Construction and Building Materials 106 (2016) 659–669

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Ground penetrating radar wave attenuation models for estimation of moisture and chloride content in concrete slab

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HIGHLIGHTS

- GPR wave attenuation is measured on a concrete slab saturated with water and chloride.
- The moisture content (MC) shows a strong linear correlation with the wave attenuation.
- The chloride content (CC) attenuates radar waves at a higher rate than the MC.
- Two models to estimate MC and CC in concrete slab are proposed.
- The extent of these corrosion agents are useful in condition rating decisions.

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 30 November 2015
Accepted 22 December 2015
Available online 2 January 2016

Keywords:
Ground penetrating radar
Moisture
Chloride
Amplitude attenuation

ABSTRACT

The detection of moisture and chloride ingress through concrete cover is important for estimating the extent of corrosion in reinforced concrete (RC) components. The concentrations of the substances are monitored by observing the ground penetrating radar (GPR) amplitude attenuation in water and chloride saturated concrete slab samples. The amplitude attenuation significantly correlates with the amount of both substances. Two multiple nonlinear regression models were developed. The proposed models demonstrate a strong correlation with the radar amplitude attenuation data as both substances are varied in the concrete cover. The developed models can be employed to estimate the moisture and free chloride content in – concrete cover for improved quantification of corrosion level.

1. Introduction

The deterioration of reinforced concrete structures due to corrosion has received substantial attention from civil engineers due to its common occurrence and high cost of repair. This impairment is accelerated if concrete possesses high permeability due to improper mixing and compaction during the concrete casting process [1]. A high water–cement ratio in concrete facilitates the ingress of water and chloride ions through the capillary pores in its cover prior to the destruction of the rebar in subsequent stages.

The existence of moisture and chloride ions in a concrete cover is a form of conditioning that can initiate the corrosion mechanism. Chloride may also exist in a concrete surface via cracks in concrete or the presence of contaminated sand or aggregates. Once the chloride ion reaches the rebar level and exceeds the chloride concentration threshold value, the protective thin passive layer surrounding the rebar will gradually be destroyed, which will cause the development of anodic and cathodic sites on the rebar. Due to generations of electrical potential differences at anodic and cathodic sites on the rebar, iron is oxidized at the anode and dissolved in the concrete pore solution as ferrous ions (Fe^{2+}), whereas electrons that move towards cathode and hydroxyl ions (OH^-) will be released. With sufficient oxygen at the anodic sites, a rust component $-Fe(OH)_2-$ is formed when the hydroxyl ions reacted with the ferrous ion. Further oxidization of $Fe(OH)_2$ into different corrosion products will produce a high volume of corrosion products that comprise six times the original volume [2]. With this volume increase, the interface between concrete and steel will experience high tensile stresses that can cause damage initiation (cracking, delamination and concrete spalling). The rebar corrosion-damage process in concrete structures is a time-consuming process that exhibits symptoms once the electrochemical reactions at the anode and cathode sites produce corrosion-damage to concrete due to expanding rust on the concrete-rebar interface.

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http://dx.doi.org/10.1016/j.conbuildmat.2015.12.156
0950-0618/

The presence of moisture can caused several forms of attack on concrete which leads to chemical or physical deteoriation. The forms of attack on concrete can be caused by internal or external source of moisture. One of the common form of attack in concrete structures is due to the sulphate attack (SA). This traditional attack is initiated by the chemical interaction of sulphate-rich soil or water with high sulphate content within the cement paste. The destructive nature of SA causes cement paste to disintegrate, which eventually leads to a weaker cement matrix [3]. Several attempts were done on how to assess concrete resistance to SA, however, the experiments required a long term observation that will take years as it involves the sulphate ingression by diffusion mechanism in concrete, thus. An accelerated test has been proposed to access the sulphate resistance on concrete made with ordinary Portland cement and slag cement [4].

Water expansion in concrete pores during winter season is another phenomena that can cause damage to the concrete in long term duration. When water freezes, it will expands approximately 15% from its original volume [5]. As the water in moist concrete freezes, it produces pressure inside the capillaries and concrete pores. Once the tensile strength of concrete is exceeded, the pores will dilate and rupture. Further successive freeze–thaw cycle will caused significant expansion, cracking and crumbling of the concrete. In view of this situation, few methods has been applied on concrete to improve its freeze–thaw durability. The use of air-entraining agent and the hydraulically pressed concrete were the possible ways and its performance of this method can be found elsewhere from other references [6,7].

Alkali-silika reaction (ASR), has been identified as one of the deteorioration phenomena in concrete facilitated by the presence of moisture. In this phenomena, some reactive aggregates react with the akali hydroxide in concrete to produce gels; causing expansion and cracking over a period of years. The typical indicator of this reaction is the formation of random map cracking on areas with frequent supply of moisture, i.e. near joints and close to the waterlines. Moisture allows migration of alkali ions to the reaction sites in concrete and the resulting gel absorb moisture, leading to expansion on concrete. The expansive reaction can occur in concrete having a relative humidity more than 80% [8].

Therefore, an assessment of the chloride and moisture content in concrete cover during the early stage of corrosion is essential for planning the maintenance of deteriorated concrete structure with a relatively lower cost compared with maintenance after severe damage over a certain period of time.

To assess the state of moisture and chloride ion content in a concrete cover, a number of techniques have been developed to measure both contaminants in concrete. The most prominent and direct method for measuring moisture content in concrete is the gravimetric method [9]. This method can be used to measure the moisture content by observing the change in mass; however, it is not a practical technique for quantifying moisture in large concrete structures. The neutron hydroprobe is a non-invasive method that relates the scattering of neutrons with the moisture content of concrete [10]. Unfortunately, this technique is only applicable in a laboratory and may pose health risks to an operator. For quantifying the chloride content in concrete, concrete dust samples are obtained at different depths and titration method using silver nitrate is used to determine the chloride content. However, this method is time consuming to be applied to a large area of concrete surface. Ground penetrating radar (GPR) has great potential in enabling operators to measure the moisture and chloride content using electromagnetic waves. This nondestructive method facilitates rapid data collection in large concrete areas, and only requires a single-sided surface of concrete for inspection work.

Previous GPR researches have provided GPR wave attenuation models based on one parameter: the effect of the water content [11–13] or the effect of the chloride content [14]. The effect of water content on GPR amplitude with 1.5 GHz antenna was studied using concrete sampels of 7 cm thickness [11]. They provide a numerical simulation by modelling the amplitude variation with degree of saturation and the results are correctly simulated with the experimental values, except in the range of saturation laying between 0% and 20%. The quantification of volumetric water content in 12 cm thickness concrete samples was conducted by Klysz & Balayssac, 2007 [12]. They analysed the direct waves of 1.5 GHz antenna and successfully model the relationship between the normalized amplitude with the saturation degree. The relationship between the volumetric water content in fresh concrete mix and its relative dielectric constant was obtained using GPR wave [13]. Microwave non-destructive testing has been used to evaluate the separate effect of moisture and chloride contamination in concrete and its relationship with relative dielectric constant and loss factor were determined [14]. However, this current study will focussed on studying and modelling the effect of both moisture and free chloride content in concrete cover to the ground penetrating radar amplitude; which has been identified to be the objective and the novel aspect in this work. The first scope of the work is the collection of radar signals on concrete cover that was saturated with varying moisture and free chloride content. The following scope of work is to develop the attenuation model of radar amplitude due to moisture and free chloride content in the concrete cover.

1.1. Ground penetrating radar

GPR is a method that is common for infrastructure inspection work involving concrete structures. GPR can be used for subsurface condition assessment and to monitor concrete infrastructures, such as bridge decks [15–17] and building components [18]. It is a nondestructive method that has been employed in geological studies to map the embedded geological features [19], however, with the advancement of new high-frequency GPR antenna and better data processing software, the application of the method has evolved from geological field applications to civil engineering applications, such as the estimation of pavement thickness [20] and the detection of defects in pavement [21].

In principle, this nondestructive method is dependent on measuring the reflection of the reflected the electromagnetic wave that propagates in certain lossy dielectric mediums, such as concrete, after it impinges any embedded layer that possesses different electrical properties of the propagated medium, i.e., the dielectric constant and the conductivity. The degree of this wave reflection is quantified by the reflection coefficient R, which is computed as the ratio of the incident wave amplitude at an interface or object to the reflected wave amplitude on the targeted layer or object, as shown in Eq. (1) [22]:

$$R = \frac{A}{A_p} \tag{1}$$

where A is the reflection wave amplitude from the top surface of the concrete structure and A_p is the wave reflection amplitude from the metal plate placed at the concrete soffit.

The reflection of the wave in concrete is influenced by two main electrical properties of the medium, i.e., the dielectric constant and the conductivity, as concrete is a lossy material. The dielectric constant describes a material's ability to store and release electromagnetic wave energy by electrical charge displacement and a polarization process when an electrical field from the radar antenna is applied [23]. The original energy of waves is subsequently converted to heat energy during the displacement and polarization process, which causes amplitude attenuation to the original wave amplitude. The moisture content in concrete has