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Using a novel shear apparatus coupled with acoustic emission to investigate shear fracture evolution of cement-based materials in macro- and micro-views

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HIGHLIGHTS

- A novel shear apparatus with an opened-shear-box was designed.
- Shear fracture initiation and propagation of cement mortar was observed.
- The angular-shape aggregate has higher stiffness than rounded-shape aggregate.
- The crack initiation occurred near the center part of the specimen.
- The distribution of AE events before the peak consists with that of macro-crack.

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ABSTRACT

It is difficult to investigate the shear fracture triggering position and subsequent fracture propagation using traditional direct shear testing due to its closed-shear-box design. To examine the fracture evolution of cement-based materials subjected to shear stresses, a novel shear apparatus with an opened-shear-box and crack displacement control coupled with a non-destructive technique of acoustic emission (AE) was developed in this study. The complete loading curve in the macro-view and corresponding AE event (micro-crack) development were then obtained. The fracture behaviors affected by the shear angle and the aggregate shape of cement mortar were also investigated. The test results showed that the stiffness and peak shear stress decreased with an increase in the shear angle. The stiffness of the specimen with angular-shaped aggregate was higher than that of the specimen with rounded-shaped aggregate. The localization of AE events occurred before the peak and were located near the middle of the specimen. The position of the AE localization was related to that of the macro-crack initiation. After localization, the AE events then propagated following the shear direction. A comparison of the distribution of AE events before the peak with the position of the macro-crack showed good agreement. The results obtained in this study provide a better understanding of the shear fracture mechanism of cement-based material.

1. Introduction

Conventional direct shear tests are often used to study shear behavior and determine strength parameters, such as cohesion (c) and friction angle (ϕ), in a macroscopic view. Lajtai [15] studied the failure process in a direct shear test and indicated that with low normal stress, tension cracks form and pinch at an angle with the shearing surface, as shown in Fig. 1a. With high normal stress, the initial crack represents a tension crack, whereas later cracks are frequently shear cracks. Shear cracks link with tension cracks to form a continuous shearing surface, as shown in Fig. 1b. Therefore, macroscopic shear properties are closely related to the evolution of micro-cracks, including crack initiation and propagation during shear tests.

To investigate the evolution of micro-cracks, the nondestructive technique of acoustic emission (AE) has been widely adopted. A number of recent studies have incorporated AE detection methods into the direct shear testing of rock materials, rock-concrete joints, and coal-rock joints to elucidate the relationship between the AE

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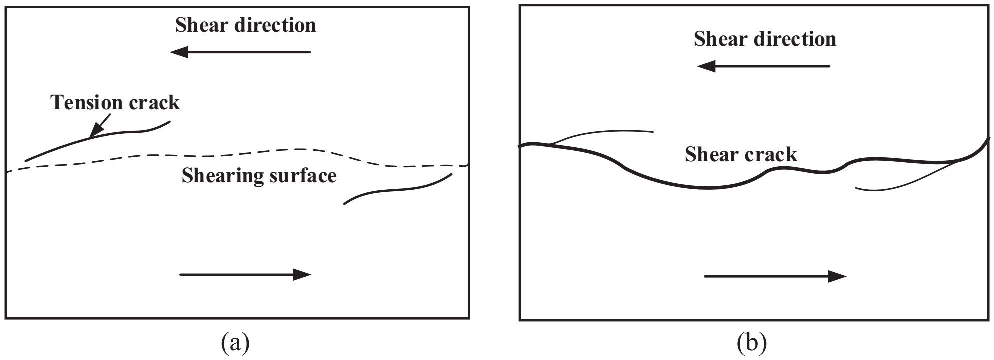

Fig. 1. Schematic of (a) a tensile fracture and (b) a shear fracture occurring in a direct shear test.

energy rate and shear stress [12,17,19,21]). However, a review of the above literature revealed no test results that describe the distribution and development of micro-cracks (AE events) in the materials during the shear tests. The closed-shear-box design of direct shear tests limits the installation space of AE sensors. In a previous study, a minimum of five AE sensors were used to determine the arrival time of AE activity signal at each sensor, and the location of micro-cracks could then be detected [4,13].

To improve the traditional shear test, this study developed a novel shear apparatus with an opened-shear-box design for an inclined shear test and used it in conjunction with the AE technique to identify the distribution of micro-cracks within cement-based materials. Moreover, two classified fracture types of post-peak behavior for rock, snap through (Class I) and snap back (Class II), were defined using uniaxial compressive tests [25], as shown in Fig. 2. In Class I fractures (a stable type), the post-peak cumulative strain energy cannot sustain crack propagation, and the carrying capacity of the specimen decreases with the increase in strain. In Class II fractures (an unstable type), the post-peak strain or degree of specimen displacement decreases; however, the energy stored in the specimen can sustain crack propagation even without external pressure. To investigate the post-peak behavior of a shear test, a crack displacement control technique was used.

An extensometer of crack displacement could be installed in a newly-developed shear device due to the opened-shear-box design. The measured crack displacement was used as a feedback signal to avoid an unstable failure of the specimen. The complete loading history, including the pre- and post-peak stages with respect to AE evolution, could therefore be obtained. The applicability of this new test method (inclined shear test) was discussed by Chen et al. [8], who conducted the inclined shear test associated with the acousto-optic technique for gypsum and cement mortar material and indicated that the cohesion (c) obtained by the inclined shear test was consistent with that obtained by the direct shear test, whereas the friction angle (ϕ) was slightly higher. In this study, an inclined shear test coupled with acoustic emission was employed to investigate the fracture evolution of cement-based material. The cement-based specimen was prepared with both angular- and rounded-shaped aggregate. The influence of the aggregate shape for fracture evolution was discussed. The newly-developed shear fracture test method in this study can also be conducted on natural rocks to study seismic fracture resources induced by geologic faults, which can be applied in earthquake engineering.

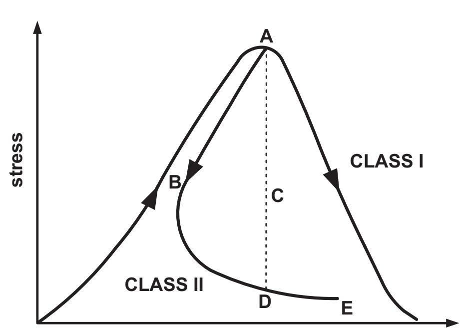

Fig. 2. Classification of rock failure behavior in uniaxial compression, adapted from Wawersik [25].

2. Nondestructive technique of acoustic emission

When brittle materials encounter a change in their external environment, energy accumulates within the materials. When the absorbed energy reaches its threshold, it will be released with the contemporary formation of micro-cracks and internal damage. According to ASTM E610-82 [1], the AE phenomenon is defined as a transient elastic stress wave generated by energy being rapidly released from localized sources within a material. It is employed as a nondestructive technique that can record microseismic sources.

A significant contribution to AE detection was made by Kaiser (1953). When materials are reloaded, the AE signals only occur if the reloading stress is greater than the maximum. However, this so-called Kaiser effect has not been observed in rock in laboratory tests [11]. AE has also been used to investigate the released energy magnitude of micro-cracks. Scholz [22] investigated the frequency–magnitude behavior of micro-cracks in rock under uniaxial and triaxial compression tests using AE data. In the 1980s, AE was widely applied in civil engineering.

Ohtsu [20] used AE to assess damage to concrete. Labuz et al. [14] applied the AE technique to detect the fracture process zone in rock. Shah and Labuz [23] classified the crack type in rock from the source characterization of AE. In recent years, the AE technique has been used to detect the location of micro-cracks for cement mortar, concrete, and rock materials [3,4,7,5,9,10,13,16,18,24,26,27].

The location of AE events (micro-cracks) can be detected by using the arrival time difference method [7]. It accounts for the difference in the arrival time of the AE signal at each sensor. The location of the damage can be obtained when the arrival times from different sensors are multiplied by the wave propagation speed. Fig. 3 shows a cube sample with n sensors placed on the cube faces. Based on the arrival time difference method, the AE signal travel distance for each sensor can be written as:

$$\sqrt{(x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2} = V_p(t_i - t_0) + \varepsilon_i \tag{1}$$