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Effect of inundation on shear strength characteristics of mudstone backfill

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ABSTRACT

A group of lithologies which includes claystone, siltstone, mudstone and shale also known as mudrocks are indurated sediments widely encountered throughout the world. Shear strength and deformation characteristics of mudstone were investigated using a fully automated hydraulic stress path testing system under three rock states: dry, short-term inundated, and long-term. It is observed that the maximum deviator stress, q appeared to decrease meaning the strength deteriorated as the rock states changed from dry to wetted and to degraded conditions. Furthermore, critical state interpretations of the mudstone under all three rock states have shown unique high curved Mohr–Coulomb failure envelopes which are normally exhibited only by crushable soil. Nevertheless, M which is the slope of stress path and angle shearing resistance values, ϕ' obtained from dry specimens were always higher than the partially saturated specimens. However, as dry mudstone sheared under higher mean effective stress (700 kPa), the *M* value exhibited is similar to *M* value of wetted mudstone which is 1.20 and remained the same as mudstone degraded. It is believed that the strength of mudstone decreasing as it begins to crush and gradually became constant.

1. Introduction

Fredlund (1995) acknowledged a partially saturated soil as a three-phase material which is composed of air, water and soil skeleton. It can exist in three states: dry soil with continuous air phase and discontinuous water phase, two fluid phases (continuous air and water phases), and capillary fringe with continuous water phase and discontinuous air phase (Fredlund, 1995). Inundation of partially saturated soil often leads to shear strength changes, differential heave, or collapse (Peterson, 1988). Most opencast coal mine backfills in UK are compacted at optimum or close to optimum water content and frequently unsaturated which are likely to be in at least two fluid phases if not dry soil.

Partially saturated fill which has not been heavily compacted and placed relatively dry may undergo a reduction in volume when the moisture content is increased even without any change in overburden stress. This phenomenon is termed collapse compression as it involves volume changes due to the collapse of soil skeleton. It is also sometimes referred to as 'hydrocompression', 'hydroconsolidation', 'hydrocompaction', and 'saturation shrinkage' (Barden et al., 1973; Charles and Watts, 1996; and Blanchfield and Anderson, 2000). Collapse compression will take place during inundation of the backfill either due to a rising groundwater level once mining operation has ceased or by downward infiltration of surface water into the fill via shallow excavations through the surface crust (Bell et al., 1986; Reed and Singh, 1986; Reed et al., 1987; Charles and Watts, 1996; Hills and Denby, 1996; Blanchfield and Anderson, 2000; Charles and Skinner, 2001).

In UK, opencast coal mines and quarries are reinstated with substantial depths of fill materials to provide land for residential and industrial developments as a result of rapid economy growth and for an environmental sustainability. About 20% of low-rise building in Britain takes placed on this filled ground (Charles and Watts, 1996). During the development of opencast coal mines, a substantial amount of Coal Measure rocks which consist of a series of mudstone and sandstone that accompany coal seam may be excavated, which will then be used to backfill the void. However, brittle-ductile transition of mudstone during groundwater recovery may change the shear behaviour of mudstone and cause major settlement problems when used as a fill such as primary compression due to immediate placement of the fill, fairly short-term but often extensive strain collapse due to inundation and finally long-term creep and consolidation (Reed and Singh, 1986; Hills and Denby, 1996; Goodwin et al., 2003). Therefore, critical precautions must be taken when dealing with mudstone which cannot be classified as rock like or soil like in terms of their behaviour. The most recent, Sutton et al. (2013) conducted a study on Irish pyratic mudstone/siltstone fill material as these materials had caused extensive damage in the east of Ireland.

Research on changes of rock behaviour in regards to wetting has been widely studied (Badger et al., 1956; Barden et al., 1973; Popescu, 1986; Bally, 1988). However, the research only focus on the specific condition not on the transition from soft rock (dry) to clay (wetted)

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Fig. 1. Mudstone collected (scale 1:1.5).

upon wetting and degradation. Therefore, three test series were designed with the main objective of defining the shear strength parameters and deformation characteristics of mudstone backfill at three different soil conditions: dry, short term inundated, and long term to mimic the compression which is due to placement of fill, the large and rapid strain collapse due to inundation and long-term creep consolidation respectively.

2. Materials and methods

2.1. Materials

Mudstones which were extracted for brick manufacture on site collected from Waingroves brickwork quarry in Ripley, Derbyshire, United Kingdom were used in this study. The site is accessed from Whiteley Road via Peasehill Road to the south of Ripley town centre (Coordinates: 53:02:34N, 1:24:02W). Geological map indicates a Middle Coal Measures of Carboniferous age which comprises of mainly mudstone with a bed of sandstone and siltstone, with subordinate coal seams and seat earths (see Memoir to 1:50,000 scale Sheet 125: British Geological Survey Map (1972)). Waterloo Marker fault is seen to be near the material and the bed is dipping towards the west. The material taken from site was in various sizes of block. It was a moderately strong, dark grey, fresh, fissile, clayey mudstone. The blocks were broken down to certain particle sizes and the breaking process caused the particles to be angular in shape (Figure 1). Engineering properties of the sampled mudstone were measured in accordance with BS 1377 (BSI, 1990) procedures (Table 1).

Durability is seen to be one of the important engineering properties of mudstone which can be investigated using slaking test (Bell et al., 1997). Therefore, slaking test was conducted at initial stage of the research in order to investigate the weathering resistance of this material as the degree of slaking governs the behaviour of mudstone particularly when used as a backfill material. Slaking immersion and slaking index tests used by Sadisun et al. (2002) were selected. The slaking immersion test where oven-dried particles with 28 mm to 37.5 mm in diameter were left under water immersion at room temperature (20 °C) showed that this material started to disintegrate just a few minutes after immersion in water and were 90% disintegrated in 30 min (Table 2). It was rated as class 3 based on the visual observation of deterioration during the first 30 min (Table 3). According to Sadisun et al. (2002), during immersion, low strength rock would easily develop cloudiness around the base of the specimen and exhibit severe hairline cracks whilst medium strength rock would show signs of disaggregation with a slight cloudiness and severe hairline cracks in less than three minutes. Nevertheless, the high strength rock will sustain hairline crack even after five minutes of immersion. Hence, this material can be classified as low strength rock.

Oven-dried particles were also subjected to five dry–wet cycles in a slaking index test (Figure 2). Slaking index test was then calculated using Eq. (1). Based on the first cycle slaking index values, $I_1 = 6.80\%$ it was categorised as class 2 which indicates that the slaking process has a low effect on it (Table 4).

$$Is = \frac{Wx - Wx'}{Wx - B} \times 100\% \tag{1}$$

where I_s = slaking index at s number of cycle, W_x = total mass of the 6 beakers and oven dried material, $W_{x'}$ = total mass of the 6 beakers and oven dried material retained on a 2.00 mm sieve, and B = total mass of the 6 beakers.

Table 1
Summary of engineering properties of mudstone.

Engineering properties	Mudstone (Derbyshire, England)
Natural moisture content (%)	1.7
Liquid limit (%)	35
Plastic limit (%)	21
Plasticity index (%)	14
Specific gravity	2.75

Table 2
Observations during slaking immersion.

Time	Observations
1 min	CD (base), MC, D (edges)
2 min	SC (lamination), D (edges)
3 min	CP (half lower), CD (half upper), D
5 min	CP, CD, D, SC
8 min	D, B
15 min	CP, SC, D
30 min	D (>90%)
1 h	D (>90%)
2 h	D (>90%)
4 h	D (>90%)
8 h	D (>90%)
24 h	D (to small pieces & some powder)

Legend: MC = minor hairline crack, SC = severe hairline crack, D = disintegrate, CD = cloudiness, SC = slight cloudiness, CP = collapse, B = bubbles.

Table 3
Criteria for classification of argillaceous rock in the slaking observation test (Sadisun et al., 2002).

Class	Criteria
0	No visible change or change is allowable; only very minor hairline cracking.
1	Severe hairline cracking without spalling, mud and sand particles start to break away from the rock surface.
2	Crack opening with minor spalling and little suspended mud and sand particles.
3	Further process of crack opening with major spalling and suspended mud and sand particles.
4	Completely disaggregation or disintegration, with remarkable portion of suspended mud and sand particles.