Construction and Building Materials 170 (2018) 737–746

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effects of natural fiber inclusions and pre-compression on the strength properties of lime-fly ash stabilised soil

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HIGHLIGHTS

- Pre-compression reduces unconfined strength of fiber reinforced lime-fly ash stabilised soil.
- Mechanical properties of fiber reinforced stabilised soil improve with fiber inclusions.
- Fully cured lime-fly ash stabilised soil composite offers considerable resistance to compression.
- Ductility of the fiber-soil composite significantly improves with fiber inclusions.

ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 18 February 2018
Accepted 25 February 2018

Keywords:
Fiber
Composite
Strength
Soil stabilisation

ABSTRACT

In this study, the synergic effects of pre-compression and fiber inclusions, on the mechanical behaviour of lime fly ash stabilised soil were investigated. Randomly distributed 25 mm sisal fibers were mixed with stabilised soil at the contents of 0%, 0.25%, 0.5%, 0.75% and 1% by dry mass of the soil. Both fiber composite and unreinforced soil specimens were subjected to the pre-compression stresses equivalent to 10% and 20% of the strength mobilised by the un-precompressed specimens. The pre-compression stresses were applied after 4 h, 8 h and 24 h of accelerated curing at 40 °C, after which the conditioned specimens were allowed to continue curing under constant conditions. The 7 day strength of the fully cured composites was determined by a series of unconfined compression tests. The results revealed that optimum strength of 3.5 MPa was mobilised by un-precompressed specimens at 0.75% fiber content. Pre-compression with 10% UCS showed maximum strength of 2.8 MPa at 0.25% fiber content whereas 20% UCS indicated optimum strength of 3.04 MPa at 0.25% fiber content. In comparison, pre-compressed specimens exhibited lower strength values than un-precompressed specimens. This was attributed to the redistribution of bond strength, evolution of matrix cracking and fiber-matrix interfacial debonding. The maximum strengths of specimens for both pre-compression levels occurred after 24 h of curing. This was due to the progressive strength development that endowed the composite with some resistance to compression that was responsible for matrix cracking and debonding. Fiber inclusions significantly improved ductility of the stabilised soil. The theoretical crack model of damage mechanisms in cementitious fiber composites can predict strength behaviour of composites that were pre-compressed after short period of curing.

1. Introduction

Lime stabilisation technique has been applied for ages in construction of improved subbases and subgrade of railways, highways and airfields embankments [1,2]. In practice, the technique is effectively applied to expansive or clayey soils. Lime stabilisation improves plasticity index, swelling, shrinkage, permeability and typical engineering properties such as shear strength and, compressibility of soil [1,3–8]. The combined addition of lime and fibers increases the efficiency to transfer load from matrix to fibers especially at extended curing time and also significantly affects the rate of unconfined compressive strength gain of the soil [9,10]. Literature has shown that compressibility of fly ash is highly affected by lime dosage and duration of load increments. The addition of lime to fly ashes triggers hydration process that in turn causes formation of cementitious compounds that are responsible for enhanced cementation of particles. The lime-fly ash mixtures exhibit low compressibility and high equilibrium void ratio values. On the other hand, longer duration of load increments allows considerable curing time for the pozzolanic reaction between lime and

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https://doi.org/10.1016/j.conbuildmat.2018.02.194

flyash. Ultimately, the improved stiffness and strength due to pozzolanic reaction offer resistance of fly ash to compression [11].

To allow pozzolanic reaction to occur in fly ash mixtures, an activator such as Portland cement or lime is added in ratio of 1:2 to raise the PH up to 12.4. In some cases, the self-cementing fly ash possesses calcium oxide (CaO) in concentrations typically ranging from 20 to 30 percent which allow pozzolanic reaction to occur. Lime can also be added when concentration of calcium oxides is insufficient to facilitate pozzolanic reaction. However, high PH associated with the dissociation of hydrated lime Ca $(HO)_2$ reduces with the progression of pozzolanic reactions [11]. In this respect, accelerated curing ensures rapid reduction of pH as pozzolanic products (calcium silicate hydrates (CSH) and calcium aluminate hydrates) are formed at the elevated temperature [8,12].

Exposure of natural fibers to alkaline environment below optimum alkaline concentration is reported to offer benefits to the properties of fiber composite. The natural fiber modification by sodium hydroxide (NaOH) of pH 13 (mercerisation) is the common and cheap chemical treatment to fibers that improves fiber-matrix bonding. Alkali treatment removes fiber constituents including hemicellulose, lignin, pectin, fat and wax which exposes cellulose and increases surface roughness/area providing for improved interfacial bonding [13–15]. Improvement of fiber strength is reported to occur with alkali treatment [14,16]. Many studies have reported improvements in interfacial shear strength and improved tensile strength, Young's modulus, failure strain, impact strength, fracture toughness, flexural properties, thermal stability and long term moisture resistance, the latter of which is attributed to the reduced moisture uptake by alkali treated natural fibers [16,17]. For crystallisable matrices, natural fiber treatment with alkali has also shown to influence the degree of matrix crystallinity, with exposed cellulose acting as a nucleation site for crystalline [18].

Several researchers have reported the benefits of fiber inclusions in the soil. Fibers improve engineering properties of soil such as shear and compressive strengths, bearing capacity, tensile strength and ductility**.** Application of conventional synthetic fiber elements in soil reinforcement exhibits better engineering properties than natural or vegetable fibers. However, cost-benefit analysis favours the use of natural fibers due to their low energy demand and cost effectiveness in production, are renewable resource, for which production involves CO_2 absorption, whilst returning oxygen to the environment [19–21]. Some fiber plants i.e. sisal can stay up to 12 years while consuming CO_2 in exchange of oxygen [22]. Furthermore, natural fibers are hydrophilic in nature, can swell with water ingress, have greater variability in properties, exhibit lower durability than synthetic fibers, however durability of natural fibers can be significantly improved by proper physical and chemical treatments such as coating with hydrophobic compounds, corona-discharge treatment, steam explosion treatment, high energy ray radiation processing, autoclave treatment, mercerisation with alkali (NaOH), acetylation and silane treatment [19].

Fly ash stabilisation effectively improves desired properties of soil [23,24]. The use of fly ash as a binder is more attractive because fly ash is an industrial by-product that is relatively inexpensive compared to cement and lime [25]. Additionally, using fly ash for soil stabilisation, promotes sustainable construction through reduction of energy use and emissions of greenhouse gases [26]. Although field mechanised mixing and compression of lime-flyash mixtures may promote carbon foot print emission, the application of natural fibers in construction ensures the balance between emitted and consumed carbon. Spreading moist fly ash and hydrated lime using surfacing paver is an ideal approach to reducing dust emission during mixing operations.

Irrespective of benefits offered by soil chemical stabilisation, research has shown that the stabilised soils exhibit high stiffness and brittle behaviour [27–31]. Incorporating fiber reinforcements within soil is an effective and reliable technique to improve the ductility of the soil [32,33]. Soil composites with randomly distributed fibers are easy to prepare and fibers limit potential planes of weakness that can develop parallel to oriented reinforcement [19,28]. In comparison, lime stabilisation with fly ash and natural fibers is more cost effective than cement stabilisation since fly ash and natural fiber are cheap products.

In this study, randomly distributed 25 mm sisal fibers were used to reinforce lime fly ash stabilised soil with a view to investigating the effects of fiber inclusions viz. 0%, 0.25%, 0.5%, 0.75% and 1% by dry mass of stabilised soil, pre-compression and curing time, on the mechanical properties of the composite. The composite specimens were pre-compressed by stresses equivalent to 10% and 20% of the strength mobilised by un-precompressed specimens. The pre-compression was applied after 4 h, 8 h and 24 h of accelerated curing conditions at 40 °C. The combined effects of fiber inclusions and pre-compression were eventually investigated after 7 days of curing by the unconfined compression tests. Of the special interest were the macro mechanical effects of pre-compression level, curing period at which pre-compression stress was applied and fiber inclusions. The changes in the mechanical properties of the pre-compressed composite relative to the un-precompressed counterpart were analysed to determine potential benefits of the pre-compression.

2. Materials and experimental programme

2.1. Materials

The soil used in this study was designed by blending different particle sizes obtained from dry sieve analysis. Batches of granular and fine soil were locally obtained from places within the vicinity of the University of Johannesburg. The granular and fine batches were mixed and air dried for 7 days. Dry sieving was conducted by firstly passing particles through 9.5 mm sieve and subsequently sieved using 75 μm, 4.75 mm sieves to separate clay-silt, sand and gravel. The collected soil particle sizes were mixed in the ratio of 30:60:10 by mass for silt clay, sand and gravel respectively. Wet sieving for blended soil was eventually carried out in accordance with ASTM D1140-17 and the grading curve of the soil is shown in Fig. 1. The soil is classified as CL in accordance with Unified Soil

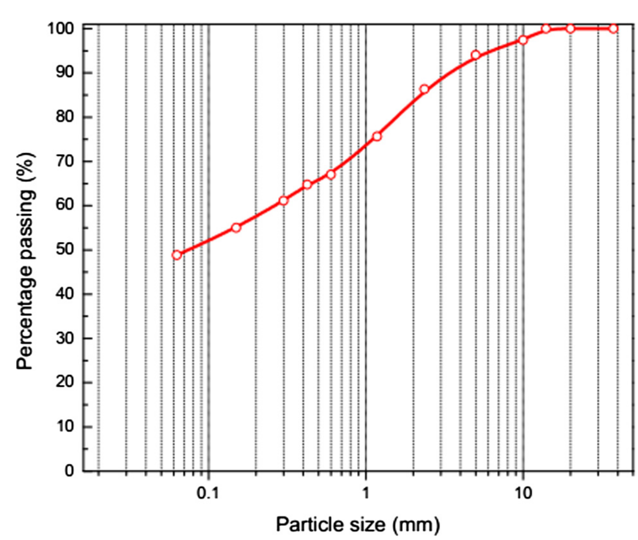

Fig. 1. Gradation curve for soil.