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Chloride penetration monitoring in reinforced concrete structure using carbon nanotube/cement composite

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HIGHLIGHTS

- CNT/cement composite could be used as chloride sensor in concrete structure.
- Conductivity of the CNT/cement composite was influenced mainly by the sodium chloride content.
- A CNT content in the composite was an important factor on the chloride monitoring accuracy.

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ABSTRACT

A novel non-destructive method of monitoring chloride penetration in reinforced concrete structures prior to corrosion is proposed. By measuring the change in the electrical characteristics induced by chloride in cement composites containing carbon nanotubes (CNTs), chloride penetration in the structures could be monitored in real time. To evaluate the feasibility of this method, cement composites containing various amounts of CNTs and sodium chloride were fabricated and their electrical characteristics were measured. Although the conductivity of the composite without CNTs fluctuated as a result of both reinforcement and moisture content, that of the composites with CNTs was seldom influenced by these factors, and the conductivity generally increased with increasing chloride content. The chloride content in the composites was estimated via regression analysis based on the electrical characteristics, implying that the CNT/cement composite could be used as a sensor for chloride penetration monitoring.
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1. Introduction

One of the most severe deterioration of reinforced concrete structures is the corrosion of reinforcements by chloride penetration [1]. Reinforcements rust even in alkaline environments owing to the presence of chloride ions [2]. Therefore, monitoring of chloride penetration is an important issue from the standpoint of maintenance of concrete structures [3]. Several technologies have been developed for chloride penetration monitoring in concrete structures. Observing the penetration profile of chloride in concrete is the most accurate monitoring method [4]. However, to use this method, the concentration of chloride needs to be measured directly by grinding concrete samples taken from various depths [5]. Moreover, complicated test procedures are needed to extract the chloride ions from the ground concrete powder [1]. A colorimetric method for measuring chloride penetration depth in concrete structures is a simpler way of chloride monitoring [6–8]. The penetration depth of chloride in the concrete is distinguished by spraying a silver nitrate solution on a cross-section of freshly broken concrete surface [6]. However, this is also one of several destructive methods that have limitations in terms of time and location.

Measuring changes in the electrical characteristics of corroded reinforcements is one of the non-destructive monitoring methods [9–12]. The electrical conductivity and impedance of steel is changed by corrosion, and by measuring these electrical characteristics, the corrosion of the reinforcement can be monitored [9,10]. By applying advanced measuring techniques, the corrosion of reinforcements can be monitored based on this method in real time [11,12]. However, when using this method, it is difficult to obtain advance notice of corrosion damage because the electrical characteristics of reinforcements change gradually according to the progression of the corrosion.

In the present study, a novel non-destructive method for monitoring chloride penetration in concrete structures prior to corrosion reinforcement is proposed. A cement composite containing carbon nanotubes (CNTs), i.e., a CNT/cement composite, was applied as a chloride sensor in concrete structures. The electrical

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conductivity of the cement composites was improved by the incorporation of CNTs, which have very high conductivity [13–15]. The typical range of conductivity of the CNT/cement composite is higher than that of normal water, as shown in Fig. 1 (c.f. [16]). Therefore, the conductivity of the CNT/cement composite is little affected by the amount of water absorbed, i.e., the moisture content of the composite [13]. In a previous study, the conductivity of saturated CNT/cement composites was equivalent to that of dried composites when the CNT content in the composite was higher than 0.3% by cement weight [13]. Meanwhile, the conductivity range of the CNT/cement composites was generally lower than that of sea water containing chloride ions (Fig. 1) (c.f. [16]). Moreover, the conductivity of water is sensitively changed by the chloride content. For this reason, the conductivity of the CNT/cement composite may increase with increasing chloride content, regardless of the moisture content. By measuring the conductivity of a CNT/cement composite embedded in a concrete structure, the chloride penetration in the structures could be monitored in real time. Note that the conductivity of conventional cement composites could change not only as a result of chloride penetration but also as a result of moisture content. Moreover, if the composite were embedded in a concrete structure, its conductivity may be influenced by various factors, such as reinforcement in the vicinity of the composite, the geometry of the concrete structure, the types of concrete in the structures, etc. However, for a CNT/cement composite with high conductivity, its conductivity might be much less influenced by these factors than conventional cement composite.

The feasibility of monitoring chloride penetration in concrete structures using a CNT/cement composite was investigated in the present study. Prior to investigating the conductivity change as a function of chloride content, the effect of a reinforcement steel bar embedded in normal mortar on the conductivity of CNT/cement composites also embedded in the vicinity of the bar was examined. To evaluate the feasibility of using CNT/cement composites as chloride sensors, cement composites containing various amounts of CNTs and sodium chloride were fabricated and their electrical conductivities were measured. In addition, the chloride content in the composites was estimated by using regression analysis based on the electrical characteristics.

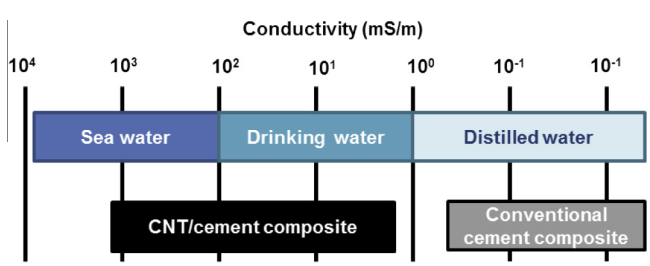

Fig. 1. Conductivity ranges of various types of water and cement composites (c.f. [14]).

2. Experimental program

2.1. Materials and mix proportions

The materials and mix proportions used in the current study were identical to those used in previous studies [13,17,18]. As binder materials, Type I Portland cement and silica fume (EMS-970D, Elkem Inc.) were applied. Multi-walled CNTs produced by Hyosung Inc. were used in the CNT/cement composites. The CNTs were produced by a thermal chemical vapor deposition process and their purity was higher than 95%. Their diameters and lengths were in the range of 12–40 nm and approximately 10 μm, respectively. Detailed specifications of the CNTs are given in Kim et al. [13]. A polycarboxylic acid-based superplastisizer was used to improve the workability of the fresh composites. As a chloride source, sodium chloride with 99% purity was used. Distilled water was applied for mixing and curing of the composite.

The mix proportions of specimens without sodium chloride are shown in Table 1. Three different amounts of CNTs, i.e., 0, 0.3, and 0.6% by cement weight, were added. The flow characteristics and mechanical properties of the mixtures were reported in Kim et al. [13] and Kim et al. [15]. To evaluate the effect of chloride content on the conductivity of the CNT/cement composites, sodium chloride in amounts of 0%, 1%, 2%, 3%, 4%, and 5% by water weight were applied for each mixture.

For normal mortar, a type of river sand with a specific gravity of 2.65% and 0.5% water absorption was used as the fine aggregate. A D10 reinforcement steel bar (SD400) was embedded in the mortar. The mass ratio between water, cement, and fine aggregate in the mortar was 1:2:5.

2.2. Experimental details

The fresh mixtures were mixed in a 3 L-capacity electrical mixer. The cement, silica fume, CNTs, and distilled water with superplastisizer were mixed first for 10 min and then mixed again with the sodium chloride for 1.5 min. The addition of sodium chloride in fresh cement composite has been applied in many studies to simulate chloride penetration in the composite [19–21]. It worth mentioning that the addition of sodium chloride in fresh cement composite seldom has an effect on the properties of fully hardened composites, although it did hasten the setting time of fresh mixtures [19–21].

To measure the electrical conductivity of the CNT/cement composites, fresh mixtures were poured in 20 × 20 × 78 mm prism-shaped specimens, as shown in Fig. 2. At the edges of the specimens, stainless steel plates 10 mm in diameter and 1 mm thick were embedded as electrodes. The specimens in the molds were sealed by plastic film and cured for 5 days. The specimens were then demolded and submerged in the water containing sodium chloride for 28 days. The concentration of sodium chloride in the curing water was equivalent to that in mixing water with sodium chloride. If distilled water were used as the curing water, the chloride ions in the specimens may diffuse into the curing water. Therefore, an attempt was made to prevent massive

Table 1
Mix proportions of CNT/cement composites and their electrical conductivity.

Specimen	Weight composition[a]					Electrical conductivity(mS/m)	
	Water	Cement	Silica fume	superplastisizer	CNT	Saturated condition	Dried condition
CNT 0%	0.275	1	0.2	0.003	0	0.240	0.025
CNT 0.3%				0.006	0.003	0.95	0.40
CNT 0.6%				0.009	0.006	53.6	43.7

[a] Mass ratios of cement weight.

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