



Effect of internal water content on carbonation progress in cement-treated sand and effect of carbonation on compressive strength



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ABSTRACT

This study investigates the effect of internal water content in cement-treated sand on carbonation progress and the effect of carbonation on compressive strength. To alter the internal water content, specimens were cured under three conditions: sealed, drying, and water sprayed. The carbonation coefficient, which was determined by a phenolphthalein spray test, decreased as the internal water content increased because of water sprayed. However, a thermal analysis revealed that the amounts of portlandite consumed and calcium carbonate generated by carbonation exhibited dissimilar trends: the amount of generated calcium carbonate was the maximum when there was a small increase in water content by water sprayed. Further increments in water content significantly lowered the amount of generated calcium carbonate. The measured compressive strength increased linearly with the amount of calcium carbonate. This implies that the amount of calcium carbonate is a good indicator of the effect of carbonation on the strength development of cement-treated sand and that both these quantities are affected by the internal water content.

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1. Introduction

Cement-treated soils or cement-stabilized soils are used widely in many countries for constructing road bases, earth dams, and other foundation structures because of their improved properties. Previous studies on cement-treated soils focused mainly on compressive strength as the key material property [1–6]. It was reported that the strength of cement-treated soils can be affected by carbonation [7–10] in addition to materials used, mix proportions, and curing conditions [11,12]. Carbonation is the process whereby carbon dioxide (CO₂) in the ambient air penetrates cementitious materials (e.g., cement-treated soils, concrete, and mortar) and reacts with cement hydrates, such as portlandite (Ca(OH)₂) and calcium silicate hydrate (C–S–H), to form calcium carbonate (CaCO₃). The carbonation process of cementitious materials depends on several parameters such as those related to mix

proportion (e.g., water/cement ratio, cement type, and cement content) and environmental conditions (e.g., curing condition, relative humidity, temperature, and CO₂ concentration).

In the field of concrete engineering, there are numerous studies on the carbonation of concrete that discuss the durability of concrete structures [13–19] and the relevance of the carbonation of concrete to environmental conservation [20–22]. In reinforced concrete structures, carbonation is disadvantageous because it decreases the pH in concrete. This decrease destroys the passive film around the rebar, thus rendering the steel vulnerable to corrosion [18,19]. On the other hand, studies on the carbonation of concrete and recycled concrete have revealed that carbonation can improve the properties of concrete. For example, it may decrease permeability, and increase compressive strength and splitting strength in its early stage [22–25]. In addition, a few researchers have focused on the contribution of carbonation to CO₂ uptake by concrete structures from the perspective of global climate change [20,21]. For example, Yang et al. [21] estimated that the amount of CO₂ uptake resulting from concrete carbonation offsets 15.5–17.0% of the CO₂ emissions from concrete production.

The rate of carbonation in cementitious materials depends on the physico-chemical properties of these materials. In general, the

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rate is much higher in cement-treated soils than in concrete because of the larger porosity of soil. In addition, as reported in previous studies [8,26], the concentration of carbon dioxide beneath pavements could be substantially high because of the decomposition of vegetation and emissions from bituminous surfacing materials. Nakarai and Yoshida [9] and Ho et al. [10] indicated that carbonation can increase the strength of cement-treated sand; in contrast, some studies reported that carbonation decreased the compressive strength of cement-treated soils [7,8]. Whiffin et al. [27] also reported that microbially-induced carbonate precipitation can increase the compressive strength of bacteria-treated soils through the increase in the calcium carbonate content. Because of the limited amount of research as well as the lack of knowledge on the process of the carbonation of cement-treated soils, the process and its effect on material properties of cement-treated soils need to be investigated.

In the field of concrete, many studies of the carbonation process focused on extensive investigations into the effects of relative humidity [28–30]. In the case of concrete at low relative humidity, CO₂ gas diffusion happens at a high rate; however, the lack of water leads to a low rate of carbonation [31–33]. On the other hand, in the case of concrete at high relative humidity, water can fill in connective pores. This impedes CO₂ diffusion and leads to a low rate of carbonation [31–33]. Thus, at an optimum relative humidity, the carbonation rate is at its maximum. It was reported that the optimum relative humidity for the carbonation of concrete is approximately 50–70% [31,34–36]. The internal relative humidity of concrete is characterized by its internal water content, which depends on environmental conditions at the site or curing conditions in the laboratory. In the case of laboratory curing, the internal water content of specimens can be modified by water sprayed or submerging into water. Fattuhi [35,37] reported that initial water curing considerably affected the carbonation of concrete.

Compared to the volume of research on concrete, few studies have been conducted on the influence of parameters related to the carbonation of cement-treated soils on the strength of soil. Some studies revealed that altering the internal water content via sprayed water can affect carbonation and in turn influence the strength of cement-treated soils [7,8,38]. However, the effect of the change in the internal water content (through sprayed water) on the carbonation process parameters (e.g., carbonation rate and the carbonate concentration profile) as well as on compressive strength have not yet been reported adequately. Therefore, there is a need to investigate in detail the influence of parameters related to carbonation (e.g., internal water content) and that of carbonation on strength development of cement-treated sand.

The aim of this study is to investigate the effect of internal water content on the carbonation progress of cement-treated sand and the effect of carbonation on unconfined compressive strength. To alter the internal water content in this experimental study, specimens were cured under different conditions such as sealed, allowed to dry normally (termed 'drying'), and water sprayed. In order to assess the progress of carbonation, the Ca(OH)₂ and CaCO₃ contents were quantitatively analyzed by thermogravimetric analysis, and the carbonation depth was measured by a phenolphthalein spray test. The contribution of carbonation to strength development was then evaluated.

2. Materials and measurements

2.1. Materials and specimens

2.1.1. Mix proportions, mixing, and compaction

Because this is a fundamental study investigating the effect of internal water content on the carbonation process and the effect of

carbonation on strength development through water-sprayed method, cement-treated sand was used in this study. Specimens were prepared by mixing Toyoura silica sand, ordinary Portland cement, and tap water. Toyoura silica sand used to be a standard sand for experiments in Japan that has the particle size shown in Table 1, and ordinary Portland cement is the standard cement in JIS R 5201 (similar to the 52.5N strength class cement). This preparation process was largely based on the JGS 0811–2000 standard by the Japan Geotechnical Society. The specific densities of sand and cement were $2.65 \times 10^3 \text{ kg/m}^3$ and $3.15 \times 10^3 \text{ kg/m}^3$, respectively. The partial analysis of cement and sand were determined by inductively coupled plasma (ICP) and shown in Table 1. The designed values of cement content (ratios of cement to dried sand by weight), water content of the sand, and the density of fresh specimen were 8% w/w, 8% w/w, and $1.70 \times 10^3 \text{ kg/m}^3$, respectively. Based on these values, the porosity and water content were calculated to be 30.0% v/v and 7.4% w/w, respectively.

As the first step, dried sand and water were mixed using a mechanical mixer for 1 min to control the water content. Then, the mixture was stirred by hand for 1 min to remove material attached to the bowl and the paddle of the mixer. Thereafter, the mixture was mixed again in the mixer for 1 min. Subsequently, cement was added to the mixture and incorporated into it by operating the mixer for 1 min. Following this step, the mixture was stirred by hand for 1 min to achieve high homogeneity. Finally, the mixture was mixed in the mixer for 1 min. After this mixing process, cylindrical specimens 100 mm in diameter and 200 mm in height were cast by compaction, using a rammer with a weight of 2.5 kg; this process is largely based on the JCAS L-01:2006 standard. Each specimen had three layers; the height of each layer was approximately one third of the height of the specimen. The rammer was dropped 38 times from a height of 300 mm onto each layer of each specimen. Although the specimens were prepared in several batches because of the limitation of mixer and space in the laboratory, the quality of mixing was verified by preliminary experiments and checking specimen densities.

2.1.2. Curing conditions

To investigate the effect of internal water content on the carbonation of cement-treated sand, the specimens were cured under three conditions: sealed, drying, and water sprayed. The number of specimens for each condition (protocol) is shown in Table 2; whereas each set at each age had three specimens. As

Table 1
Partial analysis of the ordinary Portland cement and Toyoura silica sand (%).

Chemical composition	Ordinary Portland cement	Toyourea silica sand
Ignition loss	2.8	0.37
SiO ₂	20.2	92.54
Al ₂ O ₃	5.2	2.96
Fe ₂ O ₃	3.0	0.35
CaO	64.0	0.19
MgO	1.0	0.05
SO ₃	2.1	0.02
Na ₂ O	0.3	0.58
K ₂ O	0.4	2.75
Free lime	0.9	–
Cl	0.0181	–
TiO ₂	–	0.10
MnO	–	<0.01
P ₂ O ₅	–	0.02
BaO	–	0.05
Particle size distribution		
% < 2 μm	-	0
% < 80 μm	-	0.1
% < 300 μm	-	100

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