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Improvement of soft clay with cement and bagasse ash waste

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HIGHLIGHTS

- The construction material "CBA-admixed soft clay" is created.
- The replacement of OPC with BA can enhance the strength as much as OPC alone.
- 20% BA is optimal because of appropriate proportions of SiO_2 (from BA) and $Ca(OH)_2$.
- Average strength losses of 42.5 and 22% are observed due to soaking.
- The void ratio, curing time, CSH and Et products affect strength development.

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ABSTRACT

The main objective of this study is to assess the effectiveness of bagasse ash (BA), a type of agricultural waste from the sugar industry, as an admixture to improve the unconfined compressive strength, chemical composition and microstructural properties of soft clay. Ordinary Portland cement (OPC) type I is partially replaced with BA and mixed with soft clay to generate CBA-admixed soft clay. The test results show that the replacement of OPC with BA can enhance the strength by as much as that of OPC alone, and 20% BA is considered optimum. The correlation between the modulus of elasticity and the unconfined compressive strength can be expressed as a linear function. The loss of strength due to soaking during the early stage is higher than that during the final stage. Multiple regression analysis is conducted to predict the strength while accounting for four parameters that affect strength development, namely, the after-curing void ratio, the curing time, and the concentrations of the calcium silicate hydrate and the ettringite products.

1. Introduction

The improvement of soft clay properties has been performed widely to mitigate problems in civil engineering projects that result from construction on top of soft clay deposits. It is well known that soft clay has a low shear strength and high compressibility [1]. Chemical stabilization is used extensively in deep soil mixing techniques in which a cement-based slurry is mixed with the existing soft clay [2]. The resistance of stabilized soft clay to compression and the resulting increase in the strength of stabilized soft clay will increase as the curing time increases. Type I ordinary Portland cement (OPC) is commonly used as a cementing agent to improve the properties of soft clay because of its compressive strength, high bearing capacity and low compressibility for various applications [3,4]. However, OPC is both valuable and expensive, resulting in higher construction costs. The feasibility of using cheap pozzolanic materials to replace OPC has been studied [5]. Pozzolanic materials are SiO_2- and Al_2O_3-based materials that react with the calcium hydroxide generated by hydrating cement to form additional cementitious materials that, in themselves, generate little to no cementing functionality. Industrial waste is increasingly being considered as a soil stabilizer. By-products such as sludge and bottom ash have been observed and found to be useful as pozzolanic materials for the improvement of the properties of fine-grained soils [6,7]. Another interesting material that could be used to replace OPC is bagasse ash (BA). BA is a by-product of natural agricultural waste that is generated during bagasse

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Notation

A and *B*	dimensionless constants	OPC	ordinary Portland cement
BA	bagasse ash	p_a	atmospheric pressure
CBA	cement bagasse ash-admixed soft clay	q_u	strength of CBA-stabilized soft clay
CSH	calcium silicate hydrate gel	$q_{u,D}$	strength of CBA-stabilized soft clay after *D* days of curing
D	curing time (day)	$q_{u,28}$	strength after 28 days
D_{50}	diameter at which 50% of the particles have a smaller diameter	SEM	scanning electron microscopy
e_{ot}	void ratio after the curing time	XRD	X-ray diffraction
Et	ettringite	XRF	X-ray fluorescence
E_{50}	modulus of elasticity at 50% of the q_u value		

combustion in the sugar industry. BA can be used as a mineral admixture in mortar and concrete because its chemical composition is appropriate for use as a pozzolan, mainly due to its high silica content [8,9]. Several studies have been conducted to investigate the chemical effects and pozzolanic activity of BA and have indicated that BA is a pozzolan that improves the performance of concrete when mixed with cement [9–12].

Many researchers have reported that BA exhibits satisfactory behavior as a blended cementitious material in concrete and has great potential for use in other applications [13]. BA can be ground to obtain fine particles and then added to concrete to produce high-strength concrete. The use of 10–30% BA in concrete (by dry weight) was observed to increase the concrete strength and decrease the concrete porosity and resistance to chloride penetration because the fineness of BA contributes to a finer pore structure, which reduces chloride permeation and diffusion [14]. The replacement of cement with 20% BA by dry weight was optimum, and the strength of the soil increased with curing time. The main advantage of using BA is that it reduces chloride diffusion by more than 50% without negatively affecting the other properties of the hardened concrete [15]. The addition of 10% BA increased the compressive strength of cement paste at all hydration ages [10]. As a construction material, clay and BA can be combined to produce bricks with properties similar to the properties of original clay bricks. Previously, it was found that BA can be used as a filler material in clay bricks to reduce the use of natural raw materials [16]. The chemical deterioration of blended cement is also reduced due to the pozzolanic nature of BA and the reduced permeability of BA-containing mixtures [15,17]. In summary, the most common pozzolanic materials used for the improvement of the engineering properties of soft clay are OPC, lime, fly ash, bottom ash and industrial waste.

However, a limited number of studies on the use of BA as a stabilizer for soft clay have been reported. The main objective of the study is to determine the compressive strength of soft clay stabilized using OPC alone and OPC partially replaced with BA. Based on compressive strength tests, an optimum ratio of BA replacement is proposed. The development of strength in the stabilized soil is investigated relative to curing time, the changes of the structure of the stabilized soft clay are observed using scanning electron microscopy (SEM), and the products resulting from the chemical reactions of the soil and cement are observed using X-ray diffraction (XRD).

2. Materials and Methods

2.1. Materials

The clay used in this study is typical soft Bangkok clay that was excavated from the site of a condominium building project near the Chaophraya River in Nonthaburi Province, Thailand. Soil samples were collected at depths of 3–8 m from the original ground level. The basic physical and engineering properties of the soft clay are listed in Table 1. The natural water content, wet unit weight and specific gravity were 81%, 15.18 kN/m^3 and 2.68, respectively. The liquid and plastic limits were 78 and 34, respectively, which correspond to a plasticity index of 44. The undrained shear strength obtained using the torvane test was 14.5 kPa, which indicated that the soil is classified as soft clay. Based on the Unified Soil Classification System, the soil is classified as inorganic clay with high plasticity (CH). This soft clay is too soft and weak to support upper infrastructures in construction projects, which makes it an excellent candidate for soil improvement. The cement used in this study was type I OPC according to the standard industrial cement TIS 15-2547 [18] and ASTM standard C-150 [19]. The specific gravity and fineness of OPC are 3.15 and 2900 cm^2/g, respectively. The BA employed in this study was obtained from a cleaning boiler at a sugar production factory in Singburi Province, Thailand. The BA was burned at a temperature of approximately 600–800 °C to generate electricity. No standard for burning temperatures exists. However, ranges of such temperatures are optimum to obtain BA that contains amorphous silica, which is able to react with calcium hydroxide. The specific gravity of the BA was 2.35, and the fineness of the BA ranged from 2800 to 3000 cm^2/g after grinding for 30 min.

Table 2 shows the chemical composition of the soft clay and BA compared with that of OPC according to X-ray fluorescence (XRF) spectrometry. The soft clay contains 62.5% silicon dioxide (SiO_2), 18.14% aluminum oxide (Al_2O_3), 8.49% ferric oxide (Fe_2O_3), 2.35% magnesium oxide (MgO), and 1.07% calcium oxide (CaO). Note that all compositions are considered inert relative to those of OPC and BA. The total amount of the major components (SiO_2, Al_2O_3 and Fe_2O_3) in the BA was 86.1%. The $SiO_2 + Al_2O_3 + Fe_2O_3$ content of the BA accounts for more than 70% of the total composition, which is higher than the limited value specified by ASTM C618 [20] for a class N pozzolan material. Thus, the BA used in this study had a high pozzolanic composition and could be used for the partial replacement of OPC to improve the quality of soft clay. A small amount of CaO was found in BA (5.9%). In the ash collecting process, lime powder ($CaCO_3$) was sprayed to transform SO_3 from the gaseous to the solid form. The by-product was gypsum ($CaSO_4$) intermixed in the BA. Based on chemical composition, OPC mainly consists of CaO (69.5%), with minor amounts of SiO_2 (16.3%), Al_2O_3 (3.72%) and Fe_2O_3 (3.55%) oxides. In addition, chemical analysis indicated that the silica content of BA is three times higher than the silica content of OPC. BA contains considerable amounts of Al_2O_3 and Fe_2O_3 but lower concentrations of CaO relative to OPC.

The grain size distribution curves of the OPC and BA were obtained via laser particle size analysis, and the grain size distribution curves of the soft clay were obtained using a hydrometer. These curves are plotted together for comparison, as shown in Fig. 1. The D_{50} (i.e., the diameter at which 50% of the particles have a smaller diameter) of the OPC and BA were 0.015 and 0.018 mm (15 and 18 μm), respectively, while the D_{50} of the soft clay was 0.005 mm (5 μm). Thus, the average particle sizes of OPC and BA were similar, and the average particle size of the soft clay was approximately three times smaller than the average particle sizes of the OPC and BA.

Table 1
Properties of unstabilized soft clay soils.

Property	Value
Natural moisture content (%)	81
Specific gravity	2.68
Initial void ratio	2.16
Wet unit weight (kN/m^3)	15.18
Undrained shear strength (kPa)	14.5
Liquid limit (%)	78
Plastic limit (%)	34
Plasticity index (%)	44
Unified soil classification	CH