



Analysis of strength development in cement-treated soils under different curing conditions through microstructural and chemical investigations

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HIGHLIGHTS

- The strength development of cement-treated soils was quantitatively investigated.
- Carbonation and cement hydration/pozzolanic reaction interactions were considered.
- Sand, sand-loam, and sand-bentonite were cured under sealed and drying conditions.
- Under sealed conditions, the strength of all mixtures steadily increased.
- Under drying conditions, behaviors varied with soil mineralogy.

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ABSTRACT

This study investigated the strength development of cement-treated soils by considering not only the interactions among cement hydration and pozzolanic reaction, but also the carbonation process. Indeed, the chemical and microstructural changes in cement-treated soils are due to carbonation combined with previous reactions and no studies took into account all processes at the same time. Three soil specimen types (specifically, sand, sand-loam, and sand-bentonite mixtures) were cured under sealed and drying conditions and their unconfined compressive strength, microstructural and chemical properties subsequently measured over time. Under drying conditions, behaviors varied with soil mineralogy. The compressive strength of all mixtures significantly increased with decreasing total micropore induced by carbonation and suction effects. However, in the sand-clay mixture under long-term drying, the compressive strength remained constant or slightly decreased after 28 days, correlating with the increase in large capillary pore caused by shrinkage of bentonite and C–S–H carbonation. These results revealed that carbonation could have both positive and negative impacts on strength development of cement-treated soils.

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1. Introduction

Cement-treated soils are applied extensively throughout the world for soft-ground improvement. The compressive strength of cement-treated soils is usually considered as a key parameter to characterize soil behavior [1–7]. Short-term strength development in cement-treated soils is mainly produced by cement hydration, whereas long-term strength development is attributed to poz-

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zolanic reaction [8,9]. Detailed investigations of the contribution of both processes have been conducted with X-ray diffraction (XRD) and mercury intrusion porosimetry (MIP) techniques [10–13]. However, not only cement hydration and pozzolanic reaction, but also carbonation and water content simultaneously affect the strength of cement-treated soils under drying conditions [14–16].

The strength development of cementitious materials can be generally explained by pore structure formation. Indeed, the compressive strength measured on cement paste increases with decreasing porosity (i.e., increasing hydrated cement products) [17,18]. Numerous studies have been conducted with particular focus on pore structure associated with cement hydration, pozzolanic reaction, and carbonation in the field of cement and concrete [19–25].

It is well known that pozzolanic reaction between hydrated cement products and admixture particles (e.g., fly ash and metakaolin) produces additional calcium silicate hydrates (C–S–H) and/or calcium aluminate hydrates (C–A–H), which compose the gel pore volume of cement paste [19–21,26,27]. As a result, the pore structure of the blended cement paste over the long term is finer than that in neat cement paste [19–21]. Conversely, the carbonation effect on concrete microstructure shows two different trends. A few studies [28–31] have shown that carbonation reduces the porosity of Portland cement paste because the molar volume of CaCO_3 is greater than that of other hydrates, which is at the origin of a reduction in total porosity. On the other hand, carbonation of cement paste in the presence of mineral admixtures increases the total porosity of the material, composed initially in large part of C–S–H produced by pozzolanic reaction, and such pozzolanic reaction may generate a poorly-hydrated silica gel of a low molar volume [24,25,32].

In addition, several researchers [33–36] have stated that carbonation causes shrinkage in cement paste. The carbonation shrinkage could be initiated in the C–S–H phase [34,35]; Chen et al. [34] pointed out that carbonation shrinkage is a side effect of decalcification. Indeed, carbonation of C–S–H is associated with a decrease in the Ca/Si ratio and the degree of polymerization in C–S–H increases because of the removal of interlayered Ca cations when $\text{Ca/Si} < 1.2$ [36]. The polymerization of the silicate chains in C–S–H is the direct source of shrinkage and carbonation may also induce cracking [35,37,38].

In the geotechnical field as well as in the concrete domain, researchers have definitively accepted the fact that cement hydration, pozzolanic reaction, and carbonation have significant effects on the microstructure of cementitious materials and the microstructure governs the strength development. Studies on the microstructure of lime/cement-treated soils [11,39–43] have found, for example, that cement hydration and pozzolanic reaction can reduce total pore volume and increase the gel pore volume, resulting in strength increment after chemical reactions. Therefore, the investigation reported in this paper is based on the coupling of the change in strength of cement-treated soils and reactions observed through the chemical and microstructural point of view. The strength development of cement-treated soils is clearly explained by chemical and microstructural changes caused by cement hydration and pozzolanic reaction [11,39–43]. However,

to the best of our knowledge, no studies have stated clearly that the chemical and microstructural changes are due to carbonation combined with previous reactions. Thus, this study investigated the strength development when coupled reactions (cement hydration, pozzolanic reaction, and carbonation) are considered. Various conditions were applied: seven curing periods, two curing conditions (e.g., under drying and sealed conditions), and three soil types. Thermal analysis (TG-DTA), powder X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP) were used to explain the compressive strength development, measured by an unconfined compression test. This paper is an extension of previous study [15], in which only two kinds of materials (specifically, sand and sand-loam mixtures) were tested for three months. In this study, long-term measurements were conducted (a period of one year) with three types of specimens, including sand-bentonite mixture.

2. Materials and methods

2.1. Materials and specimens

2.1.1. Materials

Toyoura silica sand was chosen to study sand, sand-loam, and sand-bentonite mixtures with cement, because of its recognition as a natural standard sand for experiments in Japan. Kanto loam, produced in Kasama (Japan), is a kind of volcanic cohesive fine material, while bentonite (Kunigel V1), produced in Yamagata (Japan), is a commercial swelling clay. Mixtures were prepared with ordinary Portland cement (OPC). Table 1 presents the characteristics of the cement, sand, loam, and bentonite. Specific densities and particle size distributions were measured based on French standards [44–46]. The particle size distributions of pure materials (sand, loam, and bentonite) and mixtures are shown in Fig. 1.

2.1.2. Specimen preparation

Three kinds of specimens were obtained by mixing sand, sand-loam, or sand-bentonite with OPC and tap water. The designed values of the specimens are listed in Table 2. The added water in the mixture was chosen to be equal to the cement quantity ($W/C = 100\%$) and this value of water addition is also referred to as standard compaction of Toyoura silica sand in the Japanese standard.

Table 1
Characteristics of ordinary Portland cement (OPC), Toyoura silica sand, Kanto loam, and bentonite.

Characteristics	Methods	OPC	Sand	Loam	Bentonite
Loss on Ignition (LOI) ^a %	TG-DTA	2.8	0.37	9.94	5.32
SiO ₂ %	ICP/OES	20.2 [*]	92.54 [*]	57.24 [*]	75.30
Al ₂ O ₃ %	ICP/OES	5.2	2.96 [*]	18.87 [*]	15.43
Fe ₂ O ₃ %	ICP/OES	3.0 [*]	0.35 [*]	4.56 [*]	0.50
CaO%	ICP/OES	64.0 [*]	0.19 [*]	0.79 [*]	1.87
MgO%	ICP/OES	1.0 [*]	0.05 [*]	1.20 [*]	2.41
K ₂ O%	ICP/OES	0.4 [*]	2.75 [*]	2.45 [*]	0.37
Na ₂ O%	ICP/OES	0.3 [*]	0.58 [*]	0.84 [*]	3.51
SO ₃ %	ICP/OES	2.1 [*]	0.02 [*]	0.11 [*]	0.48
TiO ₂ %	ICP/OES	–	0.10	0.60 [*]	0.05
MnO%	ICP/OES	–	<0.01 [*]	0.07 [*]	0.02
P ₂ O ₅ %	ICP/OES	–	0.02 [*]	0.06 [*]	0.03
BaO%	ICP/OES	–	0.05 [*]	<0.01 [*]	0.02
Cl%	Given by OPC supplier	0.0181	–	–	–
Free lime%	Given by OPC supplier	0.9	–	–	–
Specific densities (t/m ³)	NF P94-054	3.15	2.65	2.79	2.60
% <2 μm	NF P94 057	–	0	14.1	49.5 ^{**}
% <80 μm	NF P94 056	–	0.1	78.7	97.8 ^{**}
% <300 μm	NF P94 056	–	100	84.8	100 ^{**}

^a Loss on Ignition (LOI) was obtained from 105 to 1000 °C using TG-DTA measurement.

^{*} Data obtained from previous study [15].

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