Construction and Building Materials 26 (2012) 448–458

Contents lists available at ScienceDirect

Construction and Building Materials

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

Inspection of Insulated Concrete Form walls with Ground Penetrating Radar

Cherif Amer-Yahia *, Todd Majidzadeh [1]

Resource International, Inc., 6350 Presidential Gateway, Columbus, OH 43231, United States

ARTICLE INFO

Article history:
Received 5 October 2010
Received in revised form 16 June 2011
Accepted 18 June 2011
Available online 13 July 2011

Keywords:
Ground Penetrating Radar (GPR)
Insulated Concrete Forms (ICF)
Concrete
Honeycombing
Void detection
Nondestructive Testing (NDT)
Dielectric contrast

ABSTRACT

Insulated Concrete Form (ICF) walls are widely used for a full range of building designs including residential, theaters, schools, and hospitals. ICF manufacturers cite several advantages compared to traditional building materials but builders are concerned by honeycombing that may occur during the pouring of the concrete, where gaps are left in the concrete. The development of gaps generally occurs between the foam and the surface of the concrete. Acoustic sounding, a traditional inspection technique to locate voids, would be unsuccessful due to the plastic foam. In this research study, Ground Penetrating Radar (GPR) was proved successful in detecting gaps that developed between the foam and the concrete, voids intentionally created in the concrete, and voids that developed during the pouring operation. Small voids (e.g., less than ¾ in.) were difficult to detect but are not likely to cause any hazard to the structural integrity of buildings. The tests were performed at different stages of concrete curing using both the 1500 MHz and the 2600 MHz antennas. It is shown in this paper that the first void in the concrete was detected at day 7. However the best results were achieved at day 28 of curing. Data analysis has shown the success of the 1500 MHz antenna, but also the limits of the 2600 MHz antenna in the detection of buried voids in ICF structures.

1. Introduction

Insulated Concrete Forms (ICFs) are made of rigid plastic foam walls that hold concrete together during the curing operation and remain in place permanently afterwards to serve as thermal insulators. ICFs are becoming today widely used for a full range of building designs including residential, theaters, schools, and hospitals. ICF manufacturers cite several advantages compared to traditional building materials but builders are concerned by honeycombing that may occur during the pouring of the concrete, where gaps are left in the concrete. When a wet concrete is poured into wall forms and spread out, air-voids can occur within the mixture. Large air-voids that may form could reduce the structural integrity of the buildings. The use of a vibrator during the pouring operation to resolve this issue is not always a success. The development of gaps generally occurs between the foam and the surface of the concrete. Acoustic sounding, a traditional inspection technique to locate voids, would be unsuccessful due to the plastic foam. Among the range of available tools, Ground Penetrating Radar (GPR) has been used successfully by many researchers and practitioners in a variety of applications, including the investigation of concrete structures to detect defects and structural elements [1–3].

GPR is a nondestructive ultra-wide-band testing device generally used for a variety of geophysical, engineering, and structural investigation applications. This device uses radio waves with the frequency between 100 MHz and 2600 MHz to determine the location, size, and orientation of objects below the surface of pavements, decks, or walls. The ability to detect a subsurface feature depends upon contrast in electrical and magnetic properties of the material the wave is propagating through. The GPR system operates by transmitting discrete pulses of electromagnetic energy into the medium and capturing the reflections from each layer interface. While part of this energy is absorbed or transmitted through the interface, the reflected portion of the signal travels back to the antenna. The receiver antenna detects the returning signal and sends it back to the control unit where it is processed and displayed.

Air-voids are high contrast targets. They are detectable using GPR because the dielectric constant of air is significantly lower than most existing construction materials. The greater the contrast (i.e. the difference between the dielectric constants of materials), the stronger the reflection will be. However, even an air-filled planar fracture parallel to the surface, would have to be at least 0.6 in. (15 mm) thick to be detected with a 1500 MHz antenna [4].

There are very few studies that reported the use of GPR to identify air-filled voids through ICF structures. In a study conducted by the Portland Concrete Association, Gajda and Dowell used GPR to successfully locate a number of voids in ICF structures [5]. In a research investigation, Roberts et al., found that GPR is useful for

* Corresponding author. Tel.: +1 614 823 4949; fax: +1 614 823 4990.
E-mail addresses: cherifa@resourceinternational.com (C. Amer-Yahia), toddm@resourceinternational.com (T. Majidzadeh).
[1] Tel.: +1 614 823 4949; fax: +1 614 823 4990.

0950-0618/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2011.06.044

locating voids at the concrete form boundary and voids buried in the concrete [6]. They reported that voids can be detected after three days of curing, but did not illustrate this statement by GPR images. Morcous and Sekpe reported in a paper published recently that GPR was an efficient and reliable technique for inspecting ICF walls. They scanned an ICF specimen built with air-voids, steel bars, and utility pipes to determine the accuracy of GPR in detecting these targets [7]. However the paper did not specify at what stage of curing the voids were detected. In our study, three ICF walls were built and air voids were intentionally created in two of them to demonstrate the application of GPR for void detection in ICF structures. A vibrator was used to avoid air pockets from developing in the third wall. A ½ in. (12.5 mm) drywall was put on one side of each wall. Pipes with different diameters were utilized to create voids within the concrete and removed few hours after the concrete was poured. Some gaps developed between the foam and the concrete in structures where the vibrator was not used. All three walls were tested at incremental calendar dates using 1500 MHz and 2600 MHz ground-coupled antennas. The results obtained are interesting in the sense that the gaps developed between the foam and the concrete during the pour were clearly identified at all calendar days. GPR was also capable of identifying voids created within the concrete with the 2¼ in. (56.25 mm) diameter pipe and voids that developed after the concrete was poured. However smaller voids, made with the ¾ in. (18.75 mm) diameter pipe, were difficult to recognize. The tests were performed at different stages of concrete curing. It is shown in this paper that the first void in the concrete was detected at day 7. However the best results were achieved at day 28 of curing.

2. Fundamentals of GPR

The dielectric constant of a material, ε_r, also known as a relative permittivity, is an important parameter in characterizing its density [8,9]. An increase in density will increase the dielectric of the material while an increase in void content will decrease it. Ranges of dielectric constants for typical construction materials, obtained from the literature, are given in Table 1.

GPR is a technique that uses radio waves to acquire subsurface information. The electromagnetic (EM) waves that are transmitted into the surface of a structure are reflected back at boundaries of materials having different dielectric constants. The velocity, v, of a radio wave through a nonmagnetic material is inversely proportional to the square root of the material's dielectric constant and can be determined with the following equation [8,10], where c is the speed of light in air (c = 11.8 in./ns, or 3×10^8 m/s).

$$v = c/\sqrt{\varepsilon_r} \tag{1}$$

For example, since the dielectric constant of air is 1, radio waves travel through a vacuum at the speed of light. However when radio waves pass trough concrete, the velocity of propagation decreases given that the dielectric constant of cured concrete varies from 4 to 10. If a radio wave travels through concrete having a dielectric constant of 9, the speed of propagation would be three times less than the speed of light.

Table 1
Dielectric constants of common construction materials.

Material	Dielectric constant (ε_r)
Air	1
Water	81
Concrete	4–10
Dry sand	2–6
Plastic strips and webs	3–4
Metal (perfect reflector)	∞

The reflected waveform is displayed on a computer screen as a graph of amplitude, in volts, against time, in nanoseconds (ns). But the most common way of viewing GPR data, for an easier interpretation, is by the use of a color transform system as shown in Fig. 1. The depth scale is shown in feet, inches (meters, millimeters), or ns, and the distance along the survey path is generally given in feet (meters).

The strength of the reflection is related to the dielectric contrast between the two materials the wave is propagating through. The reflection coefficient R can be used to quantify the reflective strength at an interface of two adjacent media, where ε_{r1} and ε_{r2} are the dielectric constants of the materials above and below the interface, respectively [8,11].

$$R = \left(\sqrt{\varepsilon_{r1}} - \sqrt{\varepsilon_{r2}}\right)/\left(\sqrt{\varepsilon_{r1}} + \sqrt{\varepsilon_{r2}}\right) \tag{2}$$

A positive reflection coefficient means that the reflected wave has the same polarity as the incident wave ($\varepsilon_{r1} > \varepsilon_{r2}$), whereas a negative reflection coefficient means that the reflected wave has a polarity opposite to that of the incident wave ($\varepsilon_{r1} < \varepsilon_{r2}$) [8]. A radio wave that travels from cured concrete (dielectric constant of 4–10) to air (dielectric constant of 1) will produce a strong and clear reflection (high amplitude value). However a wave moving from concrete to dry sand (dielectric constant of 2–6), for example, will comparatively produce a week reflection (low amplitude value). Fig. 1 is a representation of an air-filled void detected under a 6 in. (152 mm) concrete slab. It shows as a strong reflection with a black–white–black sequence of colors in a grayscale representation. This is due to the radar energy moving into a material (air for instance) with a lower dielectric constant than the concrete. On the GPR waveform, this is identified through a positive GPR signal. On the other hand, a negative reflection indicates a transition from a lower to a higher dielectric material (concrete-rebar interface or concrete-water-filled void, for example). The concrete-sand interface reflection is weak, but there is a noticeable texture change from concrete to sand. Fig. 1a and b shows the comparison between the defect and non-defect areas.

Since several papers cover the theoretical aspects of GPR [4,9,12], only the thickness h is presented in this paper to support the discussion at the end of this section.

$$h = c \times \Delta t / 2\sqrt{\varepsilon_r} \tag{3}$$

where Δt is the two-way travel time between the top and the bottom of a material layer, in ns.

In a laboratory study, Steinway et al. used Eq. (3) to determine the depth of an air-filled void by estimating the time it takes the GPR wave to travel from the top to the bottom of the void. The findings of this study indicated that it was feasible and practical to use GPR technology to locate voids beneath pavements and measure void depth up to 8.6 in. (216 mm) [13]. Chen et al. used the same equation to estimate the depth of air-filled voids under pavements [14,15]. They claimed that the selection of the bottom of the void was subjective as there are multiple reflections to choose from. However they selected the strongest positive reflection as the bottom of the void and determined the time of travel of the EM wave in the air-filled void. They concluded that this selection is subject to interpretation but they thought it was sufficient to indicate "deep" or "shallow", which is adequate for most inspections.

The minimum thickness layer, t, that can be resolved is estimated to be.

$$t = 1/4\lambda \tag{4}$$

where λ is the wavelength of the radar wave in a particular material, calculated from

$$\lambda = v/f \tag{5}$$