Using diffusivity and dissipation of electromagnetic waves in concrete as new non-destructive parameters for nuclear structures evaluation

Mehdi SBARTAÏ[1], Stephen RAZAFINDRATSIMA[2], Jean-Paul BALAYSSAC[3], Cédric PAYAN[4], Sandrine RAKOTONARIVO[5], Vincent GARNIER[6]

[1] I2M Laboratory, GCE Department, Univ. Bordeaux, 351 cours de la Libération, 33405 Talence, France, email : zoubir-mehdi.sbartai@u-bordeaux.fr

[2] LMDC, INSA/UPS Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse cedex 04 France, email : razafind@insa-toulouse.fr

[3] LMDC, INSA/UPS Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse cedex 04 France, email : balayssa@insa-toulouse.fr

[4] Aix Marseille University, Laboratory of Mechanics and Acoustics, LMA CNRS UPR 7051, 31 chemin Joseph-Aiguier 13402 Marseille CEDEX 20, France, email : cedric.payan@univ-amu.fr

[5] Aix Marseille University, Laboratory of Mechanics and Acoustics, LMA CNRS UPR 7051, 31 chemin Joseph-Aiguier 13402 Marseille CEDEX 20, France, email : sandrine.rakotonarivo@univ-amu.fr

[6] Aix Marseille University, Laboratory of Mechanics and Acoustics, LMA CNRS UPR 7051, 31 chemin Joseph-Aiguier 13402 Marseille CEDEX 20, France, email : Vincent.garnier@univ-amu.fr

ABSTRACT. Non Destructive Testing methods are very needed for better management of concrete structures. In this context, developments have been made in GPR (Ground Penetrating Radar) and looking for new parameters other than those commonly used like velocity or attenuation which could be more sensitive to concrete degradations is important. This paper presents an analysis of the diffusion of electromagnetic (EM) waves in concrete. After fitting the modelling results with the 1D analytical solution of the diffusion equation, we have compared their sensitivities with the sensitivity of the electromagnetic velocity. We have demonstrated that the "diffusivity D" and the "dissipation σ" are very interesting parameters to be used as new electromagnetic indicators to characterize the structural integrity of concretes.

RÉSUMÉ. Il est nécessaire d'utiliser les méthodes non-destructives pour une bonne évaluation des structures en béton. Dans ce cadre, plusieurs développements ont été effectués en Géoradar et la recherche de nouveaux observables autres que la vitesse de l'onde électromagnétique ou son atténuation, qui pourraient être plus sensibles à la dégradation du béton est d'une grande importance. Cet article présente l'analyse de la diffusion de l'onde électromagnétique dans le béton. Nous avons montré que la diffusivité D ainsi que la dissipation σ, obtenus après ajustement des signaux de modélisation avec la solution analytique 1D de l'équation de diffusion, peuvent être utilisés comme nouveaux paramètres électromagnétiques pour caractériser l'intégrité structurale du béton.

KEY WORDS: diffusion; GPR; modelling; concrete; coda.

MOTS-CLÉS : diffusion, Géoradar, modélisation, béton, coda.

1. Introduction

Concrete structures in civil engineering are subject to ageing and depending on the environment where they are, various context of stresses (mechanical, thermal, hydric) often lead to degradation process of these structures. Cracking, corrosion of the reinforcing steel, carbonation need to be detected by Non-Destructive Testing methods for better management of these structures. Particularly, in radioactive waste management, a characterization of the decommissioning structures and also nuclear containers is needed. In this context, developments have been made in GPR (Ground Penetrating Radar), these last decades. This method is fast and reliable for this context. Different indicators of the concrete structural integrity have been used: relative permittivity, velocity, attenuation, arrival time, amplitude[1]. It appears that looking for other parameters which could be more sensitive to concrete degradation is important. Diffusion approximation for acoustic waves,

[1] [SBA 06]

electromagnetic waves and elastic waves have been considered in the literature[2] and 1D, 2D and 3D solutions of the diffusion equation have been used. The objective of this research is to prospect if the diffusion of GPR waves can be simulated in concrete. The wave energy is dispersed in time and space by the influence of scattering in concrete, where a large number of elements of varying composition, size and shape exist. Therefore, the signal is composed of coherent and incoherent parts. The coherent part which resists to spatial average is a wave which has propagated in an effective medium. The incoherent part of the signal has taken a very tortuous path, and is therefore an indication of the microstructure complexity at the scale of one wave length. The incoherent part of the signal is also called “coda” in the literature, by the analogy with the final part of a music composition. Ultrasonic Coda has been used in the literature to detect damage in concrete[3] but, to the best of our knowledge, electromagnetic (EM) Coda has never been studied. This paper presents an analysis of the diffusion of electromagnetic waves in concrete. After a presentation of the numerical model, we present the analysis of the Coda using a 1D analytical solution of the diffusion equation. Therefore, the variation of the diffusivity D and the dissipation σ, parameters obtained by this analysis is discussed as a function of EM parameters modelling.

2. Materials and methods

The modelling work has been performed with gprMax which is an open source software[4]. It uses Finite Difference Time Domain method in order to simulate electromagnetic wave propagation. Figure 1 shows the geometry of the 2D model we performed. The dimensions of the model are the following: x direction from left to right: 50 cm, y direction from bottom to top: 20 cm in total with 5 cm of free space (air) and 15 cm of concrete (composed by cement paste, sand and aggregates). The z direction is perpendicular to x and y directions. Perfectly Matched Layers (PML, on the edges of the model) are also presented with default configuration (10 cells of the spatial discretization dx=dy=dz=0.002 m). A “Transmission” configuration is considered with the electromagnetic (EM) source and the receiver face-to-face. The source signal is an electric excitation (hertzian dipole) represented by a current density polarized in the z direction. A Ricker waveform (second derivative of Gaussian function) is therefore associated with this excitation. The distance between source and receiver is fixed to 15 cm and the steps for the scan is 5 mm, from left to right, which represents 84 A-scans.

Two groups of stones, randomly distributed in the concrete, have been modelled: (i) small-stones, with diameters varying from 5 to 20 mm and (ii) medium-stones, with diameters varying from 20 to 40 mm. Moreover, 3 frequencies of the source signal have been considered: 1.5, 2.6 and 4 GHz. Three contrasts of relative permittivity between the aggregates (ε_a) and the matrix (ε_m): ε_a=5 ε_m=7, ε_a=5 ε_m=13 and ε_a=7 ε_m=13 have been considered. In this study, the conductivities of the aggregates and the matrix have been considered the same, constant and equal to 0.02 S.m^{-1}. For both aggregates and matrix, the relative permeability and the magnetic loss are constant and respectively equal to 1 and 0 Ω/m.

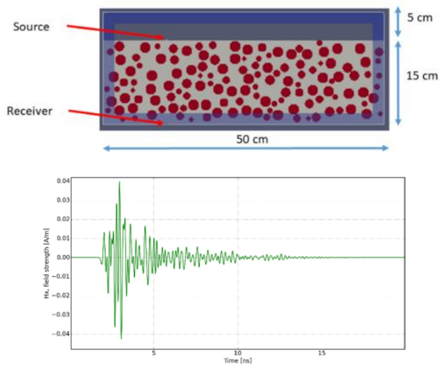

Figure 1: 2D geometry and dimensions of the concrete model and typical simulated signal

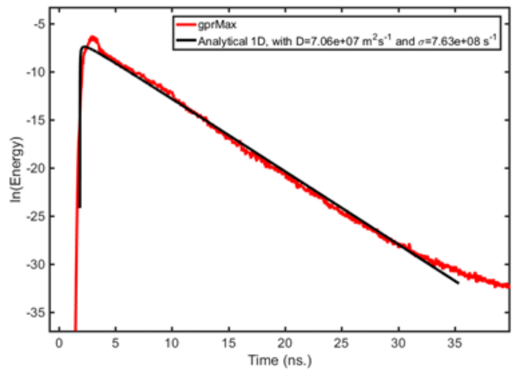

Figure 2: Fitting the 1D analytical solution of the diffusion equation with the solution given by the model for a frequency of 4 GHz

[2] [ROSS 99], [RYZ 96]

[3] [QUI 12], [SCH 11]

[4] [WAR 16]

The diffusion of electromagnetic energy in the concrete sample can be modelled by one-dimensional diffusion equation as the one used by Anugonda et al[5] , originally developed for elastic wave. In this study, Equation (3) in their publication will be used to fit the GPR signal obtained with simulated data.

The steps are the following: First we compute each A-scan (84 in total), then we compute the coherent signal, which is the mean of all the A-scans. Therefore, we subtract this coherent signal from each A-scan, which let us have the incoherent part (coda) of the signal for each A-scan. The coda from each A-scan is squared to have the corresponding energy and a mean energy is calculated from all the A-scans. Following that, natural logarithm of this energy is computed and fitted with the 1D analytical solution of the diffusion equation by matrix inversion with matlab ©. Finally, the diffusivity D and the dissipation σ are deduced. The precision of the fit is evaluated by the Normalized Root Mean Square Deviation (NRMSD). The normalization is carried out with the maximum minus the minimum values from the numerical simulation.

3. Results

Figure 2 shows a fit at frequency of 4 GHz for small-stones and relative permittivity contrast of ε_a=7 ε_m=13. Values of D=7.06e7 m^2s^{-1} and σ=7.63e8 s^{-1} are deduced. We have repeated the procedure for the studied parameters and have obtained values of D and σ with NRMSD ranging from 1.6 % to 4.2 %.

Figure 3 presents the comparison of D values for the three relative permittivity contrasts considered in this study. It is seen that D decreases with frequency for the relative permittivity contrasts of ε_a=5 ε_m=7. For the other relative permittivity contrasts, the effect of frequency is almost inexistent. Moreover, if we calculate the EM velocity in concrete corresponding to the relative permittivities of 7 and 13 at a frequency of 1.5 GHz, the velocity increases by a factor of 1.3. In the same way, if we calculate D at the same frequency 1.5 GHz, D increases by a factor 20 between relative permittivity contrasts of ε_a=5 ε_m=7 and ε_a=5 ε_m=13. It means that the observable D is 20 times more sensitive than the usual EM velocity at 1.5 GHz and for the considered relative permittivity contrasts.

Figure 4 presents the comparison of σ values between the three considered relative permittivity contrasts for small and medium-stones. We see that σ decreases with the frequency when the relative permittivity contrasts are ε_a=5 ε_m=13 and ε_a=7 ε_m=13, for both small and medium-stones. Whereas no obvious effect of frequency is observed for the relative permittivity contrast ε_a=5 ε_m=7. At a frequency of 2.6 GHz, between relative permittivity contrasts of ε_a=5 ε_m=7 and ε_a=5 ε_m=13, the EM velocity increases by a factor of 1.3 while σ increases by a factor of 6 at the same conditions. It means that σ is six times more sensitive than the EM velocity in this case.

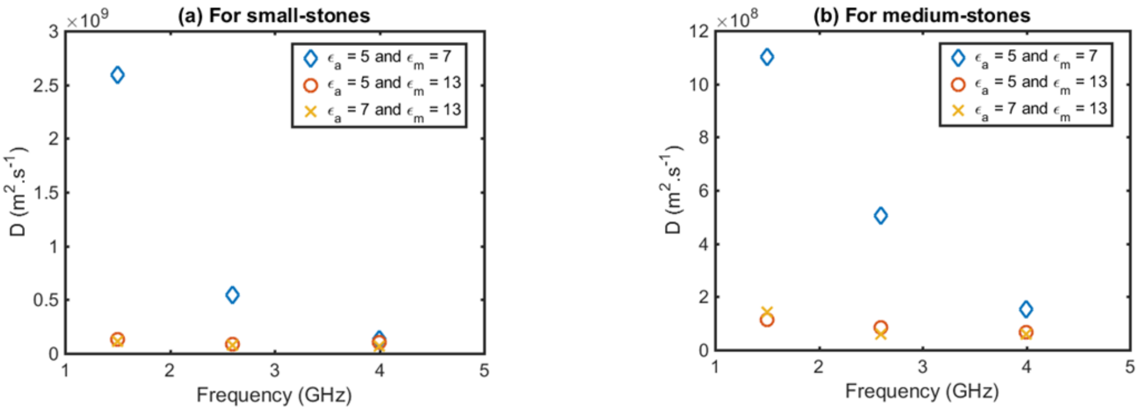

Figure 3: Comparison of D values between the three considered permittivity contrasts for (a) small-stones and (b) medium-stones

[5] [ANA 01]

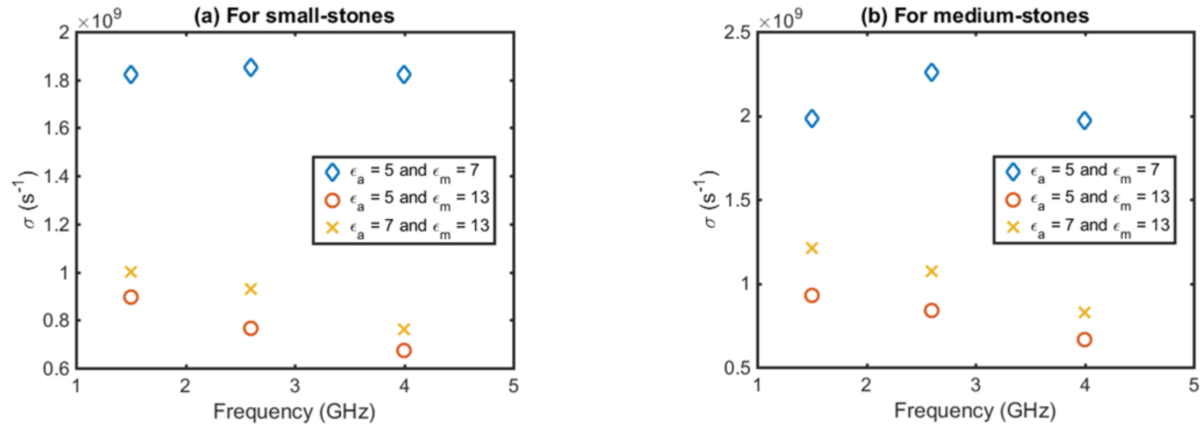

Figure 4: Comparison of σ values between the three considered permittivity contrasts for (a) small-stones and (b) medium-stones

4. Conclusions

We have demonstrated in this paper that the dissipation σ and "diffusivity D" can be used as new electromagnetic parameters to characterize the structural integrity of concretes. Indeed, in the most favorable cases, they are 6 to 20 times, respectively, more sensitive than the EM velocity, common observable used in Non Destructive Testing of concrete. These coefficients have been obtained by modelling the multi-diffusion of electromagnetic waves in concretes. D and σ are sensitive to the frequency of measurement, to the size of the aggregates and also to the relative permittivity contrast between the aggregates and the matrix. Future work will be to take into account the variability of the conductivities and 3D modelling with commercial antenna. It is also planned to make experimental measurements in order to transfer this knowledge to practical applications.

5. Acknowledgment

This project has been funded by the French Government project "Investments for the future" whose management has been committed to the French National Radioactive Waste Management Agency (Andra).

6. References

[ANA 01] ANUGONDA, P., WIEHN, J. S. & TURNER, J. A. « Diffusion of ultrasound in concrete ». *Ultrasonics* 39, 2001, p 429–435.

[QUI 12] QUIVIGER, A., PAYAN, C., CHAIX, J.-F., GARNIER, V. & SALIN, J. « Effect of the presence and size of a real macro-crack on diffuse ultrasound in concrete ». *NDT & E International* 45, 2012, p 128–132.

[ROSS 99] van ROSSUM, M. & NIEUWENHUIZEN, T. M. « Multiple scattering of classical waves: microscopy, mesoscopy, and diffusion ». *Reviews of Modern Physics* 71, 1999, p 313-371.

[RYZ 96] RYZHIK, L., PAPANICOLAOU, G. & KELLER, J. B. « Transport equations for elastic and other waves in random media ». *Wave motion* 24, 1996, p 327–370.

[SBA 06] Sbartai, Z. M., Laurens, S., Balayssac, J.-P., Ballivy, G. & Arliguie, G. « Effect of concrete moisture on radar signal amplitude ». *ACI materials journal* 103, 2006, p 419–426.

[SCH 11] SCHURR, D. P., KIM, J.-Y., SABRA, K. G. & JACOBS, L. J. « Damage detection in concrete using coda wave interferometry ». *NDT & E International* 44, 2011, p 728–735.

[WAR 16] WARREN, C., GIANNOPOULOS, A. & GIANNAKIS, I. « gprMax: Open source software to simulate electromagnetic wave propagation for ground penetrating radar », *Computer Physics Communications*, 209, 2016, p. 163–170