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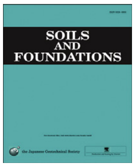

# Effect of slaking on direct shear behaviour of crushed mudstones

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## Abstract

This study investigates the effects of wetting and drying cycles, known as slaking, on the strength-displacement characteristics of crushed mudstone. A series of direct shear tests was conducted by simulating cyclic wetting and drying under different stress conditions using a modified direct shear apparatus. The effects of the stress ratio, the density of specimen, the initial water content before wetting, the slaking index, and the number of wetting and drying cycles on the test results was investigated. Experiments were also performed on less-slakable materials, including crushed sand stone, silica sand and glass beads, to compare the results with the crushed mudstone. Considerable creep displacement on the crushed mudstones was observed during both drying and wetting phases under the constant shear stress conditions. The creep displacement during the drying was more significant than during the wetting phase. The creep displacement accumulated with progressive wetting and drying cycles. The drying-induced displacement was observed when the water content became smaller than the amount of water absorption of the mudstone specimens. Correspondingly, a gradual decrease of the peak stress ratio was observed with the number of wetting and drying cycles. In contrast to the mudstones, the influence of cyclic wetting and drying on the crushed sand stone, silica sand and glass beads is almost negligible. A higher slaking index, a lower water content before wetting, and lower initial density accelerate the slaking of mudstones.

*Keywords:* Direct shear test; Wetting and drying; Slaking; Shear strength; Displacement

## 1. Introduction

Mudstones, including mud rocks and shale, can be weathered by slaking, and they are often recognized as problematic materials in the engineering practice. Rapid slaking of the mudstones on exposure to wetting and drying environments has given rise to slope stability problems (Regues et al., 1995; Yatabe et al., 2000; Popescu, 2002; Cetin et al., 2000; Tovar and Colmenares, 2011). As a recent example, Hattian landslide dam formed by the 2005 Kashmir earthquake, Pakistan, breached in 2010 during moderate rainfall. It was reported that the breaching of the dam was induced by the slaking of the dam body which was composed of crushed mudstone (Sattar et al., 2010; Kiyota et al., 2011). The 2009 Suruga Bay earthquake caused a slope failure at the highway embankment in Shizuoka Prefecture, Japan. Takagi et al. (2010) reported that the major reason for the failure was the destabilization of the embankment due to the slaking of filled crushed mudstone.

A number of studies on the slaking of mudstones have been conducted for more than half a century (Ladd, 1960; Nakano, 1967; Franklin and Chandra, 1972). Generally, slaking investigations have been focussed solely on the observation of a tested sample. Recently, the effects of ver-

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tical stress combined with thermal and water variations on slaking-induced settlement were investigated by Zhang et al. (2015). In addition, slaking-induced creep displacement and the reduction in the peak shear strength in direct shear apparatus have been reported (e.g., Yoshida et al., 2002; Kiyota et al., 2011). However, the detailed mechanism of change in engineering behaviour due to slaking is poorly understood (Morris et al., 1992). In order to estimate the long-term response of slakable materials on various natural slope conditions, an understanding of the engineering behaviour of mudstones undergoing cyclic wetting and drying under the shear stress condition is essential.

In this study, a series of direct shear tests was performed with the modified direct shear apparatus under different shear stress conditions. Specimens were consolidated at prescribed stress ratios, and then were subjected to wetting and drying cycles under the constant shear stress conditions. Finally, monotonic shear loading was applied after the third wetting and drying cycles. Sieve analyses were also performed to investigate changes in particles size distribution and the degradation index.

## 2. Material and experimental procedure

### 2.1. Material

Four geomaterials; two types of crushed mudstones (CM1 and CM2), crushed sandstone (CS) and Toyoura sand (TS) and glass beads (GB) shown in Photo 1 were used. Among these materials, CM1 was the prime material in this study: it was obtained from the aforementioned landslide dam site in Pakistan that breached in 2010. Slaking of the mudstone that formed the dam was assumed to be one of the major causes of the breaching (Sattar et al., 2010; Kiyota et al., 2011). The CM1 was fine grained and deep red in color, and the source area has been classified as Murree formation formed in the Miocene age (Mirza, 1996). The CM2 was collected at the landslide site in Ishikawa Prefecture, Japan, and were later crushed in the laboratory. The source area of CM2 is sedimentary rock formation formed during middle-upper Miocene epoch. As the sedimentary rock at the sampling site is highly porous, the density of the CM2 is relatively low.

The CS was crushed well-graded angular sandstone from a quarry in Chiba Prefecture, Japan. Toyoura sand (TS) originates from weathered granite in Yamaguchi Prefecture, Japan. Both the CS and TS have been used as testing materials in geotechnical laboratory experiments in Japan. Some tests on non-slakable glass beads (GB) were also carried out to compare the slaking characteristics with other geomaterials.

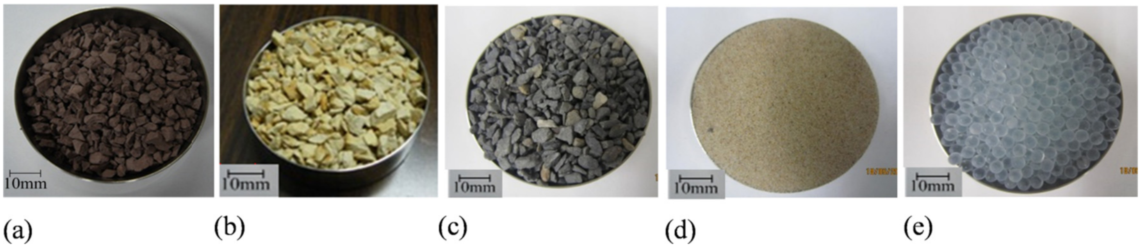
The tested materials of oven dried CM1, CM2 and CS were prepared by removing particles finer than 2 mm and larger than 4.75 mm as a necessary adjustment to the dimension (Jewell and Worth, 1987) for use with the direct shear apparatus used in this study. The specimen was divided into 7 sub-layers to obtain uniform tamping and to prevent particle segregation. Crushed mudstone was slowly poured from a negligible height. The specimens of CM1 and CM2 were carefully prepared by tamping to achieve the prescribed initial densities, and particle breakage by compaction was avoided. The initial density of CS, TS and GB was adjusted to that of the CM1. More details of the sample preparation are explained by Sharma et al. (2013).

### 2.2. Experimental procedure

#### 2.2.1. Index tests

In order to determine an index of slake-ability on the tested geomaterials, the following tests were conducted. The slaking characteristics and the other basic material properties of the tested materials are shown in Table 1.

*2.2.1.1. Slaking index.* Accelerated rock-slaking tests on the sample of CM1, CM2, CS and GB were conducted to obtain the Slaking Index, SI, based on the guideline JGS 2125 (2006). Three pieces of rock lumps, which had approximately a volume of 50 cm$^3$, were taken (Photos 2–4). Each piece of the test sample was placed in a separate container and oven-dried at a temperature of 40 °C for 24 h. Distilled water was poured subsequently into the container until the specimen was fully immersed (approximately within 1 min). The specimen was immersed for 24 h. This represents one drying-wetting cycle. Specimens were then subjected to two more drying-wetting cycles. In order to find the Slaking index of tested material, all samples were then described in terms of crack development and any disintegration that might occur as listed in Table 2. Sadisun et al. (2002) also proposed a similar slaking classification. Photographs were taken before and after test (Photos 2–4).



(a) (b) (c) (d) (e)

Photo 1. Material used (a) CM1, (b) CM2, (c) CS, (d) TS, and (e) GB.