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Effect of acid rain on geotechnical properties of residual soils

Zeinab Bakhshipour[a,*], Afshin Asadi[b], Bujang B.K. Huat[a], A. Sridharan[c,1], Satoru Kawasaki[d]

[a]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia*
[b]*Housing Research Center (HRC), Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor Darul Ehsan, Malaysia*
[c]*Honorary Research Scientist, Indian National Science Academy, New Delhi, India*
[d]*Faculty of Engineering, Hokkaido University, Sapporo, Japan*

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Abstract

In this study, the effect of acid rain on the physico-chemical and microstructural properties of two different residual soils was investigated. In order to reproduce the process of soil-acid rain-chemical interaction, an infiltration setup was fabricated. The samples were then infiltrated by different pH levels of acid rain, and for different fluxes of acid rain equivalent to the precipitation, for 1–20 years. The compressive strength, consistency limit, compaction characteristics, and coefficient of permeability were evaluated, to investigate the mechanical changes of the soils after being exposed to acid rain. In addition, zeta potential, atomic adsorption spectroscopy (AAS), scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) were carried out to identify the underlying controlling mechanisms. The results showed that low pH and high fluxes of acid rain led to a reduction in soil strength and maximum dry density as well as an increase in the coefficient of permeability, liquid limit, and optimum moisture content of the soil. The SEM, EDX, and atomic absorption analysis of the soils confirmed the reduction in the concentration of elements, and the loose structure for both soils due to the effects of acid rain.

Keywords: Acid rain; Residual soil; Atterberg limits; Compressive strength; Compaction characteristics; Coefficient of Permeability

1. Introduction

In recent years, the growing rate of soil contamination has prompted a number of studies in which the effects of chemicals on the geotechnical properties of fine-grained soils have been studied (Gratchev and Sassa, 2009). Acid rain is a result of air pollution, and the major sources of acid rain are sulfur dioxide (SO_2) and nitrogen oxides (NO_X) (Denman et al., 2007). These oxides react in rainwater to produce stronger acids and may lower the pH to 4.5 or even 3.0. The mechanical behaviour of soils is significantly influenced by changes in the chemical properties of the medium (Santamarina et al., 2002).

Many studies have focused on the effects of acid rain on mechanical properties of different soils (Brandenburg and Lagaly, 1988; Sridharan et al., 1988; Gori, 1994; Benna et al., 2002; Jozefaciuk and Bowanko, 2002; Santamarina et al., 2002; Sridharan et al., 2002; Gajo and Maines, 2007; Gratchev and Sassa, 2009). From the literature, the following chemical and physical processes may describe the mechanism of the effect of acid rain on soil (Benna et al., 2002; Jozefaciuk and Bowanko, 2002). The first process is dissolution and the leaching of cations or anions from soil based on its solubility at

*Corresponding author.
E-mail addresses: Bakhshipour.azadeh@gmail.com (Z. Bakhshipour), afshin.xxxdi@gmail.com (A. Asadi), bujang@upm.my (B.B.K. Huat), Sridharanasuri@yahoo.com (A. Sridharan), kawasaki@geo-er.eng.hokudai.ac.jp (S. Kawasaki).
[1]Formerly Professor of Civil Engineering, Indian Institute of Science, Bangalore, India.
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different pH values. Sunil et al. (2006) reported that leaching of iron from laterite soil decreased compressive strength, maximum dry density (MDD) and specific gravity, and increased the optimum moisture content (OMC), liquid limit (LL), and plastic limit (PL). The soil particles in natural conditions are held together because of the presence of iron oxide (Moh and Mazhar, 1900). The leaching of iron from the soil results in a lack of binder, and therefore changes of the mechanical properties (Sunil et al., 2006). Van Olphen and Hsu (1978) and Soga and Mitchell (1976) noted that at a low pH condition, significant changes in mineral structure might occur due to dissolution of alumina and silica from soil. It should be noted that the solubility of alumina is higher than that of silica in acidic conditions (J.B. Keller, 1964); this process would probably affect geotechnical properties such as shear strength and compressibility behaviour of soil. Imai et al. (2006) reported that acidic fluids caused the dissolution of calcium carbonates, which destroyed the carbonate bonds between clay particles/aggregates, forming “loose” structures with larger voids and thus greater compressibility. In addition, Gratchev and Towhata (2015) reported that a decrease in pH correlates with increases in compression indices and LL and PI of soils, due to the dissolution of calcium carbonate.

The second process is changes in the surface electrical properties of the colloidal fraction of soil. The highly pH-dependent surface charge of some colloids such as kaolinite characterizes the mechanical behaviour of such soils (Schofield and Samson, 1953; Brandenburg and Lagaly, 1988; Chen et al., 2000). Van Olphen and Hsu (1978) noted that at low pH, the charge on the edges of kaolinite particles becomes increasingly positive, a process that leads to the formation of more open and flocculated fabrics. The existence of such fabrics was experimentally verified by Wang and Siu (2006). Dolinar and Trauner (2007) studied clay micro-fabrics of kaolinite by means of scanning electron microscopy. They concluded that such open clay micro-fabrics would be more compressible, producing soil fabrics with higher compression indices, due to edge-to-face (EF) association.

The third process is the absorption of anions in acid rain, such as SO_4^{2-},NO_3^{2-}, and CO_3^{2-} in the soil environment. Kamon et al. (1997) showed that various cations in soils such as calcium might absorb the anions from acid rain, resulting in formation of crystalline $CaSO_4$ and $CaCO_4$ and an increase in unconfined compressive strength of soil in the process. Also, their results indicated that flux and soak period of acid rain, and the buffering capacity and cation exchange capacity (CEC) of soils, are important factors that have the potential to change the soil-acid rain interactions (Gratchev and Towhata, 2011).

The fourth process is changes in the diffuse double layer of clay size fraction due to ion exchange, and consequent changes in the van der Waals forces acting between the clay particles, which may result in a change in the engineering properties of soil affected by acid rain. When the soil becomes acidic, H^+ ions engage in the exchange process with the cations from the diffuse double layer of the clay particles. Due to its superior position in the Hofmeister series, H^+ ions would probably replace the commonly found exchanged cations (Gratchev and Towhata, 2011). From clay colloid chemistry (Van Olphen and Hsu, 1978), it is known that this process leads to a change in double layer thickness. An increase has been shown to result in a greater compressibility of soil and lower shear strength, while a decrease results in quite the opposite effects (Bolt, 1956; Peterson and Gee, 1985; Bowders Jr. and Daniel, 1987; Broderick and Daniel, 1990; Ruhl and Daniel, 1997; Kashir and Yanful, 2001).

The aforementioned reviews show that the effects of acid rain on the physico-chemical and engineering properties of soil could be different, due to the complexity of the mineral composition of the host soil, and the associated physico-chemical reactions. Therefore, further research will contribute to a better understanding of the effect of acid rain on the physical and engineering properties of natural soils for different environmental conditions.

Until the end of 1970s, the problem of acid rain was only confined to the European and North American countries. However, increased urbanization and industrialization in developing countries such as Malaysia have also provided a basis for the occurrence of acid rain (Ayers et al., 2002). Malaysia is one of the areas that are beginning to experience the effects of acid rain. The areas most seriously affected by acid rain are Kuala Lumpur, Johor, Kedah and Selangor, while a four-fold increase in the rain acidity in Petaling Jaya and Senai was observed from 1985–1988. In Malaysia from 1985–1992, the mean pH values ranged from 5.0–5.7 in the sites not close to industrial areas, and from 4.3–5.0 close to industrial and densely populated areas (Ayers et al., 2000). Zabawi et al. (2008) also showed that rain acidity was showing an upward trend, particularly in the Kuala Lumpur, Klang Valley, Pulau Pinang, Perai and Johor Bahru, and the Senai areas (Zabawi et al., 2008). It was further shown by Ayers et al. (2000) that the annual pH value of rain at Johor Bahru, Klang Valley and Kuala Lumpur is in the range of 4.16–4.40. Climate conditions in Malaysia are characterized by high humidity and particularly abundant rainfall, with annual rainfall intensity over 2400 mm. In addition, chemical weathering regularly occurs. Thus, this study aims to determine the effects of acid rain on the physico-chemical and engineering behaviour of two common types of soil in these areas; namely sedimentary residual soil and igneous residual soil.

2. Materials and methods

2.1. Soil properties

Two commonly occurring natural soils, sedimentary residual soil (SRS) and igneous residual soil (IRS), were selected. These soils were obtained from the Batu Cave and Taman Ukay Perdana, respectively, in Kuala Lumpur, Malaysia. Some relevant physical-chemical and geotechnical engineering properties of soil are reported in Tables 1 and 2. The SRS and IRS soils used here are classified as silt of high plasticity (MH) and clay of low plasticity (CL), according to the unified soil classification system (USCS). The XRF results showed that the concentration of $Fe_2O_3$is high (i.e. 54%) for SRS. Moreover, X-ray diffraction (XRD) analyses confirmed the presence of high percentages of kaolinite and goethite, and quartz in SRS and IRS, respectively.