Introduction

GPR has been widely applied to many areas that are extensively described in different and previous documents (e.g., Jol, 2009; Conyers, 2013). However, most of the usual applications are based on the analysis of the two-way travel times, and other characteristics of the radar signal are not or only slightly analyzed. Notwithstanding, these characteristics are determined by the materials and the medium properties and could be an additional source of information of them. This paper presents some tests carried out under laboratory conditions of an eroded concrete specimen, in order to determine changes on the center frequency and the amplitude of reflected waves related to the conditions of the medium. Therefore, the study of the signals amplitude in different conditions as well as the evaluation of their frequency is proposed in order to identify changes in water content. The specimen is partially wet, being dry in most of its superficial part.

The velocity of an electromagnetic wave that propagates in materials depends on the electromagnetic properties of this medium, the velocity of the wave in the vacuum (c) and the frequency content. The dependence between the wave velocity and those properties is defined in the equation (1).

$$V = \frac{c}{\sqrt{(\varepsilon_r \mu_r)(\left(1+\frac{\sigma}{\omega\varepsilon}\right)+1)}} \tag{1}$$

The amplitude of the recorded signals depends on many factors. The most important ones are: the coefficient of reflection (R), the attenuation due to the absorption of the energy, the geometrical spreading and the loss of energy due to previous reflections and random scattering. In the case of the reflection on the surface of the slab, the amplitude will be affected mainly by the contrast between the dielectric permittivity of the air and the dielectric permittivity of the specimen. That contrast will be higher in the case of high moisture content and the reflection coefficient will be also higher (see equation 1). Therefore, an increment of the first arrival wave amplitude is expected in zones with higher moisture content. This effect is consequence of the average velocity in the air and in the medium, that is effected by the dielectric constant of the water (80), the dielectric constant of the concrete (12) and the dielectric constant of the air (approximately,1).

$$R = \frac{V_1 - V_2}{V_1 + V_2} \tag{2}$$

The geometrical spreading is caused because the amplitude of the signal decreases when the front wave is enlarged during the wave propagation through the medium. The attenuation is consequence of the absorption of the energy. During the propagation, the medium takes part of the energy that is converted into heat, and the amplitude of the signal decreases. This effect is characterized by means of the attenuation coefficient (equation 3).

$$\alpha = \omega\sqrt{\mu\varepsilon\frac{\left(1+\left(\frac{\sigma}{\omega\epsilon}\right)^2\right)^{\frac{1}{2}}-1}{2}} \tag{3}$$

Therefore, during the wave propagation the amplitude is affected, but also the frequency content of the signal changes. The spectrum of frequencies suffers alteration in the bandwidth, in the maximum value of its amplitude and in the centre frequency, depending on the medium electromagnetic properties.

The effect of moisture content in the GPR signals has been widely analyzed in different works. Some of the first and most relevant experiments were developed by Topp et.al (1980)0, being the water content analyzed in terms of the electromagnetic properties of the medium. Further studies were carried out by Wollschlager and Roth (2005)0 in order to evaluate changes of volumetric water content from Ground-Penetrating Radar reflections. More recently, Benedetto (2006) 0analyzed the behavior of the center frequency of the signal for different values of water content in unsaturated soil. In general, most of the works are based in the relation existent between water content and GPR wave velocity (e.g. Huisman et al., 2003), and in the last years, these studies were complemented with inverse modelling (Weihermüller, 2007). More recent studies suggest the evaluation of the spectra of the signals in order to correlate changes in frequencies with water content and other characteristics of the medium (Rodés et al., 2015). However, the attenuation has been less used in those analysis, although some authors utilize the analysis of the change in amplitude and some interesting works are based on the determination of the signal attenuation studied by means of the spectral ratio method derived from seismic data processing and in the relation existent between water content and amplitudes in soils (Wunderlich and Rabbel, 2011) or in concrete specimens (Laurens et al., 2005). A complete revision of GPR studies of water in soils, structures and infrastructures can be found in (Tosti and Slob, 2015).

Data acquisition

The surveyed specimen is defined by a highly eroded concrete slab with visible lower spots in the surface filled with liquids. Previous the starting survey, the surface was cleaned of the lower stops to avoid damaging the equipment. The specimen can be considered an homogenous medium, without lateral or in depth changes associated to changes in materials, being more uniform than, for example, soil samples. Therefore, the most important variations that are expected in the specimen are related to differences in the water content.

Radar data acquisition was carried out with a commercial 1.6 GHz nominal centre frequency antenna, manufactured by GSSI. This antenna is designed for high resolution concrete inspection. Data was acquired in a common offset survey (Figure 1), obtaining 256 samples per scan and 0.03 ns time increment. The time window was 14 ns

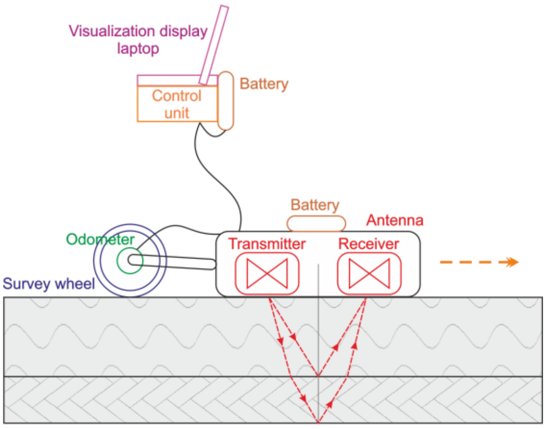

***Figure 1**. GPR data acquisition in a common offset mode.*

Two way travel time in GPR data was used to measure the thickness of the concrete slab, considering the wave velocity as a constant value. As consequence, as the wave velocity depends on the water content, changes in moisture will produce a false effect of changes in the thickness of the slab. In addition, the analysis of the frequencies and amplitudes was used in order to compare B-scans obtained in parallel radar lines. B-scans used in this second analysis were selected to be approximately equidistant, separated about 5 m and covering the entire specimen. Figure 2 shows the position of each one of the five B-scans (profile 53 to profile 93).

Data processing

Raw data was processed, and the frequencies and amplitudes were analyzed. GPR data from each one of the five profiles showed in Figure 2 were extracted and converted into a 3 columns ASCII format, being the data in each column: position of the A-scan (m), time (ns) and amplitude of wave (mV). Finally, amplitudes were normalized to the maximum value measured in the tests. Using this matrix of values, for each trace of the radargram, the amplitude of the wave corresponding to the reflection on the bottom of the specimen was determined. The center frequency was evaluated through the Fast Fourier transform. Furthermore, a mean of each of these values was obtained and associated to each one of the radar lines, and finally, this average value was plotted for each position (profile 53 to 93).

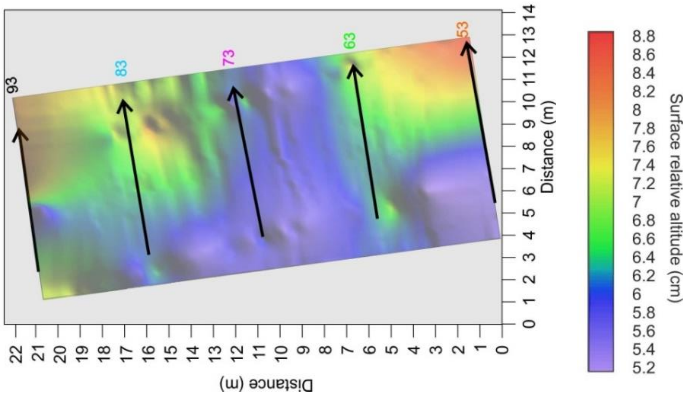

Figure 2. *Relative thickness (cm), obtained under the hypothesis of constant wave velocity.*

Results

The first analysis of the two-way travel time corresponding to the wave reflected on the bottom of the specimen provides information about possible changes on the thickness, determined for the hypothesis of a constant velocity (Figure 2). However, other possible interpretation could consider a constant thickness of the specimen, being the changes in the two-way travel time associated to changes in the wave velocity. The analysis of the matrix of data corresponding to the five B-scans shows significant variations on the electromagnetic signal response (Figure 3). The lowest normalized amplitude of the anomaly corresponding to the reflection on the base of the specimen, is observed in profiles 53 and 93. This result could be associated to the lowest water content in the material. The higher moisture is expected in the location of profile 73. Radar data obtained along this line is associated to an average normalized amplitude of the anomaly corresponding to the reflection on the base, of about 0.85. However, the highest amplitude was not obtained at profile 73 but in profile 63 being also higher the amplitude of profile 83 than the amplitude of profile 73. This result might suggest higher moisture at the zone corresponding to profile 63 followed by the zone close the profile 83. The analysis of the spectrum of frequency allows to determine one centre frequency associated to each one of the radar lines. The minimum value was 798 MHz, obtained at profile 73, which suggests the possibility of higher moisture content in this section. The spectrum of the signal obtained at profile 93 shows a shift towards low frequencies (see Figure 4), being the centre frequency of about 902 MHz. This value denotes a significant diminish of the centre frequency of the antenna that is 1600 MHz. Comparing all the results, which are represented in Figure 4, the centre frequency corresponding to radar line 93 results the lower value, probably with associated to a lower moisture content. All values in Figure 4 are compared to the emitted 1.6 GHz centre frequency (CF) value that is represented with a line, showing the shift that is produced during the wave propagation through the medium. Results consider only the moisture content, but other factors could affect the results and must be contemplated in further tests.

Conclusions

The analysis was made under the hypothesis that moisture (or water content) was the only parameter to be considered affecting both signal characteristics: the amplitude of the received waves after the reflection on the surface and the centre frequency of the spectrum of amplitude. The results show how the amplitude of first arrival is increased as the water content grows, being the higher amplitudes those associated to the radar lines that are placed in the zones with higher moisture. On the other hand, there was a visible decreasing of the centre frequency associated to the effect of the medium, acting as a low-pass filter. In all cases, the bandwidth becomes narrower, and the centre frequency moves towards lower values as the water content increases, even though in the B-scans where the effect is not significantly expressed as in the amplitude of reflection.

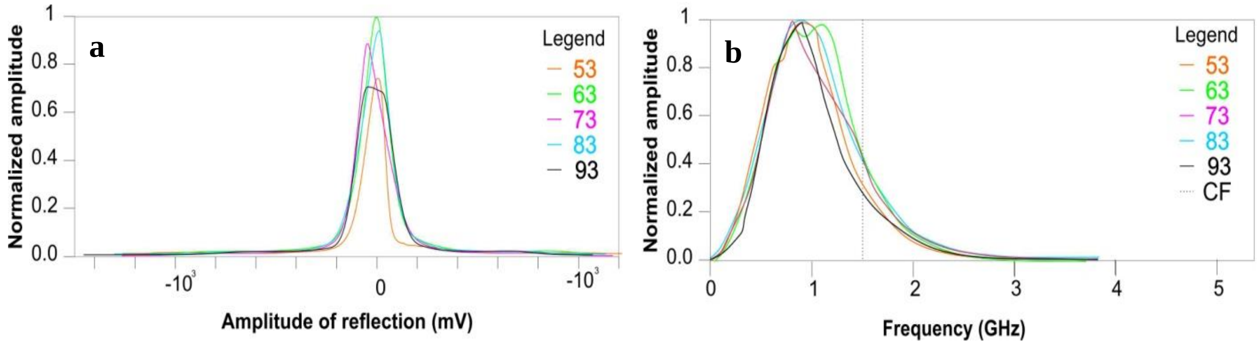

Figure 3. *a) Changes in the relative amplitude of the signal associated to the wave that is reflected on the bottom. b) Spectrum of frequency determined for each of the B-scans, showing the shift of the center frequency, compared to the nominal center frequency of the antenna, described with a vertical line at 1.6 MHz The different colors correspond to each one of the radar lines.*

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