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Swelling characteristics of soils subjected to acid contamination

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Abstract

The ever-increasing number of failures of industrial structures due to the heaving of acid-contaminated foundation soils has necessitated a better understanding of soil behavior under changing and extreme environmental conditions. Thus, this paper attempts to micro-mechanistically explain the swelling characteristics of soils contaminated with inorganic acids. Three soils with widely varying physical and chemical properties, namely, natural black cotton soil and commercially available bentonite and kaolin clay, were selected for the investigation. Special Teflon-made oedometer cells, which are entirely non-reactive to acid, were used to assess the swelling behavior. The soils were inundated with two concentrations of sulfuric acid and phosphoric acid and allowed to swell. The results indicate that, in montmorillonitic soils, the type of cation in the exchangeable complex plays a dominant role in governing the swelling behavior of clays during acid contamination. The mineralogical changes due to cation exchange reactions, along with the partial mineral dissolution, resulted in the acid-induced swelling in montmorillonitic soils. In the kaolin clay, the face-to-edge association of the particles due to the adsorption of H^+ by broken edges led to an increase in swelling along with mineralogical changes.

Keywords: Acid; Montmorillonite; Kaolinite; Swelling; Mineralogy; Microstructure

1. Introduction

Soil contamination has become one of the greatest concerns for geotechnical engineers around the world as it involves complex chemical reactions between soils and contaminants. Soil contamination can occur through natural processes or through anthropogenic processes (Gratchev and Towhata, 2013). Weathering processes, acid rain and acid rock drainage fall into the category of natural processes ($3 < pH < 7$), whereas the accidental leakage or spillage of a variety of chemicals during transportation or storage fall into the category of anthropogenic processes ($pH < 1$). Although natural processes can affect the soil behavior to some extent, anthropogenic processes severely alter the engineering behavior of soils leading to progressive structural failures. The growing rate of the acid contamination ($pH < 1$) of soils and the consequent effects on the volume change behavior of these soils is reflected in the number of reported failures of industrial structures (Grant et al., 1974; Vronskii et al., 1978; Sridharan et al., 1981; Stephenson et al., 1989; Joshi et al., 1994; Shekhtman et al., 1995; Assa'ad, 1998; Yamanaka et al., 2002; Al-Omari et al., 2007; Parfitt et al., 2010). In some instances, the cost to repair the structure exceeded the original cost to build the structure (Izbash et al., 1989; Isaev et al., 1995). These structural failures have necessitated a better understanding of soil behavior under changing and extreme environmental conditions. Prompted by these case histories, an attempt is made in the present work to study

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the ill effects and to elucidate the mechanism of the swelling behavior of clays subjected to inorganic acid contamination.

The existing literature suggests that notable changes in the mineral structure with the dissolution of octahedral cations can take place at high concentrations of acids (Grim, 1953; Sokolovich, 1973; Mitchell, 1993; Mal'tsev, 1998; Gates et al., 2002; Komadel, 2003; Jozefaciuk and Bowanko, 2002; Tyagi et al., 2006; Onal, 2007; Panda et al., 2010; Komadel, 2016). Volume changes observed in soils subjected to acid contamination ($pH < 1$) in most field cases have largely been credited to mineralogical changes. However, the studies carried out by most researchers on soils have been limited to slightly acidic conditions ($3 < pH < 6$) in order to mimic the conditions in natural systems (Kamon et al., 1997; Sunil et al., 2006; Gajo and Maines, 2007; Gratchev and Sassa, 2009; Gratchev and Towhata, 2011; Gratchev and Towhata, 2013; Gratchev and Towhata, 2015). Few studies have reported on the volume change behavior of sulfuric acid-contaminated soils (Sivapullaiah et al., 2008; Sivapullaiah et al., 2009; Sivapullaiah, 2015; Ponnapureddy et al., 2017; Hassanlourad et al., 2017), and the effect of phosphoric acid on the swelling behavior of soils has so far been scanty. Until recently, phosphoric acid has been utilized as a stabilizing material to improve soils (Lyons and Mcewan, 1962; Ingles, 1970; Sokolovich, 1973; Ghazali et al., 1991; Medina and Guida, 1995; Eisazadeh et al., 2012). However, considering the damage potential of phosphoric acid and its wide usage, the aim of the present work is to establish the mechanisms controlling the swelling behavior of soils contaminated with phosphoric acid and sulfuric acid.

A brief review of literature suggests that the following mechanisms may affect the engineering behavior of soils in an acidic environment. The first mechanism is the dissolution of the mineral structure and the leaching of cations from the soil. Sivapullaiah et al. (2008) reported that cation exchange reactions lead to an increased swelling in calcitic soil due to sulfuric acid contamination. Spagnoli et al. (2012) reported a notable increase in shear strength in the acidic environment due to the dissolution of Al^{3+}, which acts as a coagulant by increasing the internal resistance. Liu et al. (2013) highlighted that the displacement of cations by hydrogen ions leads to a decrease in the liquid limits and the swelling index of the three montmorillonitic soils. Gratchev and Towhata (2015) reported that the dissolution of calcium carbonate from kaolinitic soils results in higher liquid limits, plasticity indices and compression indices. Bakhshipour et al. (2016) reported that the leaching of iron and aluminum from the residual soil increases the Atterberg limits, the optimum moisture content and permeability, and decreases strength and the maximum dry density. The second mechanism is the changing of the charge on the edges of the clay particles which results in the formation of more open and flocculated structures (Olphen, 1991). The high compressibility of soils due to the formation of such structures in an acidic environment was verified by Wang and Siu (2006). The third mechanism is the adsorption of anions by the soils in an acidic environment. Krebs et al. (1960) reported that the adsorption of sulphates and chlorides leads to a reduction in the liquid limits of montmorillonite, whereas the adsorption of phosphates leads to an increase in the liquid limits. On a similar note, Sivapullaiah (2009) reported that the adsorption of phosphates leads to decreased compression indices of homoionic kaolinite and montmorillonite clays. The fourth mechanism is the changes in the diffuse double layer due to the replacement of exchangeable cations by hydrogen ions in an acidic environment. Gajo and Maines (2007) reported a significant reduction in the compressibility of bentonite due to the collapse of the double layer. Subsequent to this, Gratchev and Towhata (2013) reported a remarkable reduction in strength due to changes in the double layer. The fifth mechanism is the neogenic formations. Shekhtman et al. (1995) reported that the formation of sulphate-based minerals, such as gypsum, halotrichite, potash alums, soda alums, tamaruchite and melanterite, during sulfuric acid contamination leads to heave in soils. Mal'tsev (1998) concluded that high swelling in soils contaminated with acid solutions can be attributed to mineralogical changes. On a similar note, Sivapullaiah et al. (2009) reported that the high induced swelling in black cotton soil subjected to sulfuric acid contamination is attributed to mineralogical changes.

From the above review, it can be inferred that the volume change behavior of soils is significantly affected by several mechanisms under acidic conditions. Predicting the volume change behavior of soils contaminated with highly concentrated acids becomes a difficult task. In this study, therefore, the swelling behavior of sulfuric acid- and phosphoric acid-contaminated soils were evaluated with the help of mineralogical and micro-structural changes for a better understanding of the governing mechanisms of soils with distinct mineralogy in highly acidic environments.

2. Materials and methods

2.1. Soils and solutions used

Three soils with widely varying physical and chemical properties, namely, natural black cotton soil and commercially available kaolin clay and bentonite, were selected for this laboratory investigation. The expansive black cotton soil (BCS), predominant with the montmorillonite mineral, was collected by an open excavation from a depth of one meter below the natural ground level at NIT Warangal Campus, India. The commercially available green bentonite (BT) was purchased from Vidhya Enterprises, Chennai, India and the commercially available white kaolin clay (KT) was purchased from Godavari Mines and Minerals, Visakhapatnam, India. All the clays were oven dried and sieved through a No. 40 (425μ) sieve prior to usage. The physical properties and chemical composition of the clays