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Description of the general outlines of the French project SENSO – Quality assessment and limits of different NDT methods

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ABSTRACT

The management and maintenance of the built heritage is one of the main concerns of the owners of concrete structures. Engineers wish to obtain quantitative information about concrete properties and their variability. Non-destructive testing (NDT) is very popular in this context as it quickly provides relevant information on the integrity and ageing of the material, but several kinds of indicators representative of the concrete condition need to be evaluated. Combining NDT methods is currently considered as one of the most appropriate ways to improve the quality of the diagnosis of concrete structures. This paper describes a French project named SENSO (Strategy of non-destructive evaluation for the monitoring of concrete structures) devoted to developing a methodology for the non-destructive evaluation of concrete based on a multi-technique approach. The main objective of the project was to define the sensitivity of the techniques (ultrasonics, radar, capacitive and resistivity) and the variability of the evaluation for each indicator concerned. To achieve this, a large experimental programme, involving a representative range of concretes and several indicators, was carried out. A database linking the measured values by NDT and the indicators allowed the different measurements to be distinguished in terms of quality (linked to the variability) and in terms of relevance for the characterisation of each indicator. The added value of the combination of techniques was obtained by means of data fusion. The methodology developed in laboratory conditions, involving both evaluation of the indicators and data fusion, was tested on full-scale models in which the indicators were not fully controlled.

1. Introduction

This paper presents the objectives of a French project supported by the National Research Agency, the project SENSO, "Strategy of non-destructive evaluation for the monitoring of concrete structures". This project brought together several partners specialising in the development of non-destructive testing (NDT) methods, in the diagnosis of structures and in data processing.

The need for non-destructive evaluation of structures results from increasing needs for diagnosis and requalification (structural assessment for a change of use or an increase of the loading capacity) of structures. However, even though a large panel of potentially efficient non-destructive testing methods is available for the characterisation of material condition, the relationship between the NDT measurements and the indicators of the material condition is not clearly defined. There are several reasons for this: the strong variability of material properties, the coupled effects of the indicators and the difficulty of transposing the laboratory results to the site [1].

Moreover, the usual investigation strategies result in an accumulation of measurements however, in many cases, the information provided is not fully explored, either because their degree of reliability is unknown (many sources of uncertainty, intrinsic variability of the properties not taken into account), or because no advantage is really taken of the multiplicity of the investigations, measurements being rather analysed one by one than really exploited in combination [2]. From this observation, SENSO project aimed to propose a methodology for the non-destructive evaluation of some indicators related to the durability of concrete by means of a combination of NDT methods: electromagnetic (radar), acoustic (ultrasound), electric methods (capacitive technique and resistivity), infra-red thermography and surface permeability, etc. The indicators of concrete condition selected were: porosity, E-modulus, compressive strength, water content, chloride content and depth of carbonation. For each indicator, the objectives were to evaluate its value (average and degree of variability) and to estimate the degree of reliability of this evaluation. Different studies

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on the topic of NDT methods combination are published, sometimes with results obtained from SENSO project, but generally only a part of the methodology is described. The objective of this paper is to give an overview of the project and to detail the methodology even if only partial results are presented. More precise results can be obtained in different papers [3–5].

An important experimental study was carried out on controlled samples (homogeneous regarding the variation of indicators inside). A large database was built up and explored to draw relationships between NDT measurements and indicators. A procedure of data fusion was developed to merge the data collected from several NDT methods. Full-scale models were also made and investigated in order to test the data fusion procedure in the case of non-homogeneous properties of concrete and in the presence of reinforcement. Finally, the procedure was tested on structures in service. This paper focuses only on the results obtained on controlled specimens in the laboratory and on the investigations on full-scale models. More details and results regarding on-site testing can be found in other papers [6–8].

2. Outlines of the SENSO project

The main scientific and technical issues of the SENSO project were related with a methodology of the evaluation of the concrete structures, from the acquisition of relevant data in situ to the treatment and the analysis of this data with the aim of extracting reliable and useful information. The data resulting from the testing can be classified in two categories of indicators, which may be interdependent [9]:

- pathology indicators (carbonation and chloride content in this project),
- durability indicators (porosity, moisture, E-modulus and compressive strength in this project).

The first category gathers together the data that provide information on the structural condition, in relation with the performance requirements it must satisfy. Knowing their value makes it possible either to directly evaluate the performance level of the structure, or to improve knowledge about the mechanisms by which the performance levels regarding the structural aspects are degraded (for example carbonation can be considered as durability indicator related to reinforcement corrosion which affects the structural performance of the structure). The second category groups together indicators that allow estimating the future evolution of the structure, and thus its residual lifetime. These indicators can be used as inputs to models of recalculation and, combined with the pathology indicators, allow assessing the residual design life of the structure.

The objective of the SENSO project was to propose a methodology for non-destructive evaluation of six indicators listed above.

For each indicator, the objectives were to evaluate its value (average and degree of variability) and to estimate the degree of reliability of this evaluation.

The project focused on a multi-NDT-methods approach. The following techniques were used within the framework of the project: electromagnetic (capacitive method and radar), acoustic (ultrasound) and electric resistivity. Other techniques that were used during the project included surface permeability, rebound hammer and pull-out tests.

Regarding ultrasonic methods, both surface waves and longitudinal waves were used. Surface waves were either generated and received by sensors without contact [10] or generated by a sensor with contact and received by a laser interferometer [11]. The radar technique used ground coupled antennas with a frequency in air of 1.5 GHz. The radar and the antennas were developed by Geophysical Survey System Inc., (GSSI). The measurements explored the potential of the direct wave propagating along the air-material interface [12]. It has been demonstrated in previous studies that both the velocity and amplitude of this wave are sensitive to moisture and to chloride contamination [6,12,13]. The principle of the capacitive technique was based on measuring the resonance frequency of an oscillating circuit (about 30–35 MHz) between several electrodes place on the upper face of the concrete slab [14]. A calibration yielded the concrete relative permittivity ε'_r, which was mainly related to the water content and the mix components. For resistivity measurement, two devices were used, the usual Wenner probe developed by PROCEQ® and a four-probe square device developed by Lataste [15]. With this specific device, measurements can be performed for two orthogonal directions of electrical current injection, and for two spacings between the probes (5 and 10 cm), at each investigated point.

The approach consisted firstly of characterising different concretes in which the various indicators were controlled in laboratory conditions. Eight concretes were involved with different W/C ratios (i.e. different porosities) and different aggregates. The concrete indicators (porosity, E-modulus, compressive strength, etc.) were determined by destructive tests. For each concrete, two or three samples were investigated in order to evaluate the variability of the NDT measurements.

A large database (about 200,000 data) was provided by means of statistical data analysis and data fusion. Relationships between NDT measurements and indicators were determined and the variability analysis distinguished among the NDT methods. The quality of the correlation between NDT measurements and indicators was also used as a relevance index. To better improve the implementation of different techniques in combination, a specific procedure of data fusion was also developed in the project based on the theory of possibilities. After laboratory measurements, additional investigations were performed on real-scale elements for which the indicators were not controlled but able to be assessed retrospectively. Finally, some tests were also performed on real structures.

The partnership involved academic partners (University of Bordeaux, Ecole Centrale of Lille, University of Marseille-Aix en Provence, LCPC of Nantes, University of Nice Sophia Antipolis, University of Toulouse, ONERA Toulouse) and companies (EDF, EXAM-BTP, GETEC, Port authority of Nantes Saint Nazaire, SOVEP).

3. Description of the program of SENSO project

3.1. Laboratory tests on controlled slabs

Laboratory tests were carried out on a representative range of concrete mixtures to establish a set of empirical relationships between non-destructive measurements and indicators. The concrete was considered as a homogeneous material at this stage. Cross-tests were carried out by all the partners, using all the NDT methods involved in the project and on the same samples, with the aim of carrying out data fusion.

About 135 slabs (50 cm × 25 cm × 12 cm) implementing 8 different compositions of concrete were built. The concretes analysed covered a sufficiently wide range of porosity to be representative of what is regularly found in structures. The properties of the material in relation to the indicators (water content, Young's Modulus, porosity, compressive strength) were considered as homogeneous in all the volume of the slab. The objective was to evaluate the indicators by traditional destructive methods and to determine relationships between the NDT measurements and these indicators. The non-destructive investigations were divided into three parts. The first one was intended for the characterisation of the porosity,