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Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading

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Abstract

In this paper, the fatigue behaviour of intact sandstone samples obtained from a rockburst prone coal mine and studied under dynamic uniaxial cyclic loading in the laboratory is presented. Tests were conducted on dry and saturated samples with loading frequencies ranging from 0.1, 1 and 10 Hz and amplitudes of 0.05, 0.1 and 0.15 mm. From the laboratory investigations, it was found that the loading frequency, as well as the amplitude, was of great significance and influenced the rock behaviour in dynamic cyclic loading conditions. The dynamic fatigue strength and the dynamic axial stiffness of the rock reduced with loading frequencies and amplitude. The dynamic modulus was found to increase with the loading frequency but decrease with the amplitude. In the case of the saturated samples, it was found that the dynamic fatigue strength reduced by approximately 30 per cent, while the dynamic Young's modulus reduced by about 20 per cent. From the presented study, the dynamic energy was found to be independent of the testing conditions while other rock properties were found to be dependent on these. Finally, it was concluded that rock would more readily succumb at low frequencies and amplitude than at high frequencies and amplitude for a given energy availability.

Keywords: Fatigue behaviour; Sandstone; Dynamic cyclic loading; Strength; Modulus; Stiffness; Dynamic energy; Rockburst

1. Introduction

In recent rock engineering designs, greater attention is focused on the behaviour of rock in dynamic loading, fatigue loading (cyclic loading), under varying strain-rate conditions, and in the post-failure state. The study of rock behaviour under dynamic conditions is of special interest since the diverse dynamics significantly influence rock properties. It is known that different materials show different responses under dynamic loading conditions. Some of these materials become stronger and more ductile, while others become weaker and more brittle [1]. The review of literature has shown that there has been some progress in the description of the mechanical behaviour of rock, and that the study of energy emissions during rock deformation has also been carried out. However, the available data are not sufficient to solve the practical tasks of predicting rock bursts and earthquakes, and are insufficient to formulate a scientific program for the solution of these problems [2]. According to many researchers, the prediction of rockbursts is still a mystery, even after a long history of research. Therefore, concentrated efforts are made to improve rockburst control measures.

A part of the possible solution in predicting rockbursts lies in the determination of fatigue strength and deformation characteristics of rock under dynamic cyclic loading. According to Petros et al. [3], the strongest rockbursts that occurred during the last ten years in the Ostrava–Karvina coalfield of the Czech Republic had P-wave frequencies of about 5 Hz. Thus,

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because the rock tested in this study represents the same coalfield, the laboratory investigations under dynamic uniaxial cyclic loading were carried out at load frequencies ranging from 0.1, 1, and 10 Hz. In this paper, the stress–strain characteristics discussed were obtained at the above mentioned frequencies, at three different amplitudes, and the axial displacement target set point of 0.05, 0.1 and 0.15 mm. The tests were conducted on carboniferous intact sandstone samples in dry as well as in saturated conditions. The samples tested represent the rock massif of a rockburst prone coal mine in the Czech Republic.

The insight gained through this study will provide contributions for understanding concerning how dynamic cyclic loading, in terms of loading frequency and amplitude, results in the degradation of material strength leading up to failure. The relation of these findings to in situ observations will allow for the improved assessment of damage and excavation stability in rockburst prone rock. The findings can be subsequently utilized in the area of prognosis and preventive measures to avoid and prevent rockburst hazards in the coal mines.

2. Literature review

The determination of the dynamic properties of rocks in the laboratory has been gaining importance in recent time. In the past, extensive work on cyclic loading was performed to determine whether rocks are subject to fatigue weakening. "Fatigue" is the tendency of a material to break, or the process of damage accumulation, under cyclic loading. Such work has historically been made to improve mining excavations. In general, however, the over-all effort expended in studying the fatigue properties of such materials has been limited, and the obtained results were inconclusive.

From the reported literature, it was found that intact [3–16] and failed models of jointed rock [17–20] were extremely susceptible to cyclic fatigue failure. Some have also studied the dynamic damage properties of non-jointed intact samples [21–25].

Burdine [4] first showed that compressive cycling of rock resulted in a schematic weakening of the material. Hardy and Chugh [5], Haimson and Kim [6], Attewell and Farmer [7] and others [8–16] performed many tests on a variety of rock types, which clearly demonstrated the progressive weakening of rock due to cyclic loading. A summary of work related to fatigue behaviour studied on various intact as well as jointed rock samples by different researchers in the laboratory is provided in Table 1.

Burdine [4] carried out an investigation to assess the cumulative damage to samples when exposed to cyclic stresses under various loading conditions. He found the stress-rate effect was negligible for the three frequencies tested. He subjected Berea sandstone to cyclic uniaxial and triaxial compression and found that, at 74 per cent of the monotonic (or static) compressive strength, failure occurred before 10^6 cycles. The effect of varying cycle frequency was insignificant in the range 15–55 Hz. An increased confinement was found to increase the fatigue strength, whereas an increased pore pressure decreased the fatigue strength. He suggested that the fatigue strength of rock is strongly dependent on its grain size, with fine-grained rocks having higher and more consistent strengths.

Haimson and Kim [6] studied the mechanical behaviour of White Tennessee marble under cyclic fatigue. Their results showed that the compressive strength increased considerably with the rate of loading. Cyclic uniaxial compression over a period of 10^6 cycles caused failure in Georgia marble at 50 per cent of its monotonic compressive strength, and failure in Tennessee marble at 75 per cent of its compressive strength. Young's modulus decreased with cycling. The authors also reported that no apparent difference was found between the frequencies as far as specimen fatigue life was concerned, and as the maximum compression decreased the life expectancy of a specimen also increased. They also reported that no apparent external difference was found between this type of failure and that encountered in quasi-static loading.

Attewell and Farmer [7] reported that during cyclic compression tests on concrete, mortars, and on rock specimens, the fatigue strength appeared to be reduced by 50–70 per cent of the static strength. Singh [8] investigated fatigue and strain hardening behaviour of greywacke samples having a mean uniaxial compressive strength of 185 MPa from the Australian Flagstaff formation subjected to cyclic load. A fatigue stress of 87 per cent, i.e., 161 MPa, and strain hardening up to 29 per cent, i.e., 239 MPa, were determined for these samples. It was also established that the fatigue life of rock increased with the decreasing stress amplitude. They indicated that with a decreasing stress amplitude, the number of cycles to failure increased on a logarithmic scale. Their results indicated that, at a given maximum applied stress, stress amplitude, and cyclic frequency, the percentage strain hardening increased with an increasing number of load cycles.

Zhenyu and Haihong [9] studied the behaviour of rocks under cyclic loading and made the following conclusions:

(i) during cycling, the total deformation of the specimen consisted of initial deformation induced by static loading, creep deformation and deformation and damage deformation produced by cycling itself. The damage deformation was the main factor, causing the specimen to fail;