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The Effect of Cyclic Impact Loads on Rock Properties

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Highlights:

- The drop weight test can be used as an alternative method to determine dynamic compressive strength.
- With an increase of impact load, the number of cycles until failure decreases.
- The value of uniaxial compressive strength and Young's modulus decreases with increasing number of cyclic loads.

Abstract. This study was conducted mainly in the laboratory to evaluate the effect of cyclic impact loads on rock properties. The test sample was a rock-like material made of cement, sand, and water. The sample was given an impact load from a metal pounder that was dropped at various heights. The load was repeatedly applied to the sample until it was damaged and/or until failure. The test results revealed four stages in the fracturing process, starting with cratering of the upper surface of the sample, formation of initial fractures, fracture development along the sample, and finally sample failure. The test results also revealed that with an increase of impact load, the number of cycles until failure decreases. Furthermore, the value of uniaxial compressive strength and Young's modulus decreases with increasing number of cyclic loads. The decrease is proportional to the increase of the damage value.

Keywords: *cyclic loading; drop weight test; dynamic compressive strength; rock damage; rock fatigue.*

1 Introduction

Rock fatigue is defined as rock damage due to repeated loading. A mining activity that is often associated with rock fatigue is blasting. Remaining rock mass that forms a slope may be subjected to repeated blast loads generated by several blast events. A question that often arises is what the effect is of repeated blast loads on slope stability.

Many studies related to cyclic loading have been carried out by previous researchers. Most of the available studies are related to the effect of cyclic loads on the strength of building structures [1,2]. However, only a few studies can be found related to the effect of cyclic loads on the mechanical properties of the material. The most recent study was conducted by Lin, *et al.* [3], who performed

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cyclic loading in a uniaxial compressive strength test of sandstone. One of the results showed that the deformation modulus decreases with increasing number of load cycles. Liu, *et al.* [4] examined the effect of the frequency of cyclic loading on the dynamic properties of rock. It was found that increasing the load frequency will increase the fatigue life. It should be noted that both studies used a compression machine with a loading rate of approximately 200 N/s. This loading rate is considered too slow compared to the loading rate of blasting. Therefore, in this study, the loading rate was designed to be higher through a drop weight test. The results were expected to be more suitable when the test results are applied to blasting. It should be noted that the proposed test is simply called the drop weight test because a defined weight falls on the specimen from a specified height. The proposed test must be distinguished from other drop weight tests, such as the JK drop weight test [5] and drop weight tests for metals as stated in ASTM E208 [6]. Even though all drop weight tests are basically the same, the tools, procedures, processing, and results are different. This study aimed to determine the dynamic compressive strength in order to understand the effect of the impact load value on fatigue life, and to understand the effect of cyclic loads on rock properties.

2 Experimental Setup

2.1 Sample Preparation

The sample used in this study was a rock-like material made of cement, sand, and water with volume ratio of 1:3:1. The sample was molded in a cylindrical shape with a diameter of 55 mm and dried at room temperature for 28 days before testing. The sample was cut to a length of 115-120 mm. The ends of the sample were smoothed using sandpaper, and the flatness was measured to be not more than 0.02 m using a displacement gauge.

2.2 Sample Properties

The physical properties of the sample were determined and other basic tests such as an ultrasonic velocity test and a uniaxial compressive strength test were also conducted. The test procedures followed the methods suggested by ISRM [7]. The test results are shown in Table 1.

Table 1 Summary of rock properties.

Test type	Parameter	Value	Unit
Physical properties	Natural density	1814	kg/m^3
	Porosity	26	%
Ultrasonic velocity	Ultrasonic velocity	2343	m/s
Uniaxial compressive strength	Uniaxial compressive strength (static)	10.58	MPa
	Young's modulus	2275	MPa

2.3 Experimental Conditions and Details

An important component of the drop weight test apparatus is the pounder, which is made from steel and has a weight of 2.9 kg, a diameter of 55 mm, and a length of 105 mm. The height of the drop can be adjusted by a string and pulley system. A tube sleeve is used as the drop path so that the pounder falls straight onto the sample. The sample is placed on a rectangular steel plate (not hold), to ensure it stands in an upright position. A schematic and a photograph of the drop weight test apparatus can be seen in Figure 1.

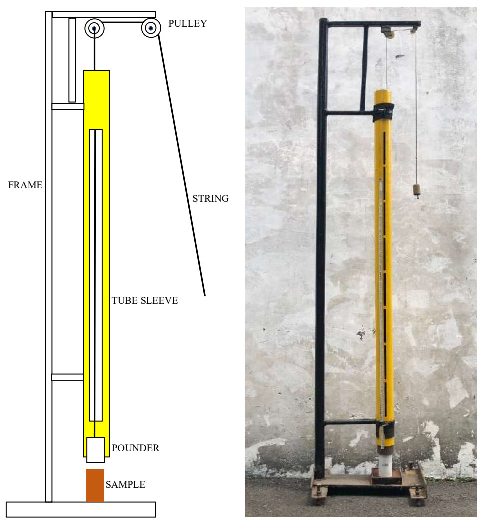

Figure 1 Schematic and photograph of the drop weight test apparatus.

2.4 Test Procedure

The test procedure included the following steps:

1. Samples in dry condition were placed on the rectangular steel plate of the test equipment parallel to the direction of the pounder falling.
2. The pounder was raised to a certain height by pulling the string. The height of the pounder could be observed through the meter reading on the tube sleeve.
3. The pounder was dropped by releasing the string.
4. The condition of the sample was observed and photographed to determine the presence of fractures.

The above test procedure was performed in three scenarios. First, the test was managed in such way that sample failure occurred after one single impact. This scenario aimed to determine the dynamic compressive strength. Second, the drop weight test at a certain height was repeated until sample failure. The height of the drop was varied at 200 mm, 300 mm, 400 mm, 500 m, 600 mm, and 700 mm. The objective of this scenario was to obtain the fatigue life. Third, the drop weight test was carried out with a fixed drop height of 700 mm and repeated for 3, 5 and 7 cycles. During the test, the sample was ensured not to be totally broken, so that the sample could still be used for the uniaxial compressive strength test. This scenario aimed to determine the decrease of uniaxial compressive strength and Young's modulus due to cyclic impact loads.

3 Results and Analysis

3.1 Fracturing Process

The test results revealed four stages in the fracturing process, starting with cratering of the upper surface of the sample, formation of initial fractures, fracture development along the sample, and finally sample failure (see Figure 2).

1. Cratering
   The first stage of the fracturing process was cratering, where craters were formed on the upper surface of the sample. Initially, they had a small size and then got bigger with increasing number of loads. This type of fracture is a common form of fracture of objects exposed to impact load. The process took place within 40 to 70 percent of the total number of loads at failure.
2. Formation of initial fractures
   Initial fractures were formed from the area of the craters. They extended parallel with the direction of the loading. The process took place within 70 to 85 percent of the total number of loads at failure.
3. Fracture development
   As the number of loads increased, the fractures gradually lengthened and increased in intensity. When fractures were formed along the sample, it can be said that the sample would soon experience total failure. This process took place within 85 to 98 percent of the total number of loads at failure.
4. Total failure
   After the three stages of the fracturing process described above, the sample lost its strength and disintegrated into several pieces.

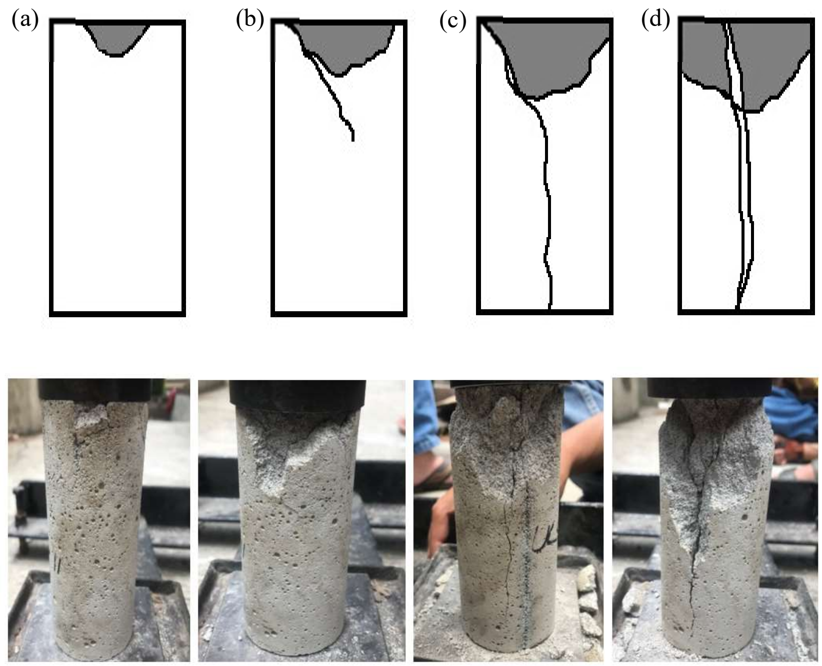

Figure 2 Illustration and photograph of fracturing process: a) cratering, b) initial fracture formation, c) fracture development, d) total failure.

3.2 Dynamic Compressive Strength

The loading rate unquestionably influences the compressive strength [8]. The faster the loading rate, the higher the compressive strength. It should be noted that in this study, there were two compressive strength values, namely static and dynamic. The static compressive strength was obtained from the uniaxial compressive strength test using a compression machine with loading rate of 0.5-1 MPa/s. The dynamic compressive strength was obtained from the drop weight test with an estimated loading rate of 121-419 MPa/s. The loading rate was calculated by dividing the dynamic compressive strength by the loading time obtained from the sample length divided by the falling velocity in Eq. (1).

Based on the test results, it was found that the dynamic compressive strength of the sample is equivalent to the stress that occurs when the height of the drop was 1750 mm. The falling velocity (v) was calculated using the following free fall equation:

$$v = \sqrt{2gh} \tag{1}$$

where g (m/s^2) and h (m) are gravitational acceleration and drop height, respectively. The stress (σ, Pa) in the sample can be calculated with the following equation [9]:

$$\sigma = \frac{v}{{}^{1}/_{(\rho_1 C_1)} + {}^{1}/_{(\rho_2 C_2)}} \tag{2}$$

where ρ_1 and c_1 are the density and ultrasonic velocity of the pounder (7180 kg/m^3 and 5238 m/s); ρ_2 and c_2 are the density and ultrasonic velocity of the sample (see Table 1).

The test results and analysis revealed that the dynamic compressive strength value was 22.29 MPa. This value was almost two times higher than the static compressive strength value. This finding is acceptable considering the results of earlier studies. Zhang & Zhao [10] showed that the dynamic compressive strength value can increase up to six times of the static compressive strength value depending on the loading rate.

3.3 Fatigue Life

The fatigue life is defined as the number of repeated loads that cause the sample to fail. To determine the fatigue life, the drop weight test was carried out repeatedly with a certain drop height until sample failure. The drop height was 200 mm, 300 mm, 400 mm, 500 m, 600 mm, and 700 mm, respectively. The test results showed that the sample was completely damaged after 10 to 12 cycles of repeated loading. A summary of the test results can be seen in Table 2. The stress experienced by the sample due to the impact load was calculated using Eq. (2). The stress value was obtained from 7.18 MPa to 13.5 MPa for a drop height of 200 mm to 700 mm, respectively. It was observed from the test results that the impact load is inversely proportional to the fatigue life. The higher the impact load, the lower the fatigue life.

In order for the test results to be used for other rock types with different strengths, the value of the impact load was normalized to the dynamic compressive strength. In this study, the result of normalization is called the impact load to strength ratio, and has a value in the range of 0 to 1. The relationship between the impact load to strength ratio and the fatigue life (n) can be seen in Figure 3, or can be written as follows:

$$\frac{\sigma_i}{\sigma_c} = n^{-0.223} \tag{3}$$

where *n* is the number of cyclic loads; σ_i is the impact load value; σ_c is the dynamic compressive strength. The use of the power function in Eq. (3) is in accordance with the previous study from Guo, *et al.* [11], which states that the relationship between shale strength and cyclic load follows the power function.

Table 2 Summary of the drop weight test results.

Drop height	Fatigue life	Impact load (σ_i)	Impact load to strength ratio (σ_i/σ_c)
(mm)	-	MPa	-
200	104	7.18	0.32
300	68	8.90	0.40
400	50	10.22	0.46
500	33	11.73	0.53
600	27	12.47	0.56
700	12	13.15	0.59

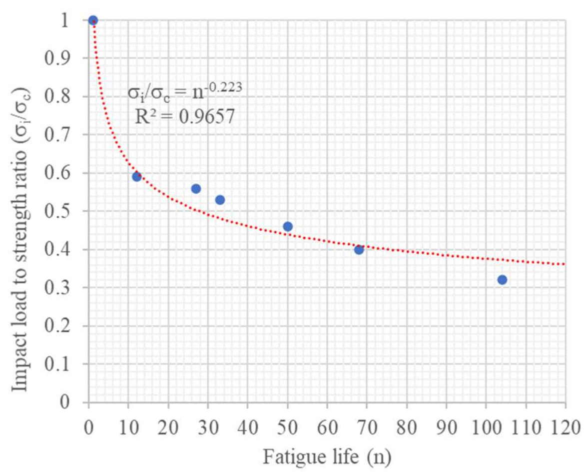

Figure 3 Relationship between fatigue life and impact load to strength ratio.

3.4 Effect of Cyclic Load on Rock Properties

The drop weight test was carried out at a drop height of 700 mm, or equivalent to an impact load of 13.15 MPa. This load was repeated for 3, 5 and 7 cycles. The time span between one loading and the next one was kept constant at around 10-30 seconds. The average frequency of load cycles per test set was 0.05-0.06 Hz. This frequency is relatively low compared to the value of the cyclic load frequency in the uniaxial compressive strength test carried out by Beser & Aydiner [12], which was 0.5 Hz. The use of low frequencies in this study aimed to provide relaxation time for fractures formed by each loading. This is in accordance with the background of this study, which was trying to represent the blast load from blasting operations for rock excavation where the time span between the blast events is quite long.

During the test, the sample must be ensured to not be totally broken, so that the sample could still be used for the uniaxial compressive strength test. As explained above, this scenario aimed to determine the decrease of uniaxial compressive strength and Young's modulus due to cyclic impact loads.

The test results showed that the uniaxial compressive strength decreases with increased number of cyclic loads, as shown in Table 3. The strength reduction was then expressed as the ratio of the uniaxial compressive strength value after cyclic loading to the uniaxial compressive strength value before cyclic loading. Below, this is called the strength reduction ratio. The maximum value of the strength reduction ratio is 1 when no cyclic load is applied to the sample. The minimum value of the strength reduction ratio is 0 when the cyclic loads cause the sample to fail (fatigue life). By performing linear regression on the data of the load cycles and the strength reduction ratio as shown in Figure 4, the following relationship is obtained:

$$\frac{\sigma_d}{\sigma_c} = 1 - 0.0799n \tag{4}$$

where σ_d is the uniaxial compressive strength value obtained after cyclic loading; σ_c is the uniaxial compressive strength before cyclic loading. Both were tested under static conditions. By assuming that the strength reduction ratio is zero, it could be estimated from Equation (4) that the number of cyclic loads causing fatigue was 12. This agrees with the test results of determining the fatigue life as shown in Table 2, when the drop height was 700 mm, or equivalent to an impact load of 13.15 MPa, and the fatigue life was reached after 12 load cycles.

Table 3 Strength reduction after cyclic loading.

Drop height	**Number of cyclic loads**	**Average frequency of load cycles**	**Uniaxial compressive strength after cyclic loading (σ_d)**	**Strength reduction ratio (σ_d/σ_c)**
mm	**-**	**Hz**	**MPa**	**-**
700	3	0.06	8.52	0.81
700	5	0.05	7.67	0.72
700	7	0.06	3.82	0.36

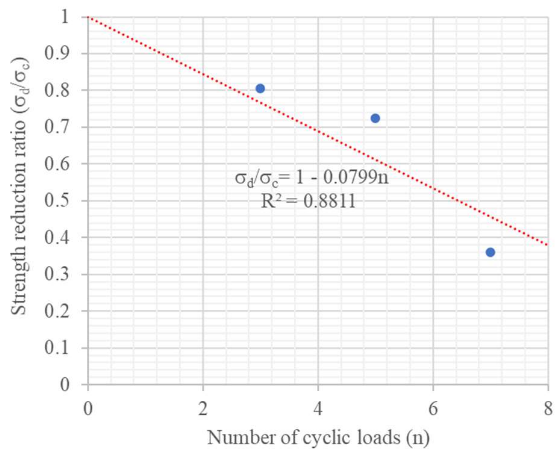

Figure 4 Relationship between the number of cyclic loads and the strength reduction ratio**.**

The test results also revealed that the value of Young's modulus decreases with increasing load cycles, as shown in Table 4. In this study, the value of Young's modulus was first converted to a damage variable (D) with the following relationship [13]:

$$D = 1 - \frac{E_d}{E_o} \quad (5)$$

where E_d is Young's modulus obtained after cyclic loading. E_0 is Young's modulus obtained before cyclic loading (see Table 1). The decrease in Young's modulus with increasing damage variable has been demonstrated by Yang *et al.* [14] and Liu & Katsabanis [15] when describing the failure mechanism of rocks under dynamic loading.

D represents the damage experienced by the sample. When D = 0, the sample remained intact (undamaged). The sample is completely damaged (failure) when D = 1. A summary of the test results in terms of Young's modulus and the damage value can be seen in Table 4. Figure 5 shows the relationship between the number of cyclic loads and the damage value. The graph indicates that the damage value is directly proportional to the number of cyclic loadings. The relationship can be written as follows (see Figure 5):

$$D = 0.0214n^{1.6037} \quad (6)$$

If the obtained relationship was used to predict the fatigue life by assuming the value of D = 1, then the fatigue life was reached after as much as 11 cycles. The drop weight test results in Table 2 show that the fatigue life for a drop height of 700 mm was 12 cycles. This fatigue life prediction result was almost the same as the test result with an estimation error of 1.

Table 4 Summary of test results in terms of Young's modulus and damage variable.

Drop height mm	Number of cyclic loads -	Young's modulus (Ed) MPa	Damage (D) [6]
700	3	1996.09	0.123
700	5	1745.00	0.233
700	7	716.37	0.685

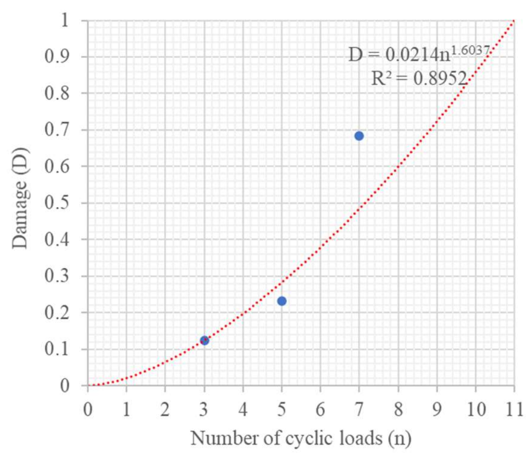

Figure 5 Relationship between the number of cyclic loads and the damage value.

4 Concluding Remarks

Fracturing of the sample due to cyclic impact load began with cratering on the upper surface of the sample, followed by formation of initial fractures, followed by fracture development along the sample, and finally sample failure. The drop weight test can be used as an alternative method to determine the dynamic compressive strength. It was found that the sample in this study had a dynamic compressive strength of 22.29 MPa, almost two times greater than its static value.

With an increase of impact load, the number of cycles at failure decreases. The value of uniaxial compressive strength and Young's modulus decreases with increasing number of cyclic loads. The decrease is proportional to the increase of the damage value.

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References

[1] Budiono, B., Dewi, N.T.H. & Lim, E., *Finite Element Analysis of Reinforced Concrete Coupling Beams*, J. Eng. Technol. Sci., **51**(6), pp. 762-771, 2019.

[2] Budiono, B., Surono, A., Pane, I. & Kurniawan, R., *The Behavior of Slab-Column Joints of Reactive Powder Concrete under Cyclic Loading*, J. Eng. Technol. Sci., **48**(4), pp. 417-429, 2016.

[3] Lin, Q., Cao, P., Mao, S., Ou, C. & Cao, R., *Fatigue Behaviour and Constitutive Model of Yellow Sandstone Containing Pre-Existing Surface Crack under Uniaxial Cyclic Loading*, Theoretical and Applied Fracture Mechanics, **109**, 102786, October 2020.

[4] Liu, E., Huang, R. & He, S., *Effects of Frequency on the Dynamic Properties of Intact Rock Samples Subjected to Cyclic Loading under Confining Pressure Conditions*, Rock Mechanics and Rock Engineering, **45**, pp. 89-102, 2012.

[5] Stark, S., Perkins, T. & Napier-Munn, T., *JK Drop Weight Parameters: A Statistical Analysis of Their Accuracy and Precision and the Effect on SAG Mill Comminution Circuit Simulation*, Australasian Institute of Mining and Metallurgy Publication Series, 2011.

[6] ASTM E208 – 95a, *Standard Test Method for Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels*, ASTM International, 2000.

[7] Ulusay, R. & Hudson, J., *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006*, ISRM, 2007.

[8] Taheri, A., *Effect of Loading Rate on Mechanical Properties of Anisotropic Sandstone Under Compressive Loading*, The ISRM 2nd International Conference on Rock Dynamics, Suzhou, China, May 2016.

[9] Zhang, Z.X., *Rock Fracture and Blasting – Theory and Applications*, 1st Edition, London: Elsevier, 2016.

[10] Zhang, Q. & Zhao, J., *A Review of Dynamic Experimental Techniques and Mechanical Behaviour of Rock Material*s, Rock Mechanics and Rock Engineering, **47**, pp. 1-68, January 2013.

[11] Guo, Y., Yang, C., Wang, L. & Xu, F., *Effects of Cyclic Loading on the Mechanical Properties of Mature Bedding Shale*, Advances in Civil Engineering, **2018**(3), pp. 1-9, 2018.

[12] Beşer, M. & Aydiner, K., *The Effect of Loading Cycles on the Uniaxial Compressive Strength of the Rock under Cyclic Loading*, 12th Regional Rock Mechanics Symposium, Turkey, 2018.
[13] Kachanov, L.M., *Introduction to Continuum Damage Mechanics*, Springer Dordrecht, 1986.
[14] Yang, R., Bawden, W.F. & Katsabanis, P.D., *A New Constitutive Model for Blast Damage*, Int. J. Rock Mech. Min. Sci. & Geomech. Abstract, 33, pp. 245-254, 1996.
[15] Liu, L. & Katsabanis, P.D., *Development of a Continuum Damage Model for Blasting Analysis*, Int. J. Rock Mech. Min. Sci., **34**, pp. 217-231, 1997.