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Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement

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ABSTRACT

Palm oil fuel ash (POFA) in both cost-effective and environmentally friendly ways has potential applications in soft soil stabilization. This study investigates the possible uses of POFA (individually and in combination with cement) on several basic characteristics of clayey soil behavior, such as proctor compaction, Atterberg limit, and unconfined compression strength (UCS). These properties are compared with those of unstabilized clay and stabilized clay with cement. Scanning electron microscopy with X-ray microanalysis is conducted on untreated and treated soil to elucidate their strength development, and the observed test results are then explained. Findings show that POFA and POFA/cement mixture treatments result in significant reductions in the soil plasticity index (PI). The results of the compaction test indicate that the utilization of POFA and POFA/cement mixture in soft soil stabilization decreases the optimum moisture content and increases the maximum dry density across selected binder dosages. The results show that using POFA alone to stabilize clayey soil results in a slight increase in the UCS of the specimens until the 28 days of curing, whereas combining POFA with cement results in a sharp increase in the UCS of the samples in the same curing time. The results demonstrate the environmental, technological, and economic advantages of utilizing this well known agricultural waste as a partial substitute for cement in stabilizing soils, particularly soft soils that usually demand high quantities of stabilizer to reach satisfactory results.

Introduction

The construction of structures on soft clay soils is a challenging task and therefore considered as one of the biggest concerns in geotechnical engineering. The utilization of soft soils in tropical regions is currently low, although construction on them has become increasingly necessary due to economic reasons. These types of soils are generally characterized by low undrained shear strength (less than 25 kPa), extremely high compressibility, poor workability and bearing capacity (Tingle and Santoni, 2003).

Soil stabilization can be a beneficial method in treating the chemical and physical features of soft soils with different additives (Sabih et al., 2011). Given its robustness and easy adaptability, stabilizing soft soils by incorporating traditional calcium-based stabilizers in this method has become increasingly popular (Akpokodje, 1985; Miura et al., 2001; Prusinski and Bhattacharja, 1999). However, the traditional cementitious stabilizers like cement are under discussion, not only for their negative environmental effects during manufacture but also for their cost.

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Palm oil fuel ash (POFA) is one of the most abundantly produced waste materials in tropical regions which has a strong potential to treat physicochemical characteristics of soft soils due to its amorphous nature and high silica content. POFA is widely produced by the oil palm industry owning to the burning of empty fruit bunches (EFB), fiber and palm oil shells (POS) as fuel to generate electricity and the waste, collected as ash, becomes POFA.

Hypothetically, the large amount of amorphous silica in POFA potentially contributes to the pozzolanic reaction during hydration, which results in cementitious compounds called calcium aluminate hydrates (CAH) and calcium silicate hydrates (CSH). These compounds are responsible for improving the engineering characteristics of soils that increase over time as the pozzolanic reaction develops (Seco et al., 2012). The potential is further strengthened and driven by the insight that oil constitutes only 10% of the palm production, while the rest of 90% is the residue (Foo and Hameed, 2009). For example, approximately 3 million tons of POFA were generated in Malaysia in 2007, whereas approximately 0.1 million tons of POFA are generated on an annual basis in Thailand (Al-mulali et al., 2015; Chiew et al., 2011). Given that open burning is no longer permitted (Yusoff, 2006), this residue is disposed of in landfills and consequently cause environmental problems such as air pollution and groundwater quality issues because of the leaching of different metals from the ash (Madurwar et al., 2013). As such, the search for suitable methods of using and consuming this well known agro-waste in civil engineering applications (i.e., ground improvement) is a valid, rational, and important task in agricultural countries that generate such type of waste.

The POFA revolution in structural science has attracted much attention mainly because of its abundant accessibility and low profitable commercial value. A large and growing body of literature has investigated utilizing POFA as a supplementary cementitious material in producing high-strength concrete in the last ten years (Awal and Nguong, 2010; Hussin et al., 2009; Chindaprasirt et al., 2007; Awal and Abubakar, 2011; Johari et al., 2012). Extensive research findings show that utilizing this type waste as construction material has significant environmental benefits, including the following (Awal and Nguong, 2010; Johari et al., 2012; Awal and Hussin, 2011; Tangchirapat et al., 2007):

(1) increase in the life of structures because of the high durability of POFA,
(2) reduction in energy use, greenhouse gases, and adverse air emissions, when manufactured cement is replaced with POFA, and
(3) reduction in the amount of palm oil residues that should be disposed in landfills.

Several studies have also validated on different occasions the benefits of using POFA, instead of asphalt, as primary road material (Ndoke, 2006; Amu et al., 2008). Ismail and Keok (Ismail and Keok, 2010) also produced bricks with satisfactory strength using POFA and paper sludge. From the geotechnical and geoenvironmental perspectives, Brown et al. (2011) reported that clayey soils treated with POFA as landfill liner exhibit an increase in optimum moisture water content despite a decrease in maximum dry density.

A review of the literature reveals that not much effort has been exerted in the past to evaluate the efficacy of POFA-stabilized soils, particularly soft soils that usually demand high quantities of stabilizer to reach satisfactory results. Framed by this context, the present study explores the possible use of POFA in stabilizing soft clayey soils under appropriate conditions.

The influence of different percentages of POFA and POFA/cement mixtures on the index properties, compaction, and unconfined compression strength (UCS) of selected clayey soil was investigated for the above purpose. Also, the microstructural changes of clayey soil before and after the treatment were investigated to determine the underlying stabilization mechanisms with the aid of energy dispersive X-ray spectroscopy (EDS) and scanning electron microscopy (SEM) analyses. This study contributes to the reduction in the environmental impact of POFA and recommends a practical work range in utilizing this residue in ground improvement applications to reduce the settlement of foundations, prevent shear deformation, and mitigate liquefaction.

Experimental investigation

Materials used

Soil

The physical properties and chemical composition of clayey soil used in this experiment are listed in Tables 1 and 2 respectively. Also, the grain size distribution of clayey soil is illustrated in Fig. 1. The investigated clayey soil is classified as high-plasticity clay (CH) according to the Unified Soil Classification System. This type of soil is often too soft and weak to support the upper infrastructure of construction projects, which makes it an excellent and challenging type of host soil for soil stabilization.

Palm oil fuel ash

The POFA used in this study was collected from a factory in Johor in the southern state of Malaysia. Raw POFA is unusable because of its unknown moisture content, uncombusted palm fibers, large particle size, and residual carbon (i.e., the major impurity of POFA). Thus, two steps were undertaken to treat POFA before its use as soil stabilizer. In the first step, after drying it inside oven for 24 h, well-dried ash was sieved using a 600 μm (No. 25) sieve to remove nutshells and fibers which were incompletely combusted. The POFA was then ground in a ball mill for 24 h and then passed through a 125 μm (No. 120) sieve. Different ball sizes in the range of 30–12 mm were used with three mills diameter of 80 cm as illustrated in Fig. 2. The mill speed was 60 RPM (around 65% of critical speed). This process effectively achieved a high specific surface and good pozzolanic reaction between the soil and POFA. The higher the specific surface is, the more rapidly the binder reacts. This explanation is similar to that reported by Janz and Johansson (Janz and Johansson, 2002), in which the reactivity of a stabilizer is largely evaluated by its