. This fact may also be interpreted that the apparent strength increase mentioned in many previous studies may be related to this situation in samples.

The maximum nominal velocity at the time of impact on samples can be computed from the following formula:

$$V_{\max} = \sqrt{2gH_d} \tag{1}$$

where g is gravitational acceleration and H_d is drop height. In this study, we also define maximum nominal strain rate by dividing the maximum nominal

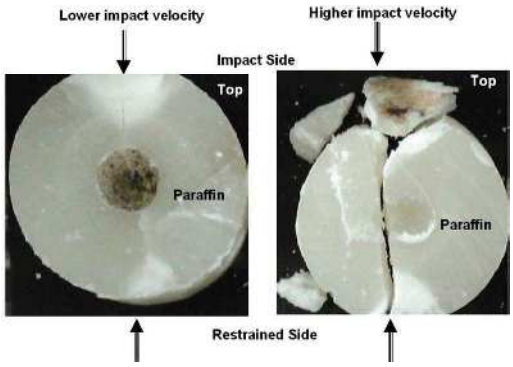

Figure 6. The deformation and failure state of sample under Brazilian shock test.

impact velocity by the sample height or sample diameter as given below:

$$d\dot{\varepsilon}_{\max} = \frac{V_{\max}}{L} \text{ or } d\dot{\varepsilon}_{\max} = \frac{V_{\max}}{D} \tag{2}$$

Maximum acceleration is obtained from the acceleration response during the experiment. It is expected to increase with the increase of strength of rock samples.

3 SHOCK TESTS

3.1 *Ryukyu limestone*

Ryukyu limestone is widely distributed in Ryukyu Archipelago. It is broadly defined as coral and sandy limestone (Tokashiki and Aydan 2010). In the experiments, coral limestone is tested under uniaxial compression and Brazilian shock tests. Figs. 7 and 8 show the force and acceleration responses of Ryukyu limestone samples. The strength of Ryukyu limestone depends upon the porosity and the static UCS ranges between 20.0 and 33.3 MPa. Similarly the Brazilian tensile strength of Ryukyu limestone depends upon the porosity and it ranges between 2.4 and 5.3 MPa. Fig. 9 compares the failure state under static and dynamic conditions.

From the comparison of experimental results given in Table 1, there is no remarkable strength increase

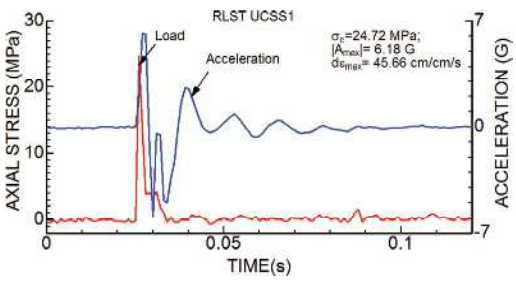

Figure 7. Axial stress and acceleration response of Ryukyu limestone sample under uniaxial compression shock test.

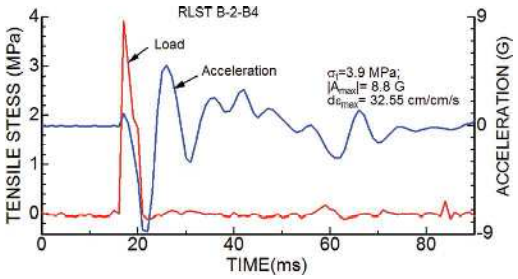

Figure 8. Axial stress and acceleration response of Ryukyu limestone sample under Brazilian shock test.

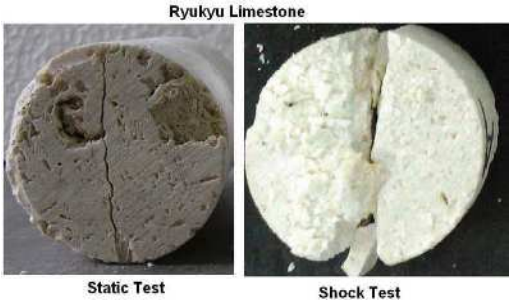

Figure 9. Comparison of fracturing of Ryukyu limestone samples under static and dynamic conditions.

under dynamic conditions for the given testing conditions. The finger-like corals are also widely distributed along the shores of Ryukyu Islands. An experiment was carried out on coral fingers samples with a diameter of 20 mm under compression shock test. Fig. 10 shows the axial stress and acceleration response during the experiment. It was quite interesting that the dynamic UCS of the coral finger is almost the same as that of Ryukyu coral limestone.

3.2 *Tuff of Fukui (Shakudani-ishi)*

Tuff of Fukui or locally known as Shakudani-ishi is a welded tuff and there are many abandoned underground quarries, which collapse from time to time. Table 2 compares the static and dynamic strength of Shakudani-ishi. Fig. 11 shows the tensile stress and acceleration response of the sample while Fig. 12 shows the fracturing state of Shakudani-ishi Brazilian samples tested under static and dynamic conditions. As noted from Fig. 12, the fracturing state is entirely different under dynamic condition than that under static condition. The damage is much more intense in dynamic shock test and it involves more energy dissipation in samples if the load exceeds the energy required to fracture under static condition.

3.3 *Tuff of Derinkuyu*

Antique Derinkuyu underground city in Cappadocia is excavated in tuff formation. The characteristics of

Table 1.Comparison of Static and Dynamics strength of Ryukyu limestone

Condition	Static (MPa)	Dynamic (MPa)
UCS	20-33.3	24.72
BRS	2.4-5.3	3.90
Coral Finger-UCS		27.94

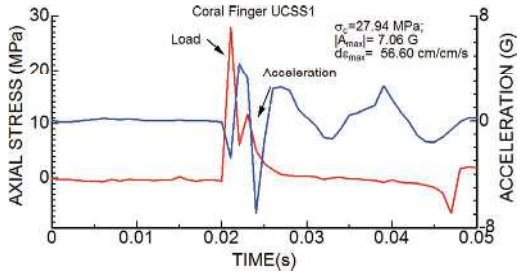

Figure 10. Axial stress and acceleration response of coral finger limestone sample under uniaxial compression shock test.

Table 2.Comparison of Static and Dynamics strength of Shakudani-ishi

Condition	Static (MPa)	Dynamic (MPa)
UCS	33.8-37.9	
BRS	3.8-	5.43

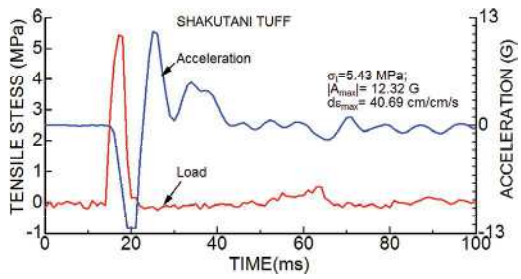

Figure 11. Tensile stress and acceleration response of Shakudani-ishi sample under Brazilian shock test.

Figure 12. Comparison of fracturing of Ryukyu limestone samples under static and dynamic conditions.

surround rock are well-investigated by Aydan and Ulusay (2014). Tuff of Derinkuyu constitutes main rock mass around the underground city. A series of experiments on Derinkuyu tuff under dynamic Brazilian and compression shock loading conditions were investigated. Fig. 13 shows the tensile stress and acceleration responses of the sample while Fig. 14 shows the views of the sample before and after testing. Table 3 compares the experimental results.

Fig. 15 shows the shows the axial stress and acceleration response during the experiment on a compression shock test on a Derinkuyu tuff sample. From the comparison of experimental results given in Table 3, there is no remarkable strength increase under dynamic conditions for the given testing conditions.

3.4 *Oya tuff*

Oya tuff is one of well-known rock in Japan and it has been used as construction material. A series of experiments on samples under Brazilian and compression shock loading conditions were carried out. Figures 16 and 17 show the dynamic response of

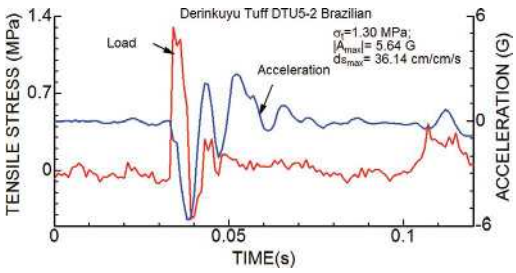

Figure 13. Tensile stress and acceleration response of Derinkuyu tuff sample under Brazilian shock test.

Figure 14. Comparison of fracturing of Derinkuyu tuff sample before and after Brazilian shock testing.

Table 3. Comparison of Static and Dynamics strength of tuff of Derinkuyu

Condition	Static (MPa)	Dynamic (MPa)
UCS	4.1-8.3	4.6
BRS	0.5-1.1	1.1

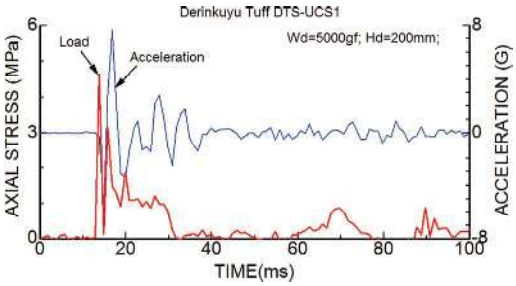

Figure 15. Axial stress and acceleration response of Derinkuyu tuff under uniaxial compression shock test.

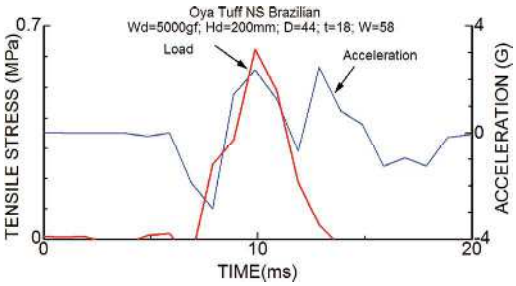

Figure 16. Tensile stress and acceleration response of Oya tuff sample under Brazilian shock test.

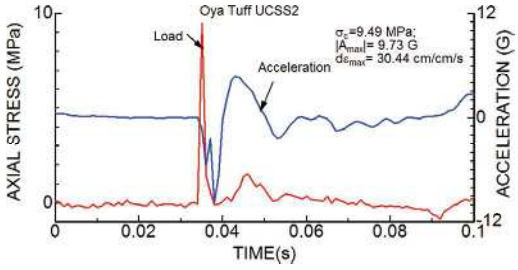

Figure 17. Axial stress and acceleration response of Oya tuff sample under uniaxial compression shock test.

Oya tuff samples under Brazilian and Compression loading conditions. Figure 18 shows the views of the sample before and after the compression shock experiment. Table 4 compares the strength of Oya tuff under static and dynamic conditions. Once again it is noted that there is no remarkable strength increase under dynamic conditions for the given testing conditions when the experimental results given in Table 3 are compared with each other. Furthermore, the fracturing state is more intense under dynamic conditions.

3.5 *Sinop red andesite*

Andesite is one of the widely distributed rock in the Sinop Nuclear Power Plant site. It has a grayish or reddish color. The grayish colored andesite has

Figure 18. Comparison of fracturing of Oya tuff sample before and after compression shock testing.

Table 4. Comparison of Static and Dynamics strength of Oya tuff

Condition	Static (MPa)	Dynamic (MPa)
UCSS	4.7-11.2	9.73
BRS	0.5-1.0	0.62

higher strength as compared with that of reddish colored andesite (Aydan et al. 2015). A series of experiments on samples under Brazilian and compression shock loading conditions were carried out. Figs. 19 and 20 show the dynamic response of Sinop reddish andesite samples under Brazilian and Compression loading conditions. Fig. 21 shows the views of the sample before and after the compression shock experiment.

4 CONCLUSIONS

The authors devised a new experimental apparatus, which may be categorized as drop-weight testing technique, to investigate the behaviour of rocks subjected to shock waves. Various rock samples

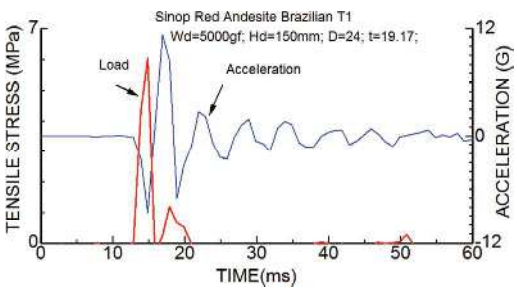

Figure 19. Tensile stress and acceleration response of Sinop reddish andesite under Brazilian shock test.

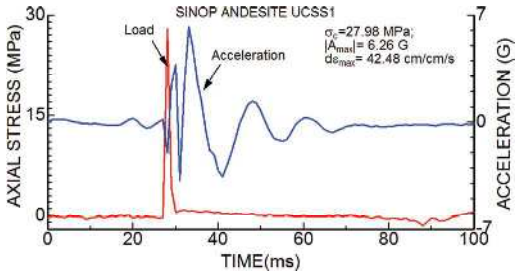

Figure 20. Axial stress and acceleration response of Sinop reddish andesite sample under uniaxial compression shock test.

Figure 21. Comparison of fracturing of Sinop Reddish andesite sample before and after compression shock testing.

having a sedimentary origin to igneous rock have been tested under Brazilian and compression testing conditions. The device is equipped with non-contact laser displacement transducers to observe the behaviour of rocks during pre-failure as well as post-failure stages. The nominal impact velocity can be easily adjusted and it can be easily correlated with the measured responses and dynamic mechanical properties. Some of important conclusions from this experimental study may be states as:

1. Under the given testing conditions, there is no remarkable strength increase under dynamic conditions as compared with that under static condition. If the load level under dynamic condition is higher than that to fracture the rock under static condition, the excess energy will be dissipated by intense fracturing as well as inertia forces. In other words, the so-called strength increase in SPHB experiments reported in literature may be due to this phenomenon (e.g. Kobayashi 1970; Aydan 2017), which cast a doubt on the truthness of the results of experiments using the SHPB technique.
2. The monitoring and high-speed video records indicated that the samples under Brazilian and compression shock test are first compressed at

the initial contact stage and they fully re-bound if they are not fractured. They will also partially rebound even they became fractured.

3. Acceleration responses are not symmetric with respect to time axis as noted previously by Aydan et al. (2011).

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