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Research paper

Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer

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ABSTRACT

This research investigates strength development and the carbon footprint of Calcium Carbide Residue (CCR) and Fly Ash (FA) based geopolymer stabilized marine clay. Coode Island Silt (CIS), a soft and highly compressible marine clay present in Melbourne, Australia was investigated for stabilization with the CCR and FA geopolymers. CCR is an industrial by-product obtained from acetylene gas production, high in $Ca(OH)_2$ and was used as a green additive to improve strength of the FA based geopolymer binder. The liquid alkaline activator used was a mixture of sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH). The influential factors studied for the geopolymerization process were Na_2SiO_3/NaOH ratio, NaOH concentration, L/FA ratio, initial water content, FA content, CCR content, curing temperature and curing time. The strength of stabilized CIS was found to be strongly dependent upon FA content and NaOH concentration. The optimal ingredient providing the highest strength was found to be dependent on water content. Higher water contents were found to dilute the NaOH concentration, hence the optimal L/FA increases and the optimal Na_2SiO_3/NaOH decreases as the water content present in the clay increases. The maximum strength of the FA geopolymer (without CCR) stabilized CIS was found at $Na_2SiO_3/NaOH = 70{:}30$ ratio and $L/FA = 1.0$ for clay water content at liquid limit (LL). The role of CCR on the strength of FA geopolymer stabilized CIS can be classified into three zones: inactive, active and quasi-inert. The active zone where CCR content is between 7% and 12% is recommended in practice. The 12% CCR addition can improve up to 1.5 times the strength of the FA geopolymer. The carbon footprints of the geopolymer stabilized soils were approximately 22%, 23% and 43% lower than those of cement stabilized soil at the same strengths of 400 kPa, 600 kPa and 800 kPa. The reduction in carbon footprints at high strength indicates the effectiveness of FA geopolymer as an alternative and effective green soil stabilizer to traditional Portland cement.

1. Introduction

The eastern part of Melbourne's Central Business District is located in the Yarra Delta, which is a low-lying area of soft marine and estuarine quaternary deposits with high groundwater levels. These characteristics have historically resulted in a large area of land near the city center remaining under-developed. However, this previously under-developed space is now experiencing a rebirth following a directive by the local state government to rehabilitate it to accommodate extension of existing port facilities, cater for the growth of the port of Melbourne as a large container center as well as to provide space for industry and waterfront residential development (Bouazza et al., 2004).

The existence of a soft (undrained shear strength in the range of 5–30 kPa) and highly compressible layer of marine sediment, Coode Island Silt (CIS), in the Yarra Delta however imposes geotechnical constraints on the design and performance of future infrastructure works. Deposits of CIS extend to depths of upto 30 m. Regardless of the magnitude of the applied loads, total and differential settlements in the range of 500–700 mm were expected for shallow foundation supported structures built on CIS (Ervin, 1992). The traditional engineering solution is deep foundation (pile) to transfer loads through the soft clay to deeper and stiffer layers. However, this solution is expensive and may not suit for low to medium load bearing structures.

Several ground improvement techniques dealing with soft soil foundation have been developed over the past 30 years (Bergado et al., 2003; Bouazza et al., 2006; Arulrajah and Bo, 2008; Horpibulsuk et al., 2012c; Shen et al., 2013a, 2013b, 2013c; Du et al., 2013, 2014; Chai et al., 2014;

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Bo et al., 2015a, 2015b; Wu et al., 2015; Chen et al., 2016). In situ deep mixing is an effective means, which has been developed over two decades primarily to effect columnar inclusions into the soft ground to transform soft ground to composite ground. The deep mixing technology was simultaneously developed in Sweden and Japan using quicklime as a hardening agent. Subsequently, ordinary Portland cement slurry was used as a cementing agent because it is readily available at reasonable cost. The influential factors, controlling the field strength of deep mixing columns such as penetration and withdrawal rates, water to cement ratio, and rate of blade rotation were extensively investigated by Horpibulsuk et al. (2004) (Ariake clay, Japan) and Horpibulsuk et al. (2011b, 2012c) (Bangkok clay, Thailand).

The high energy intensive process for the production of Portland cement are the driving forces for the constant need within the industry to seek alternative cementitious binders. The cement manufacturing process emits CO_2 into the atmosphere, which accounts for 5% of the total CO_2 released into the air (Horpibulsuk et al., 2013). The development of a new cementing agent with low carbon dioxide releases is actively sought by industry. Commercial and industrial utilization of alkali-activated aluminosilicate cements, known as 'geopolymers' has increasingly well-known over the past several decades because of their high performance (high strength and durability) and environmentally maintainable alternative to the ordinary Portland cement (Davidovits, 1991). Geopolymers belong to a group of materials with increased interest due to low CO_2 emission and energy consumption. The hardening process of geopolymers at ambient temperature results in materials with ceramic-like properties, such as resistance against acids and high temperatures. The silica-rich materials such as kaolin (Buchwald and Kaps, 2002), fly ash, and bottom ash (Davidovits et al., 1999) can be used as a precursor to react with the liquid alkaline activator. Fly Ash (FA) provides the greatest opportunity for commercial utilization of this technology due to the plentiful worldwide raw material supply, which is derived from coal-fired electricity generation (Mohapatra and Rao, 2001; Van Jaarsveld et al., 1998). Even though geopolymers have been recently used in building concrete application, its usage in geotechnical application has been very limited.

It has been reported that the mechanical properties of FA based geopolymer could be improved by high calcium additives due to the coexistence of geopolymerization products (Sodium Alumino Silicate Hydrate, N-A-S-H) and Calcium Silicate Hydrate (C-S-H) (Phummiphan et al., 2015; Yip et al., 2005, 2008; Granizo et al., 2002). Calcium Carbide Residue (CCR) is a waste material from acetylene gas factories, which has high calcium hydroxide [$Ca(OH)_2$] content. CCR could affect organisms, which depend on microbes and their by-products for growth and development (Lavoie, 1980). The high alkaline (pH ≥ 12) could result in environmental destruction such as land occupation and water pollution (Lei et al., 2011; Tub and Caulk, 2001; Hologado et al., 1992). It has been previously used itself as a green soil stabilizer (Horpibulsuk et al., 2012a, 2012b, 2012c; Kampala et al., 2013, 2014; Phetchuay et al., 2014; Vichan et al., 2013; Du et al., in press; Jiang et al., 2016) but not as an additive for FA geopolymer binder. The usage of high calcium CCR as a green additive in FA geopolymer stabilized clay is thus novel and significant in geotechnical and pavement applications.

This paper attempts to examine the viability of using FA and CCR based geopolymers as a sustainable binder to improve strength of soft marine clay, namely CIS. The Unconfined Compressive Strength (UCS) is used as a practical indicator to investigate the strength development. The influential factors studied include liquid alkaline activator content, L/FA ratio, FA content, water content, curing time, curing temperature and CCR content. Moreover, the carbon footprints of FA and CCR based geopolymers stabilized CIS are calculated and compared with those of cement stabilized CIS at the same UCS values practically used in the soil improvement. The outcome of this research will increase the usage of FA–CCR geopolymer as a sustainable soil stabilizer alternative to high carbon Portland cement, which benefits in term of engineering, economic and environmental perspectives.

2. Materials and methods

2.1. Materials

2.1.1. Coode Island Silt (CIS)

Coode Island Silt (CIS) samples were collected from the Port Melbourne area at a depth of 3–5 m. Fig. 1 shows grain size distribution of CIS obtained from hydrometer analysis. It indicates that the CIS consists of 4% sand, 29% silt and 67% clay. The specific gravity and organic content are 2.60 and 2.5%, respectively. Liquid Limit (LL) and Plastic Limit (PL) are approximately 65% and 32%, respectively. Based on the Unified Soil Classification System (USCS), the CIS is classified as highly plastic (CH). The basic properties are shown in Table 1. The X-ray Fluorescence (XRF) analysis is shown in Table 2.

2.1.2. Fly Ash (FA)

FA was obtained from a local Australian supplier. FA is a by-product from the combustion of coal used to generate electricity. It is collected by either using electrostatic precipitators, bag houses or a combination of both. Its grain size distribution, obtained from laser particle size analyzer is shown in Fig. 1. This laser particle size analyzer measures the particle size distribution of a sample powder dispersed in the air. It is for particle size distribution measurements of powders with no suitable dispersion medium and powders that dissolve in liquids. Table 2 summarizes the chemical composition of FA using X-ray fluorescence (XRF). Total amount of the major components (SiO_2, Al_2O_3 and Fe_2O_3) of FA is 94.40% while the CaO content is 1.68%; therefore, it is classified as a Class F FA.

2.1.3. Calcium Carbide Residue (CCR)

The CCR is a by-product from acetylene gas factory, which is transferred to disposal area as slurry form. After being sun-dried for a few days, the slurry form is changed to dry form and is generally disposed in landfills. In this research, the dried CCR was oven-dried at 100 °C for 24 h and was then ground using a Los Angeles abrasion machine. The CCR was passed through a No. 40 sieve (425 μm). The specific gravity value is 2.32. Table 2 summarizes the chemical composition of CCR. The high $Ca(OH)_2$ and CaO contents of the CCR indicate that it can react with FA and produce a cementitious material (Palomo et al., 1999). The grain size distribution of the CCR (from laser particle size analyzer) compared with that of the CIS is shown in Fig. 1. The average grain size (D_{50}) of CCR is 0.01 mm, which is bigger than that of CIS.

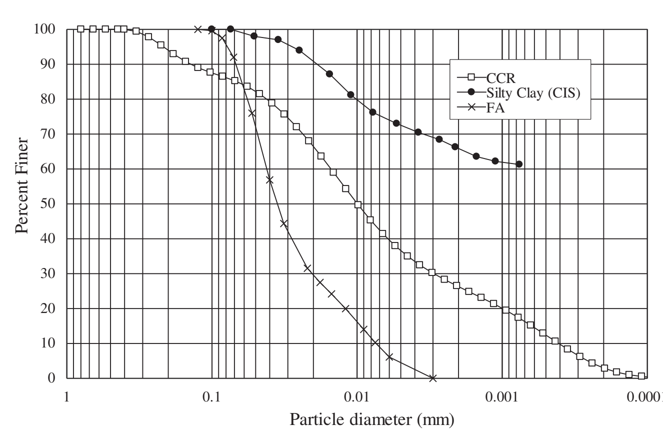

Fig. 1. Grain size distribution of clay, FA and CCR.