MONITORING THE GPR RESPONSE OF CURING CONCRETE

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Abstract:

Ground penetrating radar (GPR) is becoming an increasingly popular method for locating embedded targets in concrete. It provides rapid surveying of a concrete slab, and requires access to only one side of a slab. The basic principle of operation is to transmit a broadband high-frequency electromagnetic (EM) pulse into the concrete and detect the reflected pulse. The intensity of the reflected pulse is primarily controlled by the attenuation related to the electrical conductivity losses in concrete while the travel time is controlled by the EM wave velocity in concrete. When concrete is initially poured, it has a high free water content which causes both high attenuation and low velocity. As curing occurs, hydration removes free water and locks it into the concrete structure resulting in an increase in velocity and a decrease in attenuation. In this paper we present the results of GPR imaging of a concrete slab at regular intervals, from immediately after pouring to an apparent fully cured state. The monitoring period was 5 months. As part of the data analysis, velocity and attenuation were estimated as a function of time. The change of these properties indicates the state of water in the curing process and suggests that GPR can provide a useful in situ non-destructive technique for monitoring curing in concrete structures.

Introduction:

Ground Penetrating Radar (GPR) is gaining widespread acceptance as a useful tool for locating embedded targets in concrete. Large surface areas can be inspected with real-time results produced for immediate evaluation in a non-destructive manner. The extensive use of concrete construction worldwide suggests potential for expanding this GPR application. To reach full potential use, the behaviour of radar on different types of concrete, and what its limitations are, must be well understood.

Many studies have been performed on the electrical properties of concrete that are relevant to GPR (Davis et al, 2003; and Robert, 1998). The use of GPR for concrete non-destructive evaluation (NDE) has evolved to a point where the data have been simplified, so that a well-trained technician can use the technology routinely, rather than requiring research specialists to do the analysis. This ease of use depends on the on-site creation of plan map images through processing of raw GPR data. This paper describes a research study to investigate how attenuation and velocity change with time on a newly poured concrete slab and to determine how soon after pouring usable GPR plan map images of concrete can be obtained.

GPR Theory

GPR operates by using a dipole (transmitting) antenna which generates a high-frequency electromagnetic pulse that propagates into the material under investigation. The pulse will be partially reflected by any internal structure and is detected by a similar receiving antenna. The amplitude and the time delay from transmission to reception are measured. By moving this system along the surface, a cross section plot (i.e. B scan) of the subsurface is acquired.

The primary interest is in the travel time and signal amplitude of the reflected pulse. The importance of travel time is that we can ultimately convert that to depth by knowing the propagation velocity of the EM pulse in the concrete. If we assume that the transmitter and receiver are coincident (point source), the depth is calculated from the two-way travel time as:

$$d = \frac{vt}{2} \tag{1}$$

where d is the depth to the target
v is the velocity of the pulse in the host material
t is the two-way travel time (normally measured in ns)

Note that typically, we must take any transmitter-receiver antenna separation into account.

There are many ways to obtain velocity directly from GPR data such as using a target of known depth and fitting a hyperbola to a target scattering response. The latter is by far the most common and easiest approach since it is truly non-destructive.

A fraction of the energy in the transmitted GPR pulse is returned to the receiver when it encounters a material with differing electrical properties. The greater this difference, the greater the amplitude of the reflected signal. Signal amplitude is also dependent on the target size, geometry, depth, composition, and the host material. In concrete (and most man-made materials), is heterogeneities in the host material will absorb and scatter the GPR signal. The effect of the concrete properties on signal amplitude can be estimated with the radar range equation (Annan and Davis, 1977). Attenuation rate is very important in using GPR since in highly attenuating environments the reflected signal may be below the detection limits of the receiver.

Water and concrete

Water is the biggest factor for determining the electrical properties of concrete. Concrete is a mixture of aggregate, Portland cement, binding agents (in some cases), air and water. When concrete is first poured, there is a large amount of free water present. Eventually most of this water hydrates as the concrete cures. Any remaining free water is retained in the pore spaces of the concrete or evaporates with time. The residual free water in the concrete is the most significant factor in determining the dielectric permittivity and electrical conductivity of the concrete. The greater the amount of water, the higher the dielectric permittivity and conductivity.

Pure water by itself does not contribute to the electrical conductivity but it is the dissolved ions which enhance the electrical conductivity. Conductivity is responsible for the majority of the GPR signal attenuation in concrete. The following equation relates attenuation to conductivity and relative dielectric permittivity in low loss conditions:

$$\alpha = \frac{1.64\sigma}{\sqrt{K}} \quad \text{dB/m} \tag{2}$$

where α is the attenuation
σ is the conductivity mS/m
K is the relative dielectric permittivity or dielectric constant (dimensionless)

The permittivity also controls the velocity and for low loss materials the velocity is given by the following:

$$v = \frac{c}{\sqrt{K}} \tag{3}$$

where c is the speed of an electromagnetic wave in a vacuum. In the above two equations, K and σ are functions of volumetric water content (Topp et al., 1980; Davis et al., 2003)

Experimental setup and data acquisition

The experiments used a commercially available Conquest GPR system, manufactured by Sensors & Software Inc. Conquest is a GPR system designed specifically to image concrete using a centre frequency of 1000 MHz. Data are collected on a plastic grid to create plan map images of the concrete subsurface, thereby making it easier to locate and mark-out features.

A concrete test pad, measuring 1.2 m x 1.2 m was constructed with rebar and 2 PVC air filled pipes shown in Figure 1. All rebar is ½" diameter. The rebar running left to right are spaced 15 mm apart, while the rebar running top to bottom are spaced 20 mm apart. The arrow in Figure 1 indicates two of the rebars tied together.

Figure 1: Test pad construction prior to concrete pour.

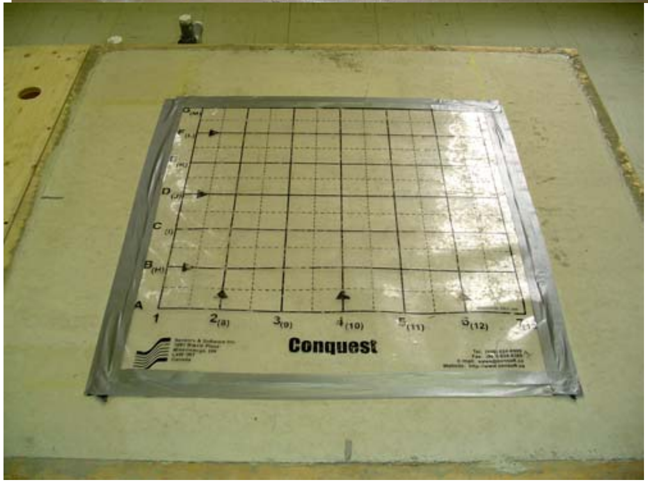


Figure 2: Survey grid sheet with alpha and numeric lines labelled

This pad was poured indoors and was allowed to cure. It was not watered but was covered with a vinyl survey grid that was centered in the middle. The grid measures 600 x 600 mm and is part of the data acquisition process of the Conquest system (Figure 2).

A complete data grid was collected at regular time intervals, frequently at first, then less frequently as time progressed. Concrete hydration changes rapidly in the first few hours and days, but slows as time progresses. Each grid collection involved collecting lines along the orthogonal lines on the grid. Lines were spaced 50 mm apart, resulting in a total of 26 lines collected per grid. The data were then processed to create plan maps.

To quantify signal amplitude, we looked at survey line ‘D’ (Figure 3) which runs from left to right as shown in the photo in Figure 2. The peak of the hyperbolic response from a rebar was used to measure the signal amplitude. For the amplitude analysis presented here, we used the second rebar response, located approximately 21 cm from the starting position in Figure 3 (the third rebar from the left in Figure 1).

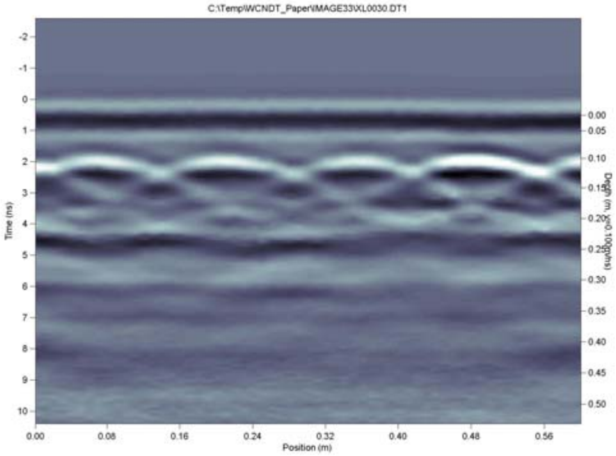
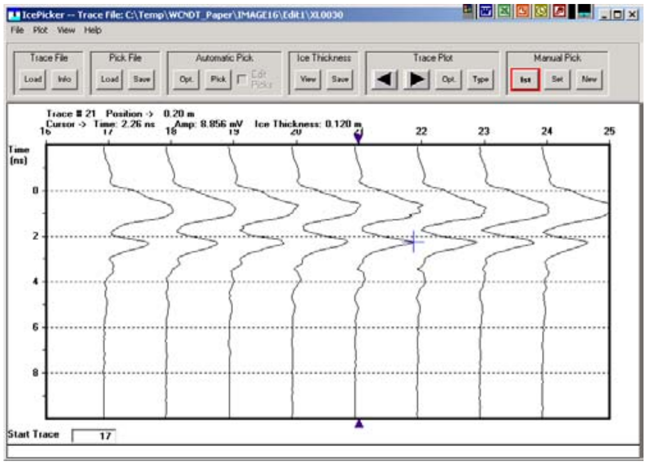


Figure 3: GPR cross section on line D



Trace # 21 Position -> 0.20 m
Cursor -> Time: 2.26 ns Amp: 8.856 mV Ice Thickness: 0.120 m

Start Trace 17

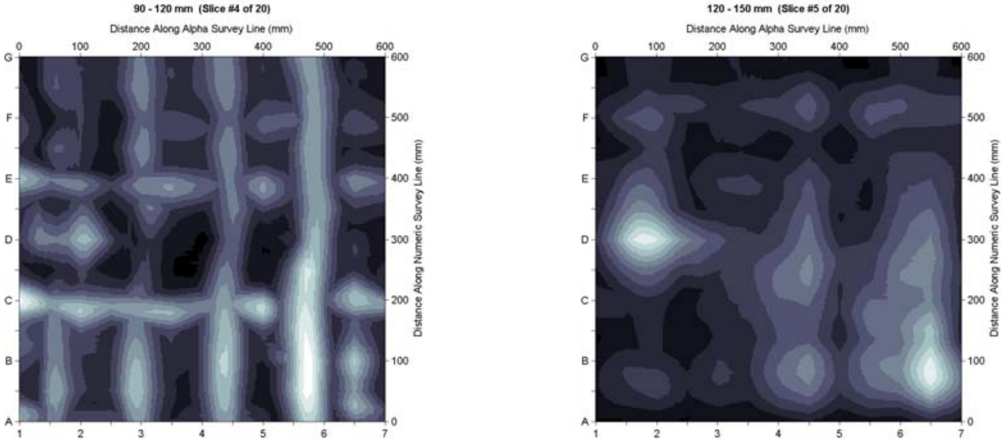
Figure 4: Enveloped GPR traces.

To determine the change in attenuation with time, we measured the amplitude of the reflected pulse returned from this 2nd rebar response. To accomplish this, we dewowed the traces to remove the low frequencies and then computed the envelope of the traces. This processed data is shown in Figure 4.

Results:

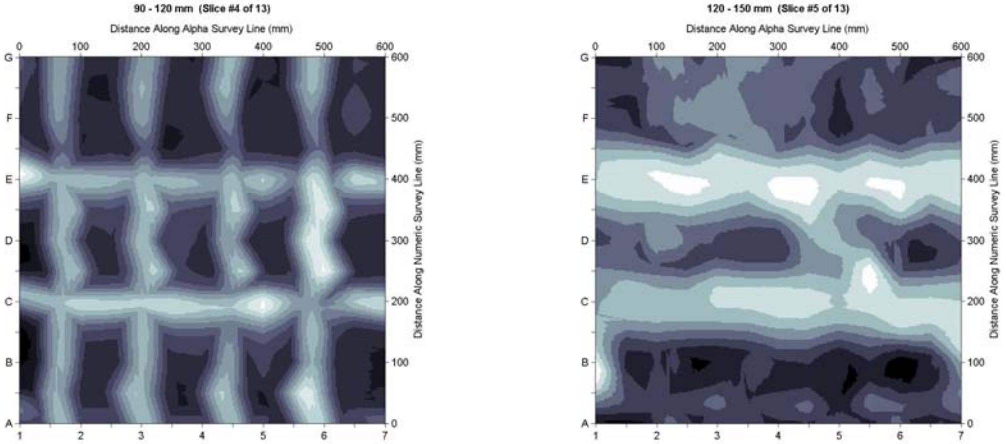
As concrete cures, the GPR velocity will increase and the attenuation will decrease. Our experiments were conducted with the following two questions in mind. First, how soon would we be able to image embedded features, and second, could we monitor changes in v and α versus time and thus have an indication of the status of curing.

Figures 5 through 9 show a series of Conquest plan map images collected over an eight day period. Two slices are shown for each measurement time. The shallower slice was chosen to show the rebar layer and the deeper slice to show the diagonal conduit. It should be noted that the conduit is air filled so it does not produce as strong a response as it would if it contained wire.



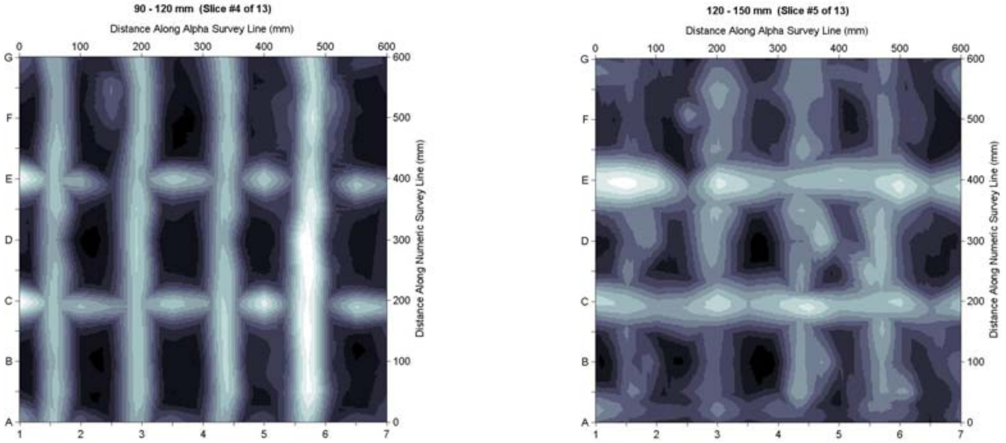
(a) (b)

Figure 5: After 5 hours (a) Rebar slice (b) Conduit slice



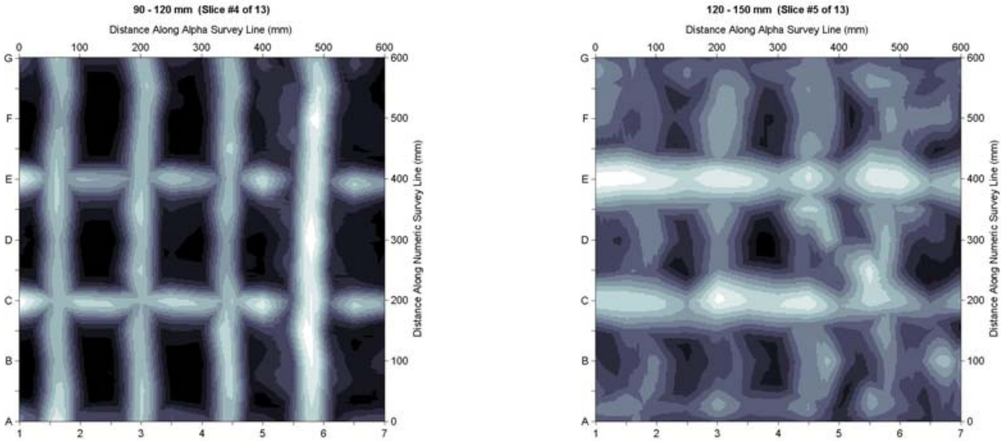
(a) (b)

Figure 6: After 1 day (a) Rebar slice (b) Conduit slice



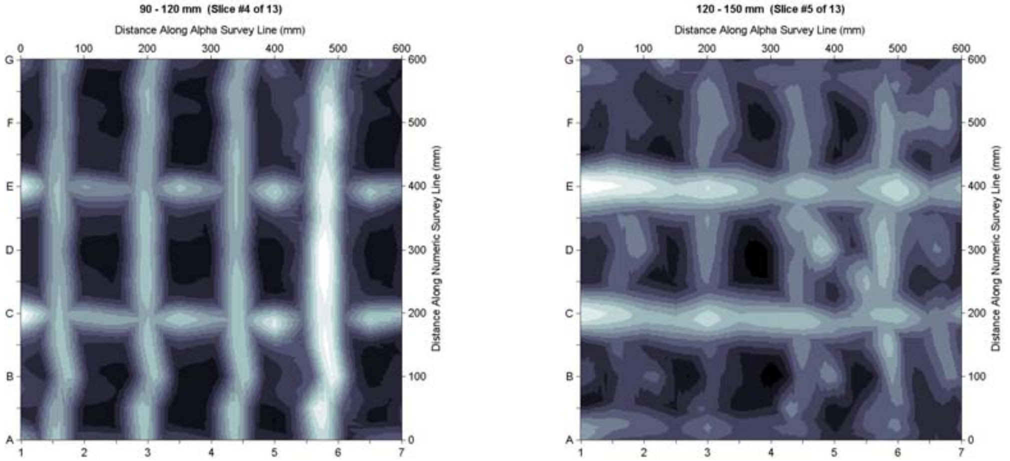
(a) (b)

Figure 7: After 3 days (a) Rebar slice (b) Conduit slice



(a) (b)

Figure 8: After 5 days (a) Rebar slice (b) Conduit slice



(a) (b)

Figure 9: After 8 days (a) Rebar slice (b) Conduit slice

The images become successively clearer as time progresses. After 3 days, image results are quite acceptable. The marginal improvement from that time to 8 days is hardly noticeable. In the slice below the rebar, the air filled diagonal pipe also becomes visible after 3 days, but is not as distinct. The rebar on the extreme right, close to line 6, is more prominent than the others. This is because two rebar are tied together (as shown in figure 1), causing a stronger reflection.

The graph in Figure 10 shows the change in amplitude of the rebar response over time. There is a very large and rapid increase in the initial hours after pouring. After 3 days, it continues to increase, but at a much slower rate.

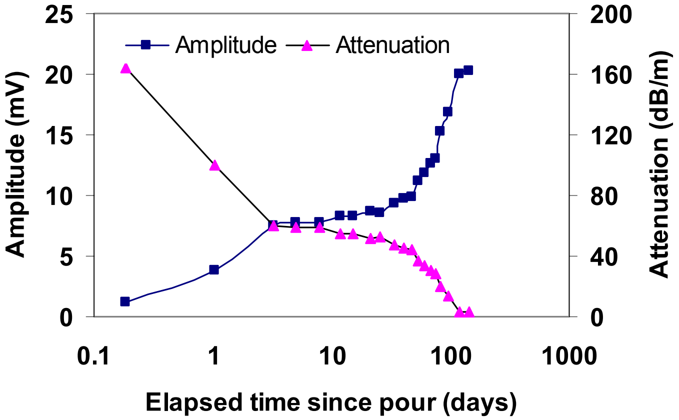


Figure 10: The rebar response amplitude versus time and corresponding attenuation derived from the amplitude.

While collecting this data, a vinyl survey grid was placed on the concrete (as shown in Figure 2). After some time, it was realized that this grid might affect the curing process or water evaporation rate by isolating the concrete underneath it from the air above. After ~ 54 days, the grid was removed. The amplitude rate of increase appears to change slightly after this point, which suggests that the vinyl grid was slowing the curing/drying process. Either way the general trend shows that the signal amplitude is increasing, which means that the attenuation is decreasing. Figure 11 illustrates the velocity increase with time. The change is similar in character to the amplitude.

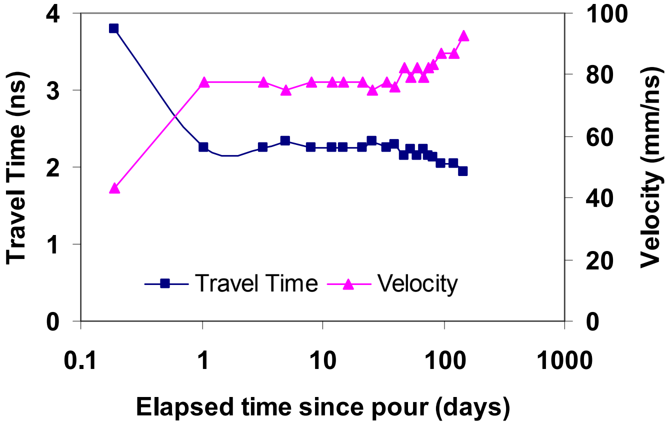


Figure 11: The two-way travel time for the rebar response and the corresponding inferred velocity.

Discussion:

The overall GPR responses are consistent with the expected behaviour. The very rapid change early in time was faster than anticipated. From the final measured velocity we can calculate the relative permittivity of the concrete to be 10. This value compares with typical values of ~13 for damp concrete and 6-8 for dry concrete. Even after 145 days, the concrete is still curing and/or drying, albeit at a very slow rate. With further investigative work in this field, a means of relating the velocity and attenuation of the GPR signal to the state of curing, and possibly the structural strength of the concrete, is quite possible, given the correlation demonstrated thus far.

Conclusions:

The experimental work described here provides some factual results for practical use of GPR for imaging concrete as well as some hints of future developments. Key results are as follows.

(a) Concrete curing is quite rapid in the early stages and GPR imaging is useful once this initial curing phase is completed.
(b) GPR velocity and attenuation likely mimic the state of curing, at least during the initial curing phase.
(c) With systematic experimental work, GPR velocity and attenuation estimates may provide good in-situ indications of the state of concrete curing.

References:

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