Construction and Building Materials 69 (2014) 285–294

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Calcium carbide residue: Alkaline activator for clay–fly ash geopolymer

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HIGHLIGHTS

- Industrial by-product: Calcium Carbide Residue (CCR).
- A green geopolymer subgrade using CCR as alkaline activator.
- Strength and microstructural analysis of CCR–FA based geopolymer.
- Role of heat temperature and curing on strength development.

ARTICLE INFO

Article history:
Received 17 April 2014
Received in revised form 12 June 2014
Accepted 3 July 2014
Available online 12 August 2014

Keywords:
Geopolymer
Strength
Microstructure
Subgrade
Fly ash
Calcium carbide residue

ABSTRACT

Calcium Carbide Residue (CCR) and Fly Ash (FA) are waste by-products from acetylene gas and power plant production, respectively. The liquid alkaline activator studied in this research is a mixture of sodium silicate solution (Na_2SiO_3), water and CCR. The primary aim of this research is to investigate the viability of using CCR, a cementitious waste material, as an alkaline activator and FA as a precursor to improve the engineering properties of a problematic silty clay to facilitate its usage as stabilized subgrade material. The influential factors studied are Na_2SiO_3/water ratio, FA replacement ratio, curing time, curing temperature and soaking condition for a fixed CCR content of 7%. Strength development is investigated via the unconfined compression test. Scanning Electron Microscopy (SEM) observation is used to explain the role and contribution of influential factors on strength development. CCR dissolves the silicon and aluminum in amorphous phase of FA and the Na_2SiO_3 acts as a binder. The maximum soaked strength of the clay-FA geopolymer is found at Na_2SiO_3/water ratio of 0.6 and FA replacement ratio of 15%. The optimal Na_2SiO_3/water ratio is approximated from index test, which is a very practical approach. The clay-FA geopolymers with 40 °C curing exhibit higher strength than those with room temperature curing, indicating the possibility of using clay-FA geopolymer for pavement subgrade applications. The 7-day soaked strength at the optimal ingredient meets the strength requirement for subgrade materials specified by the local national road authority. CCR is found to be a sustainable alkaline activator for geopolymer stabilized subgrade materials, which will result in the diversion of significant quantities of this by-product from landfills.

1. Introduction

Chemical stabilization is an extensively used soil improvement technique for road embankments and pavement applications. The resistance of compression and consequent strength development of stabilized materials increases with an increase in curing time. Portland cement is commonly used as a cementing agent for this stabilization [1–6]. The stabilization commences with mixing of the soil in a relatively dry state with cement and water specified for compaction. The compaction effort from rollers is needed to remove air from the soil (to increase degree of saturation) and to make soil particles slip over each other and move into a densely packed state. The high unit cost and energy intensive process for the production of Portland cement are the driving forces for the constant need within the industry to seek alternative cementitious additives. The cement manufacturing process emits CO_2 into the atmosphere, which accounts for 5% of the total CO_2 released into

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http://dx.doi.org/10.1016/j.conbuildmat.2014.07.018
0950-0618/

the air [7]. The development of a new cementing agent with low carbon dioxide release is constantly being sought by industry and local government.

In recent years, increasing research has been undertaken into utilization of various forms of waste materials in a range of civil engineering applications including pavements [8–11,3,12] and foothpaths [13]. Sustainable materials that have been researched include recycled concrete aggregates, reclaimed asphalt pavement, recycled glass and other forms of municipal wastes [14–16]. Research has also been increasingly undertaken as well as investigated the usage of alternative binders to Portland cement, so as to further lower the carbon footprint of roads and other infrastructures.

Calcium Carbide Residue (CCR), a waste material from acetylene gas factories has been used to stabilize silty soil due to its high calcium hydroxide [$Ca(OH)_2$] content. The strength, durability and microstructure of CCR stabilized soils have been studied to ascertain the usage of this stabilized material for pavement applications [17–19]. The improvement of engineering properties of CCR stabilized clay by an addition of fly ash and biomass has been illustrated by Kampala et al. [20] and Vichan et al. [21].

Commercial and industrial utilization of alkali-activated aluminosilicates cements, known as "geopolymers" or "zeolitic precursor" belong to a group of materials with increased interest due to low CO_2 emission and energy consumption. The geopolymers are the products of the copolymerization of the individual alumina and silica components, which takes place when aluminosilicate source materials are dissolved at a very high pH [22–24]. The silica rich materials such as clay or kaolin [25], fly ash, rich hush ash and bottom ash [22] can be used as a precursor to react with the liquid alkaline activator. Fly ash provides the greatest opportunity for commercial utilization of this technology due to its plentiful worldwide raw material supply, derived from coal-fired electricity generation [26,27]. Palomo et al. [23] reported that the different FA activated with 8–12 M NaOH cured at 85 °C for 24 h produced a material with compressive strength of 35–40 MPa and about 90 MPa if sodium silicate (Na_2SiO_3) is added to the NaOH solution. Xie and Yunping [28] indicated that the hardening process of FA activated with Na_2SiO_3 is mainly attributed to the gel-like reaction products that bind FA particles together. FA is extensively used as a precursor for geopolymers in Australia [29,30] and Thailand [31,32].

An innovative work on the development of a new green construction and building material using locally available soil as an aggregate and FA as a precursor has been undertaken by Sukmak et al. [33]. The factors controlling the strength development were investigated by Sukmak et al. [34] and the study shows that the clay-FA geopolymer can be used as a masonry bearing unit with 7-day compressive strength greater than 10 MPa. It has been illustrated that the durability against sulfate attack of clay-FA geopolymer is better than that of clay-cement; i.e., there is no major change in the microstructure and pH of clay-FA geopolymer when exposed to sulfate solutions [35].

In order to improve economic and environmental impacts, CCR can be utilized together with waste precursors, such as fly ash, biomass ash and rice husk ash to develop construction and pavement materials. The dissociation of $Ca(OH)_2$ leads to an increase in the pH values of the pore water. Strong bases dissolve the silica and alumina from FA particles in a manner, similar to the pozzolanic reaction. The hydrous silica and alumina then gradually react with Na_2SiO_3 in this geopolymerization reaction.

This paper attempts to study the viability of using CCR as an alkaline activator to stabilize problematic clay as a pavement subgrade material. The unconfined compressive strength is used as a practical indicator to investigate strength development. The microstructural observation of clay-FA geoplymer via scanning electron microscope (SEM) was undertaken to understand the role of influential factors controlling the strength development. The influential factors studied include Na_2SiO_3 content, FA content, state of water content, soaking condition, curing temperature and curing time. The outcome of this research would divert significant quantity of CCR from landfills and considerably reduce carbon emissions due to Portland cement production.

2. Materials and methods

2.1. Soil sample

The soil sample is silty clay, which was collected from the Suranaree University of Technology campus in Nakhon Ratchasima province of Thailand at a depth of 3 m. It is a problematic soil, which is sensitive to changes in water content [36]. The collapse and swelling of this compacted clay exceeds the threshold limit specified by Department of Highways and Department of Rural Roads, Thailand [37]. Fig. 1 shows the grain size distribution of the silty clay, showing 2% sand, 43% silt and 55% clay. The average grain size, D_{50}, of the clay is 0.0009 mm and the specific gravity is 2.76. The liquid and plastic limits are approximately 61% and 22%, respectively. Based on the Unified Soil Classification System (USCS), the clay is classified as highly plastic (CH). The natural water content was found to be 12%. The soil swelling potential of the tested clays was investigated by the free swelling test proposed by Prakash and Sridharan [38], which predicts the dominant clay mineralogy of soils satisfactorily [39]. The free swell ratio, FSR, is defined as the ratio of equilibrium sediment volume of 10 g of oven-dried soil passing through a 425 μm sieve in distilled water (V_d) to that in carbon tetra chloride or kerosene (V_k). The clay is classified as low swelling with a free swell ratio (FSR) of 1.4. The Cation Exchange Capacity (CEC) is 27.6 meq/100 g. The chemical composition using X-ray fluorescence (XRF) of the silty clay is shown in Table 1.

2.2. Alkaline activator and precursor

CCR from Sai 5 Gas Product Co., Ltd. and FA from Mae Moh power plant in the north of Thailand were used in this study. The CCR was oven-dried at 100 °C for 24 h and was then ground using a Los Angeles abrasion machine. Both CCR and FA were passed through a No. 40 sieve (425 μm). The specific gravity values are 2.32 and 2.39 for CCR and FA, respectively. Table 1 summarizes the chemical composition of FA and CCR. The total amount of the major components SiO_2, Al_2O_3 and Fe_2O_3

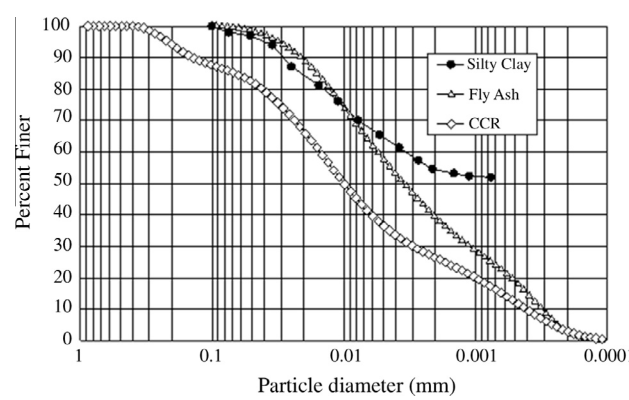

Fig. 1. Grain size distribution of clay, CCR and FA.

Table 1
Chemical properties of silty clay, fly ash and CCR.

Chemical composition (%)	Silty clay	Fly ash	CCR
CaO	26.15	30.24	70.78
SiO_2	20.10	47.51	6.49
Al_2O_3	7.55	13.14	2.55
Fe_2O_3	32.89	6.66	3.25
MgO	0.47	N.D.	0.69
SO_3	4.92	N.D.	0.66
Na_2O	ND	0.41	N.D.
K_2O	3.17	1.63	7.93
LOI	3.44	0.42	1.35

N.D. = not detected.