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Strength properties of an epoxy resin and cement-stabilized silty clay soil

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ABSTRACT

The use of new materials for soil strengthening is crucial for geotechnical engineering, especially in the methods commonly used for ground improvement, such as deep mixing. The main objective of this study was to investigate the potential use of two-component water-soluble epoxy resins to improve the mechanical properties (compressive strength, splitting tensile strength, elastic modulus, shear strength parameters, and long-term mechanical behavior) of silty clay soils because the efficacy of these resins for soil strengthening has not yet been properly investigated. The experiments were conducted using soil mixes with different epoxy resin-to-water ratios, solid-to-water ratios and cement contents, cured at different ages. The results of this study indicate that most of the epoxy resin-treated soil samples, even with the adverse influence of water content on the development of strength, appeared to have noticeable strength improvement after a curing period of 90 days. The addition of cement significantly improved the strengths of all mixes at all curing ages. The values of the strength parameters increased with cement content. This increment in strength for epoxy resin/cement-treated specimens could be mainly attributed to the consumption of large quantities of water from cement compounds, which results in the promotion of polymerization of the epoxy resin with the hardener.

1. Introduction

The deep mixing method (DMM) is now accepted worldwide as a soil improvement method. The DMM is based on mixing binders, such as cement, lime, fly ash, gypsum and other additives, with the soil by the use of rotating mixing tools in order to form columns of a hardening material due to the pozzolanic reactions that occur between the binder and the soil grains (Porbaha, 1998, 2002; Sukontasukkul and Jamsawang, 2012; Voottipruex and Jamsawang, 2014). These DMM piles act as ground reinforcements, thereby increasing the load bearing capacity of the ground (Jamsawang et al., 2011; Voottipruex et al., 2011a,2011b). The DMM method is often applied in many geotechnical and foundation applications, such as the stabilization of deep excavations or high embankments, slope stability, tunnel support, the reduction of settlement or the increase of bearing capacity of soft compressible soils for building foundations, and water retention (Bergado et al., 1999; Lin and Wong, 1999; Moseley and Kirsch, 2004). Among the binding agents used in the DMM, cement is most commonly adopted because of its appreciable improvement of soil properties, lower cost, and easier storage (Bergado et al., 1996; Khattak and Alrashidi, 2006). However, in many cases of soft clay soils, laboratory and in situ research work has shown that the material of deep cement mixing (DCM) piles has low strength and stiffness, and consequently this type of pile is not suitable for medium or high design load constructions (Kamruzzaman et al., 2000; Horpibiulsuk et al., 2002; Petchgate et al., 2003, 2004; Ahnberg et al., 2003; Puppala et al., 2003; Tabbaa, 2003; Wu et al., 2005; Impe and Flores, 2006; Lorenzo et al., 2006; Horpibulsk et al., 2011; Pakbaz and Alipour, 2012; Khemissa and Mahamedi, 2014). Additionally, the detrimental influence of some factors, such as high water or organic matter content of a soil (Saride et al., 2013) and the pH value (Yang et al., 2013), on the strength of the soil–cement mixture renders the application of the DCM impractical in many cases. It is therefore important to aid in the research and development of new materials or additives that, when mixed with clay soil alone or in combination with cement, could yield a more appreciable improvement in the strength of the solidified mixture than that with net cement.

With the development of modern construction materials, a category of non-traditional chemical solutions, such as resins and co-polymer emulsions, has been suggested by some researchers (Anagnostopoulos et al., 2003; Al-Khanbashi and Abdalla, 2006; Estabragh et al., 2011) as agents that can significantly improve the mechanical properties of soil or soil–cement mixtures. In particular, epoxy resins are one of the principal resins used for ground improvement purposes. They generally consist of two components, epoxy resin and hardener. When these two components are mixed, a chemical reaction begins that initiates the hardening of the epoxy. The epoxy molecule itself reacts again and again, growing in size, in a process called polymerization. This process of polymerizing and interlinking with surrounding molecules that are

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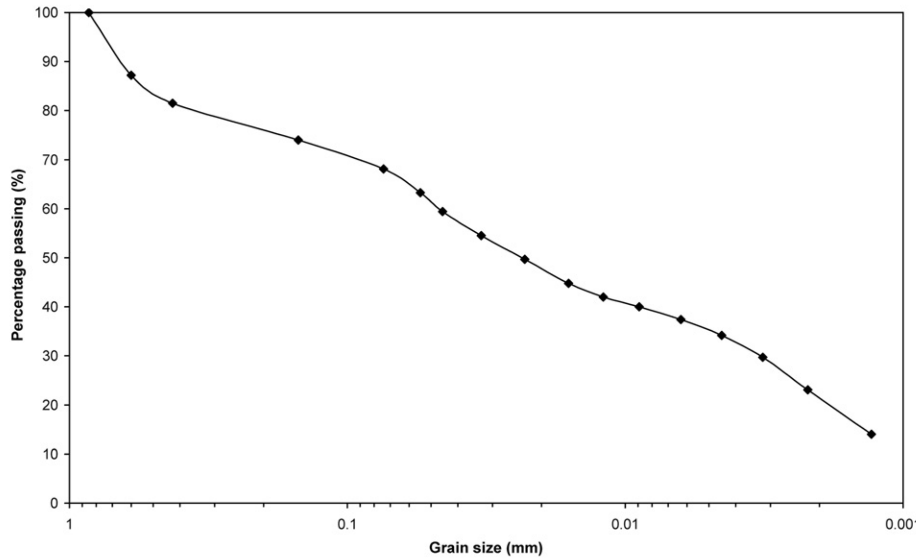

Fig. 1. Grain size distribution of the silty clay soil.

also polymerizing leads to the strong epoxy structure. The final product is characterized by high strength under compression and tension; a strong bond; high durability; high resistance to acids, alkalis, and organic chemicals; and low shrinkage when cured. In addition, some epoxies may be diluted with water up to twice their volume to provide a low-cost product and can be used for stabilizing soils with high water content in their natural state.

Although numerous studies have been conducted concerning the application of epoxy compounds for structural repair or in fractured concrete (Issa and Debs, 2007), there are limited published data (Ajayi et al., 1991; Anagnostopoulos and Hadjispyrou, 2004; Anagnostopoulos and Papaliangas, 2012) on the efficacy of epoxy resins, especially low-cost water-soluble epoxy resins, for soil strengthening and deep mixing applications.

To increase the knowledge regarding the use of new polymer additives in the chemical stabilization of soft soils, the main objective of this laboratory project was to investigate the effect of two-component water-soluble epoxy resin solutions, alone or in combination with cement, on the mechanical properties of a silty clay soil.

2. Materials

The soil samples used in the experiments were collected from the greater area of the city of Thessaloniki (Greece) at a depth between 1.5 and 2 m of depth in a layer of yellowish brown clay (Tsirambides, 2004). The soil gradation (Fig. 1) was determined using the sieve analysis and the hydrometer test according to the ASTM D 6913-04 and ASTM D 422-63 methods, respectively. The grain size distribution curve of the soil indicates that it is composed of 18.5% medium sand ($0.425 < d < 2$ mm), 13.5% fine sand ($0.074 < d < 0.425$), 33.8% silt ($0.005 < d < 0.074$ mm) and 34.2% clay ($d < 0.005$ mm). The soil does not contain any organic matter, as it was examined according to the ASTM D, 2974-07a method. It is classified as a CL (low plasticity clay) according to the Unified Soil Classification System (USCS). Oedometer tests were carried out on soil specimens of 63.3 mm in diameter and 25.4 mm in height that were extracted from undisturbed samples according to the ASTM D, 2435-04 specification. The results of the consolidation tests were used for obtaining plots of the void ratio (e) versus the consolidation stress ($\log\sigma'_v$) from which the consolidation characteristics of the soil were determined. The in situ void ratio was estimated from the $e - \log\sigma'_v$ curve as the void ratio corresponding to the in situ effective vertical stress. The method used for the determination of the specific gravity of the soil is the one proposed by ASTM D 854-02. The geotechnical properties of the silty clay soil are presented in Table 1. The shear strength parameters were obtained from unconsolidated undrained triaxial compression tests on undisturbed soil samples. The friction angle was 11.2° and the cohesion was 3.2 kPa.

Experiments were carried out using a common type of Portland fly ash-pozzolan cement (CEM II/B-M (P-W-L) 42.5 N) according to EN 197-1 with sulfate resistance properties and a low heat of hydration. It has a specific gravity of 3.15 and a Blaine fineness of approximately 4600 cm^2/g.

The chemical composition of the soil and cement is presented in Tables 2 and 3, respectively. The chemical composition of the materials

Table 1
Geotechnical properties of the silty clay soil used in the study.

Parameter	Value
Depth (m)	1.5–2
Natural water content w (%)	20.2
Liquid limit (%)	32.6
Plastic limit (%)	19.4
Plasticity index (%)	13.2
Specific gravity γ_s (−)	2.66
Activity of clay A_c (−)	0.4
Compression index C_c (−)	0.19
Recompression index C_s (−)	0.04
Overconsolidation ratio OCR (−)	1.8
Preconsolidation pressure σ'_P (kPa)	36
In-situ unit weight γ (kN/m^3)	17.6
In-situ void ratio e (−)	0.71
Consistency index I_c (%)	0.56
Classification of soil (USCS)	CL

Table 2
Chemical composition of the silty clay soil.

Constituents	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	SO_3	K_2O	Na_2O	L.O.I.
%	64.3	1.3	1.5	5.9	15.4	0.01	2.1	1.4	8.1

Table 3
Chemical composition of the cement.

Constituents	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	SO_3	K_2O	Na_2O	L.O.I.
%	26.7	46.8	3.5	4.3	7.5	3.1	0.8	1.2	6.1