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The effect of size and replacement content of nanosilica on strength development of cement treated residual soil

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HIGHLIGHTS

- Strength development of the treated residual soil were improved by nano silica.
- Compressive strength of the soil increased under effect of nano silica.
- CEC and ER of treated soil increased when nano silica was added.
- C-S-H gel of cement treated soil increased when nano silica was added.

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ABSTRACT

In this study, effects of size and replacement content of nanosilica on physical, chemical, and microstructural characteristics of cemented residual soil were investigated. Accordingly, UCS and electrical resistivity tests were conducted on cemented specimens with replacement contents of 0.2%–1% nanosilica of 15 and 80 nm at 7, 14 and 28 days. XRD, Zeta potential, CEC, FTIR, and SEM tests were performed to identify chemical and microstructural changes over time. The results showed that smaller size nanosilica had an accelerated influence on samples while nanosilica of larger size was more effective at ages after 14 days of curing.

1. Introduction

Over past decades, one of extensively used techniques for soil stabilization is using customary cementitous additives such as cement, lime, and fly ash [1–5]. Among all, cement is often used as a principle additive to enhance mechanical properties of soil such as strength and stiffness within a curing time [6–9]. One of the most dominant types of soil in tropical regions is residual soil [10]. Many researchers reported that addition of 6–10% cement to residual soil with plasticity indexes in a range of 10–20% has been recommended to achieve the maximum possible strength for base construction [7,11–13]. Improvement in properties of cement treated residual soil has been mainly attributed to soil-cement reactions [3,14], which produce primary and secondary cementitious materials in the soil–cement matrix [12,15,16]. The primary cementitious materials are formed by hydration reactions and are comprised of hydrated calcium silicates (C_2SH_x, $C_3S_2H_x$), and hydrated lime $Ca(OH)_2$ [17–19]. A secondary pozzolanic reaction between hydrated lime, silica, and alumina from the clay minerals leads to the formation of additional calcium silicate hydrates and calcium aluminate hydrates [3]. Despite enhancement of geotechnical properties of soil treated with cement, there has been a concern for adoption of cost-effective solutions and reduction in quantities of environmental impact of cement used. Accordingly, an increasing attention has been focused on use of alternative supplementary additives as replacements or additions to the cement-soil matrix [4,10,20].

With the emergence of nanotechnology, inclusion of nano materials in cementitous composites was a subject of many studies [21]. Reportedly, nano materials enhance properties of cement matrix through several mechanisms [22–25]. For example, nanosilica contributes to a denser microstructure of the cement matrix by filling pores and better distribution of hydration products through nucleation effect [25–28]. Moreover, nanosilica with high amount of SiO_2 increases the pozzolanic reaction rate and leads to a stron-

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ger interfacial transition zone (ITZ) and denser microstructure of the cement matrix [24,25]. Despite advantages of hybrid usage of nanosilica and cement in soil mechanics including seepage, grouting, and soil stabilization, very few investigations have been performed regarding application of nanotechnology in geotechnical engineering. In limited investigations performed in this field, Zhang [65] studied effects of nanoclay particles on engineering properties of fine soil. He concluded that the soil containing nanoparticles with intraparticle voids in nanoscale, usually demonstrated higher liquid and plastic limits, and the presence of nanosilica particles enhanced the soil shear strength. Mohammadi and Niazian [29] also carried out a study on plasticity and strength characteristics of clayey soil and its mixture with nanoclay. The results showed that adding montmorillonite nanoclay into the soil increased the liquid limit and plasticity index and improved the unconfined compressive strength of soil. Also, a study by Taha and Taha [30] reported that mixtures of soil and nanomaterials enhanced engineering properties of soil such as compaction characteristics, volumetric shrinkage strain, and volumetric expansive strain. As for hybrid effects of nano materials and soil treated with cement, Bahmani et al. investigated effects of nanosilica on cement treated residual soil at early ages of treatment. They reported an enhancing effect of nanosilica on mechanical properties and microstructure of cement treated soil at ages up to 7 days. They argued that small fractions of nanosilica can enhance the mechanical properties such as compressive strength and the amount of 0.4% by weight of dry soil was reported as an optimum addition level of nanoparticles [10].

So far, effects of different contents of nanosilica and its particle size on stabilization of cement-soil matrix at later ages have not yet been studied. The overarching purpose of this study is to investigate effects of particle size and content levels of nanosilica on treated soil over time at ages between 7 and 28 days. Accordingly, physical properties of treated residual soil with binary mix of nanosilica and cement were investigated and explicated using zeta potential, cation exchange capacity (CEC), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). The study can provide key insights on effects of nanosilica with different sizes and contents on strength development of cemented residual soil in a course of 28 days.

2. Experimental work

2.1. Materials

The residual soil was collected from an excavation operation at depth of 1–3 m in Malaysia. The particle size distribution curve for the soil is shown in Fig. 1. The soil was tested in compliance with standard procedures specified in BS 1377-2 [31] to determine its physical properties, namely specific gravity, liquid limit (LL), plastic limit (PL), shrinkage limit, and grain size distribution. Table 1 shows the properties of the soil, which are indicative of an inorganic clay with low plasticity (CL). X-ray diffraction results illustrated a high illite content with some quartz and kaolinite (Fig. 2). In this study, Portland cement type (I) grade 32.5 MPa was used in compliance with ASTM C150 [32]. The physical and chemical properties of the cement are given in Table 2. Cement was replaced by 0.2, 0.4, 0.8, and 1% nanosilica with average sizes of 15 and 80 nm and surface areas of 640 ± 12 m^2/g and 440 ± 32 m^2/g (BET), respectively. The density was 0.14 g/cm^3 with 99.9% trace metal basis and melting point of 2040 °C (lit.) manufactured by Nanostructure & Amorphous Materials, Inc. (USA).

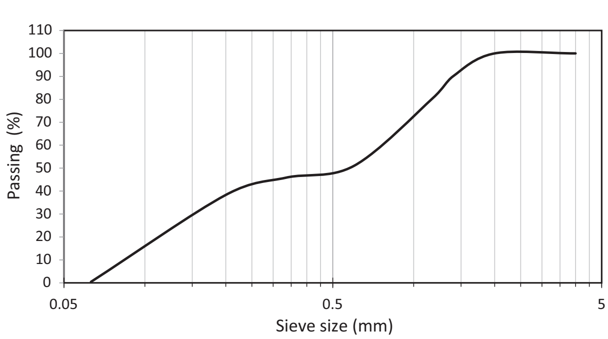

Fig. 1. Particle size distribution of the residual soil.

Table 1
Properties of the residual soil.

Properties	Value
Physical properties	
Natural water content (%)	21
Liquid limit (%)	51.48
Plastic limit (%)	30
Plasticity index (%)	20.48
Linear shrinkage (%)	12.12
Compaction properties	
Maximum dry unit weight (kN/m^3)	15.1
Optimum water content (%)	20
pH	4.01
Specific gravity	2.63
Unified soil classification system (USCS)	CL
Chemical properties	
Silica (SiO_2) (%)	71.3
Alumina (Al_2O_3) (%)	17.55
Iron oxide (Fe_2O_3) (%)	6
Potassium oxide (K_2O) (%)	1.5
Magnesia (MgO) (%)	0.17
Loss in ignition (%)	1

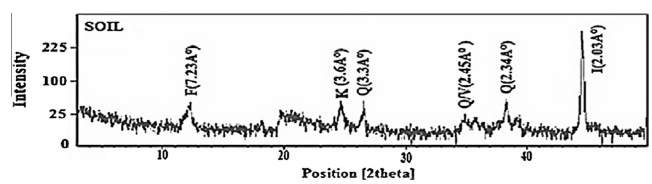

Fig. 2. X-ray diffraction pattern of the residual soil.

2.2. Sample preparation

A mini compaction apparatus devised by Asuri and Puvvadi [33] was used to prepare samples for unconfined compressive strength. The apparatus consisted of a mould with an internal diameter of 50 mm and a height of 100 mm with a falling hammer weighing 1.0 kg. Forty blows per layer were applied to three layers of soil. This apparatus is simple and quick to use, requires comparatively little effort, and saves on soil. Test specimens for compressive strength can be obtained quickly and with minimal disturbance. The specimens were comprised of the residual soil; cement treated soil with 6 and 8% cement with 0, 0.2, 0.4, 0.8, and 1% nanosilica as cement replacement to evaluate the compaction properties of untreated and treated samples. All the proportions were measured as percentage by weight of dry soil. Throughout this study, samples are denoted with cement percentage and nanosilica content and size, (e.g. 6% cement +0.2% SiO_2 −15 nm).

Table 2
Properties of the cement.

Properties	Value
Physical properties	
Specific gravity (g/cm^3)	3.12
Fineness	1.7
Chemical composition	
Silica (SiO_2) (%)	22.15
Alumina (Al_2O_3) (%)	5.3
Iron oxide (Fe_2O_3) (%)	4.48
Calcium oxide (CaO) (%)	63.74
Magnesia (MgO) (%)	1.03
Sulphur trioxide (SO_3) (%)	2.67
Sodium oxide (Na_2O) (%)	0.18
Loss on ignition (%)	0.41