（様式 2）

氏　　名　: 高橋　良尭

論 文 名　: STUDY ON OCCURRENCE OF FRAGMENTED ROCK INDUCED BY BLASTING AND ITS FLIGHT CHARACTERISTIC IN OPEN-PIT MINE
(露天掘り鉱山における発破による起砕物の発生とその飛翔挙動に関する研究)

区　　分　: 甲

論 文 内 容 の 要 旨

Flyrock is serious mining accidents in Japan caused by rock blasting in open-pit mining, resulting from insufficient understanding of rock mass conditions or inappropriate blasting designs. Unlike other mining accidents such as blast-induced ground vibration or dust, it can directly damage to surrounding buildings, or inhabitants in the worst case and 31 flyrock accidents have been reported in recent 10 years in Japan. Although many prevention or prediction methods for the accidents have been proposed, the mechanism of rock fracture induced by blasting and the effect of change of blasting designs have not been discussed yet since rock mass and geological conditions are extremely different in each mine or blasting face. Moreover, major counter measures for flyrock can have negative influence on the productivity, the size of blast-induced fragmented rock, which complicate the blasting operation in mine. Therefore, this study aims to elucidate the rock fracture mechanism induced by blasting and the effect of rock mass conditions and blasting designs on flight characteristic, and to establish a guideline for safe and efficient blasting operation.

Chapter 1 described the background of this study, including mining industry in Japan, the accidents as a result of blasting, general blast-induced fracture theory, and the problems of blasting operation in Japan, in addition to the purpose of this study.

In chapter 2 fracture mechanism induced by blasting was discussed in small-scale blasting experiment. The new method to evaluate 2-dimensional dynamic strain of brittle material was successfully developed by means of digital image correlation (DIC) on a basis of a series of images captured by high-speed camera, which can realize quantitative evaluation of crack occurrence or propagation. By applying this new method, the fracture mechanism of rock mass induced by blasting was quantitatively discussed. In this experiment, cracks were generated at the area where peak strain rate value was over 100 [1/s]. Moreover, the results showed the crack occurrence was strongly influenced by not only strain but only strain rate. In addition to the discussion of the fracture mechanism, fundamental information for building the numerical simulation model was obtained.

In chapter 3, stress wave and crack propagation behavior inside rock mass after detonation were elucidated by means of 3-dimensional finite element method impact analysis software, AUTDYN-3D. The input parameters were correlated based on the strain-rate recorded in small-scale blasting experiment in chapter 2. The results showed high compressive pressure waves propagate in concentric circles, reflect at the free face and change into tensile stress waves. Due to the tensile stress waves, tensile failure was generated not immediately after stress waves reflect at the free face, but after reflected tensile stress waves from two blasting holes superposed. The failure zone propagates with spreading the superposed tensile stress waves.

Moreover, the position of tensile stress wave superposed move to near free face by reducing burden length, leading to remarkable failure zone around the free face. On the other hand, it was difficult to occur the superposition of tensile stress wave because of enlargement of hole spacing, leading to decreasing of failure zone. Delay time also influenced on the failure generation mechanism inside rock mass due to the change of stress wave propagation behavior. When setting the delay time, the position of superposition of tensile stress wave were changed. Hence the position of failure zone can be controlled by changing delay time. This result suggested that flight direction of blast-induced fragmented rock can be controlled by setting delay time. Besides, in terms of the size of failure zone, huge influence of delay time could be recognized. It might be indicated that there can be other factor to control the size of blast-induced fragmented rock such as the direction of firing.

In chapter 4, flight characteristic of blast-induced fragmented rocks was demonstrated in order to establish guidelines for preventing and controlling flyrock accidents by conducting field experiment in operating mine. On a basis of flight behavior of blast-induced fragmented rock captured by high-speed camera, initial velocity of the rocks was analyzed by image analysis. The results showed not only blasting designs such as powder factor or burden but also strength or crack conditions strongly influence on the initial velocity. In addition to quantitative assessments of the flight characteristic, prediction equation for maximum initial velocity considering both blasting designs and rock mass conditions could be successfully obtained by multiple regression analysis. As the result, initial velocity, V, was expressed by V [m/s] = 75.46 × (Powder Factor [kg/t]) - 1.83 × (Burden [m]) - 0.01 × (Delay Time [ms]) - 0.09 × (RMR) - 11.23. On a basis of this equation, the maximum flight distance in each blasting designs and Rock Mass Rating (RMR) could be calculated and the brand new guidelines for setting blasting designs to prevent flyrock was successfully established. Moreover, in terms of flight direction, it was revealed that strike of the joint system inside rock mass influence on the flight direction. When the strike is between 0°～30° or 60°～90°, the fragmented rock tends to fly perpendicular to the blasting face. On the other hand, the fragmented rock is likely to fly not perpendicular to the blasting face but in various directions due to the influence of joint system when the strike angle is between 30°～60°, which will be one of the guideline for preventing flyrock accident.

In chapter 5, finally, control and prediction methods of the size of blast-induced fragmented rocks in operating mine were proposed from the aspect of productivity. In addition to blasting designs and rock mass strength, the result showed that crack conditions had an obvious impact on the size. In other words, it is important to assess the crack conditions before blasting for predicting the size of blast-induced fragmented rocks. Under the similar rock mass conditions, the size was improved by increasing charge explosive and reducing burden. On the other hand, remarkable improvement of the size could not be obtained by changing hole spacing. This result suggested that improvement of the size can be performed safely and efficiently by altering burden or charge explosive within the range of guideline for controlling flyrock proposed in chapter 4. Additionally, the effect of delay time and firing pattern on the size were also discussed. The results showed that homogeneous size distribution and small size of blast-induced fragmented rocks could be obtained by conducting two directions of firing pattern compared with 1 direction of firing pattern. Furthermore, in 1 direction of firing pattern, 50 [ms] of delay time can make mean size smaller than in the case of 25 [ms]. On the contrary, remarkable deference of the size could not be obtained between both delay times. In other words, firing pattern is extremely important rather than delay time in terms of control of the size of blast-induced fragmented rock.

Chapter 6 concluded this study by summarizing the results in all of the chapters.