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Stabilization of residual soil using SiO_2 nanoparticles and cement

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HIGHLIGHTS

- Compaction characteristics and consistency of the soil were improved by nanosilica.
- Compressive strength of the soil increased under effect of nanosilica.
- Hydraulic conductivity decreased when nanosilica was added.
- pH of cement treated soil decreased when nanosilica was added.

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ABSTRACT

An experimental study was performed to determine the effect of SiO_2 nanoparticles on consistency, compaction, hydraulic conductivity, and compressive strength of cement-treated residual soil. Also, SEM, XRD and FTIR tests were carried out to identify the underlying mechanisms. The addition of nanoparticles was found to advantageously affect the compactability, hydraulic conductivity. Besides, addition of 0.4% nanosilica to the cement treated soil improved the compressive strength by up to 80%. XRD, FTIR and SEM test results showed that silica nanoparticles promoted the pozzolanic reaction by transforming Portlandite into calcium silicate hydrate (C–S–H) gel.

1. Introduction

The use of stabilization techniques has increased significantly in recent decades owing to new construction sites, increasingly being located in areas of poor quality ground. It is suggested that ground improvement will be critically important in future geotechnical practices to adopt cost-effective solutions, to achieve reductions in quantities of material used and etc. [1–3]. One of the extensively used techniques for the improvement of problematic soils in relatively tropical countries is soil treatment with customary cementitous additives such as cement, lime and fly ash.

Cement is often used as an additive to improve strength and stiffness of residual soils in tropical areas. To achieve the maximum possible strength for base construction, addition of 6–10% cement in residual soils with plasticity indexes in the range of 10–20 has been recommended [4–6]. Furthermore, benefits of cement treated soil are not only limited to its enhanced strength but also the compressibility of the cement-treated soil has much higher pre-consolidation pressure than that of the untreated soil. High pre-consolidation pressure leads to a sharp decrease in the void ratio and permeability of the soil [5,7]. In regions where problems of groundwater intrusion exist, alteration of the permeability is often an important factor in the use of cement stabilization to construct cut-off walls [8,9]. So far, the effect of cement on some influential factors such as water content, curing time, and compaction energy and its role on the microstructure and engineering characteristics of cement-treated soils have also been extensively studied [6,10–12]. Improvement of the properties of cement-treated soil has been mainly attributed to a soil–cement reaction [10,13], which produces primary and secondary cementitious materials in the soil–cement matrix [5,7,14]. The primary cementitious materials are formed by hydration reaction and are comprised of hydrated calcium silicates (C_2SH_x, $C_3S_2H_x$), calcium aluminates (C_3AH_x, C_4AH_x), and hydrated lime $Ca(OH)_2$ [15–17]. 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. This soil–cement reaction provides a clear basis by which to explain the improvement in strength of stabilized soil.

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In recent years, nanoparticles have attracted considerable scientific interest for many civil engineering applications. The types of nanoparticles that are most commonly used in cementitous composites are SiO_2, TiO_2, Al_2O_3, and carbon nanotubes [18–21]. Of all the introduced nanoparticles, nano-SiO_2 plays the most significant role. Nanoparticles of SiO_2 exhibit high pozzolanic activity due to high amount of pure amorphous SiO_2 [21–23]. According to Sobolev et al. [20], the changes observed in mixtures modified with nano-SiO_2 particles are the result of a chemical reaction between SiO_2 and $Ca(OH)_2$ during cement hydration. Furthermore, nanosilica accelerates hydration of cement due to its high surface energy [20,21,24]. Also, nanosilica causes physical alterations such as improvement in the packing density which corresponds to filling effect of its particles [18,25–27]. Another known physical mechanism is nucleation effect by which hydration products envelop the particles and hence a denser matrix with better distributed hydration products is formed [24,28,29]. Experimental results have shown that a joining effect of physical and chemical properties of nanosilica results in up to 20% strength augmentation of cementitous composites [24].

This study addresses the development of cement-treated residual soil strengthened with nanosilica as a supplementary material. Inclusion of nanosilica may reduce the cement consumption in the soil and accelerate the stabilization process. This study tends to investigate changes in consistency, compaction and hydraulic conductivity as well as unconfined compressive strength of cement treated residual soil loaded with SiO_2 nanoparticles. To further elaborate the results, induced microstructural changes were also traced. Apart from clarifying the underlying mechanisms that lead to changes in engineering behaviour of residual soils due to the inclusion of SiO_2, the results may also be representative of the engineering behaviour of other low plasticity soils after stabilization with cement and nano-SiO_2.

2. Materials and methods

2.1. Materials

2.1.1. Soil

A typical residual soil, Malaysian granite soil, was used in this study. This soil was tested to determine its physical properties—its specific gravity, liquid limit (LL), plastic limit (PL), shrinkage limit and grain size distribution—using standard procedures specified in BS 1377-2 (1990) [30]. The particle size distribution curve for the soil is shown in Fig. 1. Table 1 shows the classification properties of the soil, which is an inorganic clay with high plasticity (CH). The consistency limits of the soil are a LL of 51.4% and a PL of 30%. The maximum dry density (MDD) and optimum moisture content (OMC) are 15.1 kN/m^3 and 20%, respectively. A characteristic X-ray diffraction (XRD) plot of the soil, shown in Fig. 2, indicates that the soil is predominantly a kaolinite clay mineral with a strong diffraction line at 3.6 A°, which disappears when the clay is heated to 550 °C.

2.1.2. Nanosilica

To investigate the effects of different sizes of SiO_2 nanoparticles on the properties of cement treated soil, particles with two different sizes of 15 nm and 80 nm in powder form were purchased from Nanostructure & Amorphous Materials, Inc., (USA). Table 2 shows the chemical and physical properties of nanosilica particles.

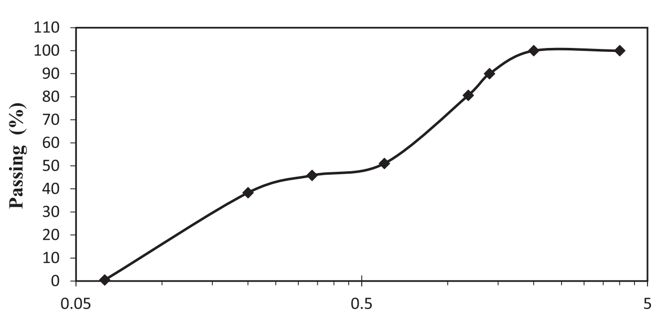

Fig. 1. Particle size distribution of the residual soil.

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) (%)	15.55
Iron oxide (Fe_2O_3) (%)	6
Potash (K_2O) (%)	1.5
Magnesia (MgO) (%)	0.17
Loss in ignition (%)	1

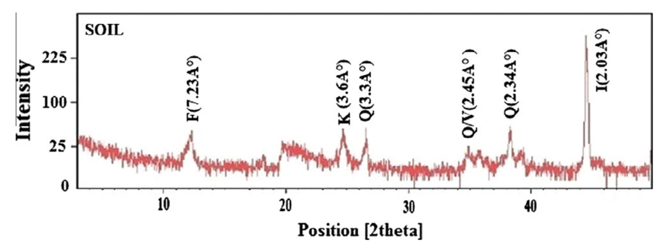

Fig. 2. X-ray diffraction of the residual soil.

2.1.3. Portland cement

An ordinary Portland cement (OPC Type I) in compliance with ASTM C150, obtained from the cement manufacturing company (Phoenix) in Malaysia, was used in this study. The physical and chemical properties of the cement are given in Table 3. The particle size distribution of the Portland cement particles, as determined by the BET method, is illustrated in Fig. 3. The specific gravity of the cement is 1.7 g/cm^3.

2.2. Laboratory tests

2.2.1. Atterberg limits

The Atterberg limits of the soil were determined in accordance with BS 1377-2 [30]. The residual soil was graded using a sieve with a diameter of 425 mm. The particles retained on the sieve were rejected. The particles smaller than 425 mm were then oven dried for at least 2 h prior to testing. Atterberg limit tests were carried out on the soils with different proportions of cement and nanoparticles.

2.2.2. Sample preparation

A modified Proctor compaction tests were carried out using a mini compaction apparatus devised by Sridharan and Sivapullaiah [31]. The apparatus consisted of a mould with an internal diameter of 48 mm and a height of 98 mm with a falling hammer weighing 1.0 kg. Forty blows per layer were applied to three layers of soil [31]. This apparatus is simple and quick to use, requires comparatively little effort, and saves on soil. Samples for strength tests can be obtained quickly and with minimal disturbance. The compaction tests were carried out on the residual soil, cement treated soil with 4%, 6%, and 8% cement with 0%, 0.2%, 0.4%, 0.8%, and 1% nanosilica to evaluate the compaction properties of untreated and treated soils. All the proportions are measured as percentage by weight of dry soil.

Table 2
The physical properties of SiO_2 nanoparticles (adapted from Nanostructured & Amorphous Materials, Inc., USA).

Diameter (nm)	Specific surface area (m^2/g)	Density (g/cm^3)	Purity (%)
15 ± 3	640 ± 12	<0.14	>99.9
80 ± 9	440 ± 32	<0.14	>99.9