The effect of aspect ratio of rock samples on the dynamic characteristics of rocks under shock loads

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Abstract. The dynamic behavior and characteristics of rocks under various dynamic conditions such as blasting, excavation and failure of rock engineering structures, the rupture of the earth crust during earthquakes have been receiving great attention in recent years. As a result, there are various studies for developing appropriate experimental techniques to understand and evaluate dynamic mechanical behavior and characteristics of rock. Split Hopkinson Pressure Bar (SHPB) experimental technique is utilized for evaluating the strength of rocks under high strain rates. The aspect ratio of rock samples used in this technique does not satisfy the conventional aspect ratio utilized in static tests and it is generally less than 1.0. It is well known that if the aspect ratio is less than 2, the failure process will be greatly influenced by the platens at the ends of samples. The authors investigated the effect of the aspect ratio on the overall behavior of rocks under shock loads using their own shock test device. Various rocks used for this purpose, including frictionless artificial material such as paraffin. The experimental results so far clearly showed that the aspect ratio is of great importance and it cast some doubts on experimental findings from the SHPB tests. The authors discuss the experimental results and discuss the effect of the aspect ratio on dynamic characteristics of rocks in this study.

Keywords: Aspect Ratio, Dynamic Strength, Shock Test.

1. Introduction
The aspect ratio (AR; ratio of height over diameter or width) is of great importance in experimental rock mechanics. The suggested method of ISRM suggests that the aspect ratio should be between 2.5 and 3.0. However, the aspect ratio utilized in many standards worldwide is 2. The earlier experimental studies [1,2,3] on the strength and deformability characteristics of rocks showed that if the aspect ratio is less than 2, the strength increases and the behavior of rock samples become more ductile. Therefore, the aspect ratio less than 2 is not recommended. On the other hand, the aspect ratio used in Split-Hopkinson Pressure Bar tests is generally less than 1. The ISRM Suggested Method published in 2012 on the determination of dynamic strength of rocks using the SHPB recommends the length to diameter ratios of 1:1 and 0.5:1 for small and large samples, respectively [4]. Although the strengths obtained from static tests and SHBP tests are compared with each other and it is claimed that the strength obtained from the SHPB tests is always greater than those from static tests on the same rock. However, as the aspect ratio is entirely different, it is simply not appropriate to do such comparisons and to discuss the strengths and deformability under static and dynamic conditions.

The authors have developed a drop-weight type shock load device and investigated the effect of aspect ratio and compared the test results with those obtained from static tests and
shock-load tests [5,6,7]. Rocks and paraffin are used for this purpose. The authors present the outcomes of the experimental study and discuss the implications of these experiments and argues the validity of the aspect ratio utilized in the ISRM SM.

2. Devices for Shock and Static Tests
A new experimental apparatus was developed to investigate the behaviour of rocks under shock waves as shown in Fig. 1 [6]. The device is equipped with a load cell, non-contact laser transducers, an accelerometer up to 500G. The non-contact type laser displacement transducers measure the displacement of the loading platen. The load cell below the lower platen is used for measuring dynamic applied loads up to 300 kN and a 100 mm thick hard rubber is placed between the device and base block in order to prevent the reflection of shock waves. The displacement of the loading platen is allowed to move downward up to 20 mm in order to prevent the complete destruction of samples upon failure. The cylindrical weights are dropped from different heights up to 500 mm with an interval of 50 mm. The device is categorized as the drop-weight apparatus and the mechanical behaviour and characteristics of rock samples under shock waves could be evaluated during pre-failure and post-failure stages satisfying the dynamic equilibrium equation at any time. Some additional monitoring is done using infra-red camera and high-speed video camera.

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

\[ V_{\text{max}} = \sqrt{2gH_d} \]  

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

\[ \dot{\varepsilon}_{\text{max}} = \frac{V_{\text{max}}}{L} \quad \text{or} \quad \dot{\varepsilon}_{\text{max}} = \frac{V_{\text{max}}}{D} \]  

Maximum acceleration is obtained from the acceleration response during the experiment. It is expected that the maximum acceleration increases with the increase of strength of rock samples. On the basis of theoretical definition of momentum, the theoretical relation for momentum \((P)\) applied to a sample may be written in the following form:
\[ P = W \sqrt{\frac{2H_d}{g}} \quad \text{or} \quad P = W \frac{V_{\text{max}}}{g} \]  

(3)

Where \( W \) is the weight given in kgf or \( N \). The unit utilized in processing experimental results is \( N \cdot s \).

Two static testing devices were utilized for evaluating the static mechanical properties of samples. The device named OA20KN and shown in Fig. 2(a) is displacement-controlled, its loading capacity is 20 kN. When samples cannot fail by this device, another testing machine with a capacity of 100 kN, which is manually operated, is utilized for uniaxial compression and Brazilian tests (Fig. 2b).

3. Samples and Tests

3.1. Paraffin Samples

Paraffin was actually the pioneering material for researchers to develop the constitutive laws such as theory of elasto-plasticity and elasto-visco-plasticity. In non-linear regime, its behavior is perfectly plastic and its friction angle is known to be nil. This material was chosen to investigate the effects of various parameters such as drop height and weight so that the effect of momentum imposed on samples. Furthermore, the material is commercially available with very low cost. We have investigated that effect of aspect ratio on the material behavior as well as strength parameters. The diameter of the samples was 50 mm while the height was 50 and 100 mm to investigate the effect of different aspect ratios. Specifically, the aspect ratio (AR) for tests on paraffin samples was 1 and 2 (Fig. 3). Table 1 gives the physico-mechanical properties of paraffin samples tested. Fig. 4 shows the strain-stress responses for two aspect ratios under static conditions. The strength of the sample with AR of 1:1 is greater than the sample with AR of 2:1 in accordance with previous investigators [1,2,3].

| ASPECT RATIO 1:1 | ASPECT RATIO 2:1 |
|-----------------|-----------------|
| Static          | Static          |
| AUX STRESS [MPa]| AUX STRESS [MPa]|
| STRAIN [%]      | STRAIN [%]      |

Table 1. Physico-mechanical properties of paraffin.
| Unit weight (kN/m$^3$) | P-wave velocity (km/s) | S-wave velocity (km/s) | UCS (MPa) |
|-----------------------|------------------------|------------------------|------------|
| 0.89-0.9              | 1.86-2.19              | 0.79-1.05              | 3.5        |
| 1:1                   | 2:1                    |                        |            |

Figs. 5 and 6 show the stress responses of paraffin samples having aspect ratios of 1:1 and 2:1 by varying the drop height and drop weight. Fig. 5 shows the effect of drop weight on responses while Fig. 6 shows the effect of drop weights on responses. As noted from the both figures, the compressive strength are much higher and generally twice or higher for samples having aspect ratio of 1:1 as compared with those with samples having the aspect ratio of 2:1.

Figs. 5 and 6 clearly imply the importance of momentum as well as the aspect ratio on the strength of samples even though the impact velocity was same for each drop height. In other words, the fundamental parameter is the momentum rather than impact velocity itself. Fig. 7 shows the post-test states of samples. As the friction angle of paraffin is nil, the Luder lines which appear on the surface of samples are inclined at 45 degrees with respect to loading direction. The failure of samples with the aspect ratio of 2 is generally confined to the top part of the samples where impact load was imposed.
Fig. 7. Post-test views of sample with two aspect ratios.

Fig. 8 summarizes the compressive strength for two different aspect ratios as a function of momentum. As noted, the uniaxial compressive strengths for AR of 2:1 are much less than those for samples having AR of 1. Furthermore, the imposed momentum has much greater influence on the overall responses as compared with that of the impact velocity. This aspect requires more careful investigation of strength and deformability properties under shock loads. Furthermore, it should be noted that shock load is a particular form of dynamic testing and it does not represent general loading conditions. The results of the static strength values are not plotted in Fig. 8. Nevertheless, results shown in Fig. 4 are in accordance with the estimations from the fitted functions shown in Fig. 8.

Fig. 8. Compressive strength of paraffin samples with different aspect ratios.

3.2. Rock Samples
Next examples are concerned with actual rocks. Samples of rocks were selected as sandstone (Kimachi), marble, Ryukyu limestone. The diameter of samples was 25 mm while the height was varied between 25 and 50 mm for two different aspect ratios, specifically 1 and 2. Before experiments, unit weight, P-wave and S-wave velocities of samples were measured.

3.2.1. Marble
Marble used in experiments is very homogenous. Fig. 9 shows the pre-post failure states of marble samples with two different aspect ratios. Fig. 10(a) shows the strain-stress responses during static and shock loading. As noted from the figure, the uniaxial compressive strength of samples greater than twice that under static tests. Fig. 10(b) shows the responses of the samples having two different aspect ratios. As noted from the figure, the uniaxial compressive strength of the sample is much greater than that of the sample having the aspect ratio of 2. These results are fundamentally similar to those of paraffin samples as well as previous static tests.

3.2.2. Kimachi Sandstone
Kimachi sandstone is sandstone of volcanic origin. An extensive study was varied out various properties of this sandstone. Fig. 11(a) shows the samples before testing and Fig. 11(b) shows responses of samples having aspect ratios of 1 and 2. As noted from the responses, the uniaxial compressive strength is much higher for aspect ratio 1 compared with that aspect ratio 2.

(a) Samples before testing  
(b) Samples after testing
Fig. 9. Views of samples before and after testing.

(a) Static and dynamic response (AR=2); (b) Responses of sample with AR=1 & 2
Fig. 10. Comparison of responses measured in static and dynamic tests on marble samples.
3.2.3. Ryukyu Limestone

Ryukyu limestone is widely distributed in Ryukyu Archipelago. An extensive study was varied out various properties of this sandstone. Fig. 12 shows a sample after testing and responses of samples having aspect ratios of 1 and 2. As noted from the responses, the uniaxial compressive strength is much higher for aspect ratio 1 compared with that aspect ratio 2.

![Sample after testing](image1)
![Responses during testing](image2)

Fig. 12. Views of a sample after testing and responses during the tests.

4. Conclusions

The authors described a new special device for shock-load tests on rocks [5,6,7]. The main purpose of this study was to investigate the effect of aspect ratio of samples on their strength and deformability. The ISRM Suggested Method published in 2012 [4] on the determination of dynamic strength of rocks using the SHPB recommended the length to diameter ratios of 1:1 and 0.5:1 for small and large samples, respectively, which is entirely different from the aspect ratio used in static tests. The experimental studies reported in this study clearly showed if the aspect ratio is less than 1, the determined strength under shock loads is much greater than that of the samples having aspect ratio of 2. Therefore, it is confirmed that the aspect ratio utilized in the SHPB tests is not appropriate and this fact clearly cast doubts on the validity of the results on dynamic strengths obtained from the SHPB testing technique.

References

[1] Hobbs DW: Rock compressive strength. Colliery Eng. 41:287–292 (1964).
[2] Mogi, K.: Some precise measurements of fracture strength of rocks under uniform compressive stress. Rock Mechanics Engineering Geology Vol. 4, No. 1, p. 41–55 (1966).
[3] Hawkes, I. and Mellor, M.: Uniaxial testing in rock mechanics laboratories. Eng. Geol., 4, 179-285 (1970).
[4] Zhou, Y.X. Xia, K., Li, X.B., Li, H.B., Mae, G.W., Zhao, J., Zhou, Z.L., Dai, F.: Suggested methods for determining the dynamic strength parameters and mode-I fracture toughness of rock materials. Int. Journal of Rock Mechanics & Mining Sciences.49, 105-112 (2012).
[5] Aydan, Ö., Ito, T., Tokashiki, N., and, Kodate, S.: Shock Tests and Some considerations. Proceedings of ISRM 14th International Congress of Rock Mechanics – Foz do Iguassu, Brazil, 1085-1092 (2019).
[6] Kodate, S., Tomiyama, J., Suda, Y., Horiiuchi, K. and Aydan, Ö.: Mechanical behaviour and characteristics of rocks subjected to shock loads. Proceedings of 2019 Rock Dynamics
Summit in Okinawa, 7-11, May, 2019, Okinawa, Japan, ISRM (Editors: Aydan, Ö., Ito, T., Seiki T., Kamemura, K., Iwata, N.), 646-651 (2019).

[7] Sakamoto, I. and Aydan, Ö.: Shock test on rounded rock fragments in Suruga Bay sediments and its implications on past mega-earthquakes. Proceedings of 2019 Rock Dynamics Summit in Okinawa, 7-11 May, 2019, Okinawa, Japan, ISRM, 170-175 (2019).