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Moisture determination of concrete panel using SAR imaging and the K-R-I transform

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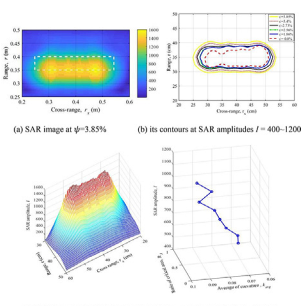
HIGHLIGHTS

- Preparing concrete specimens at different levels of moisture content.
- Imaging concrete specimens with synthetic aperture radar using microwave.
- Tests include air-drying and oven heating of Portland cement concrete specimen.
- Analyzing radar images to extract local and global features for subsurface moisture determination in concrete.
- Developing quantitative models from radar images for predicting moisture content inside concrete.

GRAPHICAL ABSTRACT



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ABSTRACT

Moisture content inside concrete affects the properties and behaviors of Portland cement concrete. It also indicates the likelihood of structural damages (e.g., steel corrosion) in reinforced and prestressed concrete structures. While several laboratory techniques are available for moisture determination, it is a challenging task to estimate the moisture content of concrete in the field without using embedded moisture sensors. In this paper, synthetic aperture radar (SAR) imaging and the K-R-I (curvature-area-amplitude) transform were applied to a concrete panel specimen (water-to-cement ratio = 0.45) for moisture determination. A 10.5 GHz center frequency radar system was used to generate SAR images of the concrete panel at various moisture levels from 0% to 3.85% (by mass). Quantitative analysis of SAR images was carried out by the K-R-I transform to understand the simultaneous change of SAR amplitude and shape at different moisture levels. It was found that integrated SAR amplitude and average maximum SAR amplitude both increase nonlinearly with the increase of moisture content in the concrete panel. Spatial distribution of SAR amplitudes can be used to indicate subsurface moisture distribution in concrete. The area-amplitude (R-I) curve of SAR images quantifies the relationship between moisture content and its distribution.

1. Introduction

Moisture content inside Portland cement concrete is instrumental to predicting the short-term strength development (cement hydration) and long-term durability performance of concrete (reinforced and prestressed) structures, as well as to detecting

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structural damages such as steel corrosion inside concrete. Not only does moisture inside concrete facilitate most durability problems (e.g., freezing-and-thawing [1–3,7], steel corrosion [4], carbonation [5], alkali-silica reaction (ASR) [6] in concrete structures, its amount and distribution also indicate the hydraulic permeability of concrete. In the freeze-thaw damage of non-air-entrained concrete, it has been reported that concrete will experience significant damage when its moisture content exceeds 80% [9]. In the chloride-induced corrosion of steel rebar inside concrete structures, high moisture content promotes the diffusion of water molecules through the capillary pores inside concrete [4,8]. Carbonation of concrete can be encouraged when the relative humidity inside concrete is between 55% and 65% [8]. Research has also shown that expansive ASR can occur in concrete when relative humidity is above 80% [9]. In addition, it is well known that saturated concrete is weaker than dry concrete by approximately 20% [10,11].

Knowing that moisture content in concrete is crucial to the performance of concrete structures, it is, however, difficult to determine the moisture content inside concrete in the field without using intrusive or embedded moisture sensors. To avoid troublesome issues associated with embedded moisture sensors, nondestructive testing/evaluation (NDT/E) techniques can be applied. Among existing NDT/E techniques, gravimetric technique [12,13], gammadensitometry technique [14,15] moisture sensors [16] thermal and microwave/radar methods [17,18] have been applied for moisture determination. The gravimetric technique is destructive and not applicable for field structures. The gammadensitometry technique is radioactive and requires coordinated inspection of a transmitting source and a receiving collimator, making it very difficult for field implementation. Commercial moisture sensors are intrusive and need to be embedded inside concrete as an anomaly. They cannot be applied to existing structures. In general, an ideal NDT/E technique for moisture determination in concrete must be quantitative, capable of detecting internal moisture distribution, and invulnerable to environmental factors (e.g., temperature, soluble salt content [19]. Ultimately, such technique should be capable of quantifying different phases (free water, bound water, and chemically bound water) of moisture inside concrete [20].

Electromagnetic techniques such as ground penetrating radar (GPR) are capable of conducting spatial and semi-quantitative moisture determination in concrete specimens [17,18,21,22] and structures [11,23]. Since electromagnetic waves (radar signals) are capable of penetrating through dielectrics like concrete, they are inherently applicable for subsurface sensing problems in concrete. Laurens et al. [24] used a 1.5 GHz center frequency GPR system to evaluate the moisture content of 0.25x0.25x0.07 m concrete slabs at various saturation levels (0–100%). They found that GPR signal attenuates linearly with the increase of moisture content. They also reported that the presence of moisture reduces the center frequency of reflected GPR signal in another similar study [17] studied the amplitudes of direct and reflected GPR signals with a center frequency of 1.5 GHz inside concrete slabs (0.75 × 0.5 × 0.08 m) at different moisture levels (0, 20, 40, 60, 80 and 100%). They found that amplitudes of direct and reflected GPR signals decrease linearly with the increase of moisture content. Klysz and Balayssac [25] applied a GPR (SIR-2000 radar system, equipped with two 1.5 GHz coupled antenna (5100)) system on concrete slabs (0.6 × 0.6 × 0.12 m) with various moisture contents (0–15.3% by volume) to investigate the effect of moisture on GPR signal amplitude and signal velocity. They found that both amplitude and velocity of the GPR signal reduce with the increase in moisture content (as an indication of dielectric dispersion). In addition, while most researchers reported linear attenuation of GPR signals with the increase of moisture content in concrete, some reported a nonlinear attenuation between GPR signal and moisture content [26,27].

From the literature review, it was reported that the amplitude of direct and reflected GPR signal from concrete specimens decreases with the increase of moisture content inside concrete. This relationship was characterized by linear models in most reported results. Other imaging radar techniques (besides GPR) have not been reported for moisture determination in concrete.

The objective of this paper is to apply synthetic aperture radar (SAR) imaging for moisture determination of a concrete panel specimen. SAR imaging is a relatively new technique in civil engineering applications. Compared to GPR, SAR imaging utilizes image superposition to improve resolution and damage detectability. In this research, a laboratory 10.5 GHz center frequency radar system was used to generate SAR images of the concrete panel. The concrete panel was air dried in a temperature-controlled room condition for 30 days to achieve up to 3.85% of moisture variation. In this paper, principle of SAR imaging is briefly introduced, followed by experimental work on specimen preparation, moisture monitoring, and laboratory SAR imaging. Finally, research findings are summarized and concluded.

2. Principle of SAR imaging

In synthetic aperture radar (SAR) imaging, high-resolution coherent (continuous wave) images are produced with adjustable frequency bandwidth and artificial radar aperture. Not only higher frequencies and wider bandwidths can lead to high-resolution SAR images, increased radar aperture created by prolonged radar movement can also produce SAR images with better resolution. Producing such coherent images from raw SAR data is essentially an image formation process. In SAR imaging, back-scattering pattern of any target is first formulated by a planar scattering problem in a domain Ω_s containing N scattering points (Fig. 1). In Fig. 1, θ_i is the incident angle and θ_s the reflection/scattered angle.

Consider an incident electromagnetic (EM) wave with unit amplitude as follows [28].

$$\psi_{\text{inc}}(\bar{r}) = \frac{1}{r}.\exp(i\bar{k}_i.\bar{r}). \tag{1}$$

where $\bar{k}_i = k_{ix}\hat{x} - k_{iy}\hat{y}$ = incident wave vector, $\bar{r}$ = position vector from the radar to any observation point ($|\bar{r}| = r$), k_{ix}, k_{iy} = wave number components in x and y axes. The scattered field from scatterer j located at $\bar{r}_j$ and observed at $\bar{r}$ can be determined by [29].

$$\psi_{\text{scat}}(\bar{r}, \bar{r}_j) = \frac{s_j(\bar{r}, \hat{k}_i)}{|\bar{r} - \bar{r}_j|} \cdot \exp(ik|\bar{r} - \bar{r}_j|) \cdot \psi_{\text{inc}}(\bar{r}) \tag{2}$$

where $s_j = s_j(\bar{r}, \hat{k}_i)$ = scattered amplitude at scatterer j due to an incident wave at $\hat{k}_i$ and observed at $\bar{r}$, $i = \sqrt{-1}$ as the imaginary

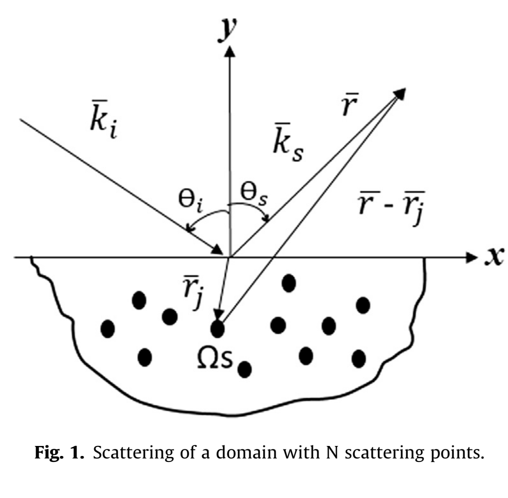

Fig. 1. Scattering of a domain with N scattering points.