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**Effectiveness of Non-Destructive Methods for the evaluation
of structures affected by Internal Swelling Reactions:
Electric, seismic and acoustic methods**

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Abstract:

Internal swelling reactions (ISR) (which mainly comprise alkali-silica reaction, alkali-carbonate reaction, delayed ettringite formation, etc) are pathologies that affect the long term durability of concrete structures. The reactions are apparently characterized by series of closely spaced, tight map cracks with wide cracks appearing at regular intervals and excessive tensile stresses in rebars. This phenomenon is alarming for affected structure managers as it deals with people safety and structures operation. Moreover, there is no easily implemented way to stop the reactions. Prediction of concrete expansion, structural degradation and assessment of efficiency and periodicity of repair works are crucial issues.

The aim of this work is to explore the applicability of some Non Destructive Techniques (NDT) of investigations (electric, seismic and acoustic methods) to differentiate the structure zones affected and not affected by the ISR for different exposure conditions. The results highlight that the coupling between some of those ND Methods can reduce the measurement uncertainty and eliminate the factors that may influence the characterisation of the structure parts affected by the ISR. Nevertheless, for the complete structure reassessment, it is desirable to also refer to global geometrical/topographical survey and to destructive analysis methods on some cored samples for chemical analysis, petrography and dimensional measurements.

Keywords: Internal Swelling Reaction, AAR, DEF, ND Techniques, Concrete structures durability, assessment of structures, structures survey.

1. Introduction:

Internal swelling reactions (ISR) can affect concrete structures by causing cracking and material expansions which lead to degradation of structures mechanical behaviour. These pathologies mainly consist in alkali-aggregate reaction (AAR) and/or delayed ettringite formation (DEF). These chemical reactions can cause internal disorders non directly visible, and external disorders that may be observed at the surface of structures¹⁻⁴.

The visual measurements of the cracking index and the relative distance measurement are currently used to characterize the overall cracking and the global swelling. Following the survey methodology based on these informations, the structural diagnosis approach is well controlled and documented⁵⁻⁶. Moreover, these informations are quantitatively used for the numerical analysis of the structure in its present state and prognosis validation of possible repair⁷⁻¹⁰. However, it requires monitoring over time and the condition of the structure must have reached a sufficiently advanced level to take the decision to monitor the structure effectively.

On the other hand, Non Destructive Techniques (NDT) could be interesting in the case of a preliminary diagnosis before the occurrence of visible disorders due to ISR at a given time of the structure-life when the sensitivity of the structure or risk analysis based on general documentation rise such a concern. In fact, it would be interesting to develop a NDT-based diagnosis methodology by comparing two areas made of the same concrete within the structure that may be respectively affected and not affected by the ISR (possibly due to different exposure conditions). This method would be instantaneous and could help rapidly evaluate a large number of structures. However, it is clear that this preliminary NDT diagnosis should be confirmed by microscopic examination, petrography and chemical analysis of some cored samples.

Presently, there are still no reliable procedures involving non-destructive techniques for the characterization and assessment of damage associated with ISR. Therefore, very few structures have been monitored by NDT methods and laboratory research has been mainly limited to the methods of ultrasonic waves velocity measurements¹¹⁻¹⁵.

This paper aims to describe and qualify the electric, seismic and acoustic NDT methods that could be used to measure some characteristic parameters of the causes and consequences of ISR at the material scale, aiming at a preliminary diagnosis approach.

Presence of water in the heart of the material (at a saturation degree above 80% for ASR, possibly 90% for DEF) is a condition which is apparently necessary for the chemical reactions to occur^{16,17}. Electric, seismic and acoustic methods are sensitive to this parameter but also to changes of the elasticity modulus E and to the presence of cracks caused by ISR development. Indeed, the ISR induces mechanical alterations with a decrease

of elasticity modulus E and evolution of the tensile and compressive strengths⁷. The effectiveness of electric resistance, mechanical wave propagation and seismic tomography methods for the evaluation of structures affected by ISR has thus been studied and is discussed in the following.

2. Electrical and electromagnetic methods

Water content has a critical influence on concrete durability and its evaluation is necessary for the prediction of structure aging. Water in concrete pores makes it possible for some endogenous chemical reactions to occur leading to concrete cracking, such as AAR and DEF. Furthermore, this presence of water in concrete structures is important for other processes engaging the structures durability as the penetration of chloride ions and/or concrete carbonation which are two causes of embedded steel corrosion. For those reasons, concrete water content on site evaluation is highly desirable.

However, the electrical and electromagnetic methods are sensitive to this moisture content of the material and to the ion concentration in the pores solution, even if they can permit to characterize the internal chemical processes in the concrete. In this context, three techniques have been tested and discussed: radar technique, capacitive method and electrical resistivity measurement.

2.1. Radar

Ground Penetrating Radar (GPR) is a geophysical non-destructive testing technique for the evaluation of structural elements and materials and is very useful for the detection of embedded objects (steel reinforcement, prestressing/post-tensioning strands, ducts, etc...), material interfaces (such as a slab to sub-base interface), and significant internal defects such as large voids and flaws in concrete^{18,19}. The technique involves the use of a high-frequency radar antenna which transmits electromagnetic radar pulses along a longitudinal scan at the surface of the concrete. The frequency of the antenna will provide deeper scans with less detail or shallower penetration depths with more detail. This method is based on measurement of the propagation time and the waves attenuation that are either reflected on a steel reinforcement or on the opposite side of the concrete structure, or transmitted at the surface between the transmitter and receiver. This latter configuration has the main advantage of not being dependent of any reflector, whose position, form or nature is never completely controlled. The depth of investigation depends on the material, its condition and on the frequency of measurement used. For a "normally dry" concrete, it can exceed one meter depending on the frequency.

Many research teams have studied the influence of the propagation velocity of radar pulses and their amplitude versus the water and chloride content of concrete²⁰⁻²². Indeed, they noticed the high sensitivity of these two electromagnetic observables, namely waves velocity and amplitude decrease when the water content increases.

As regards more particularly the chloride content, there is a greater attenuation of the signal amplitude because the material becomes more conductive.

However, little information is available on radar tests performed on concrete structures affected by ISR. Some works have shown that the expansion of some structures leads to damping of the wave amplitude. Their interpretation is that the ISR generates micro-cracks which increase the porosity and therefore the water content. To study the effectiveness of the GPR technique in detecting structure zones affected by ISR, a series of measurements was carried out on a bridge located in Northern France. This bridge is affected by ISR on one side of its pier caps, caused by water infiltration²³.

The GPR technique was applied along two horizontal profiles of 12.60 m long at the middle of transverse reinforcement, so sixty points measurement in total have been carried out.

The measurements presented in Figs 1 and 2 show the effects of ISR, in the zones where it has been detected, on the amplitude and the estimated dielectric constant which is directly deduced from the velocity of the direct wave. Two zones can be highlighted from these observables which correspond to those characterizing the presence or absence of ISR in the pier cap. Indeed, the zone located beyond 9 meters is potentially affected by ISR since the amplitude of the radar waves is clearly damped in this zone compared to that not affected (where this amplitude remains almost constant). These results are confirmed by the measurements of the dielectric constant which show that this last one becomes important in the affected zone of the pier cap (Fig. 2).

These results are confirmed by the study of Rivard *et al*²⁴ which shows a variation of about 75% between the measured amplitude of a non affected concrete and the zone most affected by the ISR.

The attenuation of the Radar waves amplitude is particularly due to the micro-cracking generated by ISR leading to an increase in porosity and to the increase in water content of concrete which occur by adsorption. Thus, the dielectric polarization and electrical conduction become higher which explains the dielectric constant increasing (Fig.2).

The use of the radar technique can delimit suspicious zones in the structures. As the electromagnetic waves are sensitive to local variations in the concrete mix-proportions, current knowledge does not distinguish the presence of the ISR from other ageing phenomena. However, signs of decrease in wave velocity and amplitude in all cases are associated with high water presence (which may be associated to chlorides attack or ISR), and therefore may be associated with a pathology risk. The radar technique should be used to target zones to be studied more precisely, either with other non-destructive techniques, or by destructive methods investigations (on cored samples taken from suspicious zones).

(Figure 1)

(Figure 2)

2.2. Capacitive methods

The capacitive method for measuring moisture is based on the functional relationship between the permittivity of a substance and its moisture content. Permittivity is determined from the value of the capacitive transducer which is filled with the tested substance. The value of this transducer, including its dielectric loss, is determined by comparing it with a parallel tuned circuit which comprises inductance and capacitance, and is coupled through an inductance or a capacitance to a high-frequency generator¹⁹.

The principle of this technique relies on measuring the resonant frequency of an oscillating circuit (around 30-35 MHz) between two electrodes placed on the concrete. If we consider these two metal electrodes, they form with the surrounding material a dielectric capacitor, the capacity depends on the geometry of the electrodes and on the value of the relative dielectric constant of the material. In practice, this results in a resonant frequency that varies depending on the dielectric nature of concrete, which is mainly related to its water content, the nature of aggregates and the W/C ratio¹⁹.

Capacitive measurements were performed on concrete slabs (50*25*12 cm) with different W/C ratio (0.30, 0.45, 0.55, 0.65, 0.90) in order to evaluate the dielectric permittivity. The results show that for all the specimens tested in this study, the capacitive measurements vary linearly and depend on concrete texture²⁵ (Fig. 3).

Until now, there is no example in the literature about capacitive results on concrete affected by ISR. The technique seems to be complementary of the radar technique in the sense that it can be carried out at lower frequency (~35 MHz) in a zone where the permittivity changes are important and where it can give an idea about the evolution of the saturation degree with depth.

(Figure 3)

2.3. Electrical resistivity

The electrical resistivity is the ability of a medium to oppose the passage of an electric current. The measurement principle consists in injecting an electric current through the concrete and measuring the electrical response of the medium (resistance or potential difference). It is a direct current with a very low frequency (static regime).

According to the application case, this measure involves two or four electrodes.

The resistivity is sensitive to a number of parameters related to the nature and condition of the medium. These include: the mineralogical nature of cement, aggregates and additions, the relative proportions of these components, the porosity, the water content and salinity of the pore solution, the temperature. Thus, logically the

resistivity depends on the W/C ratio and on the compressive strength (the latter being correlated to the porosity of concrete). The resistivity also depends on structural features (normal and pathological) being able to prevent or to promote the current flow, e.g. the presence of reinforcement or cracking.

According to the concrete mix-design, age and exposure conditions, the resistivity varies in a range covering several decades (from some $\Omega.m$ for the fresh concrete to thousands of $\Omega.m$ for an old and very dry concrete). The resistivity should be therefore an appropriate and sensitive physical quantity to characterize a concrete, particularly its water content, its cracking state and the presence of chemical agents.

Currently, resistivity techniques are mainly applied, in addition to other techniques, to detect areas of possible corrosion of steel reinforcement²⁶⁻²⁸. New applications are developed and used also to map the surface of a concrete and detect areas of resistivity contrasts.

The publications related to ISR diagnosis using electrical resistivity measurements are very few²⁸. Only Rivard and Saint-Pierre appear to have conducted a pilot program with the necessary precautions²⁴. Their results do not distinguish clearly the concrete affected by ISR. Their analysis is that resistivity is sensitive to several parameters, the effects of which compensate each other in the presence of ISR. Fig. 4 shows an example of result which highlights the effect of the dry density and the water content on the electrical resistivity of the material²⁹. Indeed, the ISR development is favoured by a high water content and the presence of alkaline agents²⁰. These two factors contribute in principle to reduce the resistivity. However, the chemical processes of ISR lower the concentration of alkali on one hand, and produce an electrically resistant gel on the other hand. Moreover, the cracking induced by the swelling of the concrete, and the filling of the cracks by the gel contribute to the increase in resistivity.

At first, Rivard *et al.*³⁰ have made preliminary measurements of resistivity. They have shown a good correlation between resistivity and compressive strength, and especially a small but significant time evolution of the resistivity of the "reactive" slabs versus the "non reactive" slabs. The cracks filled with gel would help to increase the apparent resistivity in opposing the current flow.

The same authors estimate that the anisotropy of resistivity is correlated to the expansion degree of the specimens studied: the resistivity anisotropy is induced by the cracking degree of damaged concrete and is therefore a possible indicator of the induced cracking³¹. However, the measured apparent resistivities appear to have decreased with this expansion²³.

(Figure 4)

The study of Klysz *et al.* presents the measurement campaign carried out on the deck of the Marque Bridge located in Northern France²³. This bridge is affected by ISR pathology on one side of the pier caps, activated by water infiltration. According to the authors, the profile of apparent resistivity along the cap allows observing significant variations (Fig. 5). The low apparent resistivity values (less than 120 $\Omega.m$) coincide with the zone where ISR has developed and produced significant expansion. The local decrease of resistivity is explained by the higher humidity of concrete in the area affected by ISR. In fact, a high moisture degree is necessary to the ISR chemical process. In addition, higher humidity reduces the problems of electrode-concrete coupling and improves the quality of measurements²³.

(Figure 5)

In sum, studies linking the electrical resistivity to ISR phenomena in concrete are too few, and the available results and analysis have just permitted to delimit the affected zone of the structure.

3. Seismic and acoustic methods

The seismic and acoustic parameters are sensitive to certain physical properties and characteristics of concrete, but also to its composition and its microstructure. Indeed, all the contrasts and differences in shape, nature, size, density, mechanical properties in a structure have an influence on changes in wave propagation and hence in the ultrasonic measurements³². ISR generates isotropic and/or anisotropic micro-cracks and ASR produces a gel which can change the propagation of mechanical waves with regard to a sound material.

Three techniques based on waves propagation have been investigated: ultrasonic volume waves, resonant frequency method and seismic tomography.

3.1. Measurement of ultrasonic volume waves in transmission

The most usual temporal ultrasonic technique consists in simple measurements. The inferred velocity of the waves in the material is the key parameter. The European standard (EN 12504-4) defines the method for determining the speed of ultrasonic waves in concrete³³. This one may be related to the mechanical characteristics of the material and geometric characteristics of specimens. This requires a rigorous calibration³⁴. Correlations are often volatile and are valid in controlled conditions in terms of measurement and environment³⁵.

The European norm (EN 13791) defines the conditions for establishing these correlations³⁶.

The velocity measurement has to be captured at the time signal of the first arrival. This measure can be relative (between two synchronous receivers) or not (between the source and one receiver). In the latter case the starting time of the wave must be known.

The attenuation measurement consists of measuring the amplitude of the signal and quantifying its decrease. This less usual technique can also characterize the concrete, but industrial applications are not yet operational¹⁵. However, initial results suggest a high sensitivity of this parameter to changes in the concrete and particularly to the disorders resulting from the ISR. Indeed, these expansion phenomena lead to the appearance of cracks which change the sign of the wave velocities evolution from positive to negative values.

For the sake of qualification of this method, measurements of ultrasonic wave propagation have been performed on concrete samples with different expansion rates (0, 50, 75 and 100% of maximal sample expansion)³⁷. The states of degradation and degrees of micro-cracking of concrete could be distinguished. Indeed, the representation of the wave velocities over time may indicate the progression of cracking which is a consequence of swelling. When the evolution of the velocities is positive, it reflects the filling of cracks. Under the effect of internal stresses caused by the swelling reactions, cracks appear and lead to the change of sign of the wave's velocities evolution which becomes negative. The created cracks are sealed which causes further cracking and the crack-filling cycle continue, that reflects the oscillations observed in the results of measurements of ultrasonic wave velocity (Fig. 6).

(Figure 6)

Other tests have been performed on reactive and non-reactive concrete samples kept in two different environments (20 and 38 °C)³⁷. Fig. 7 shows that the propagation velocity of ultrasonic waves for non-reactive samples remains high in comparison with that of the reactive samples. This result is due to the changes in the concrete microstructure occurring with the ongoing expansive ISR (e.g., ASR gel product formation, ettringite formation and precipitation in the cracks, aggregate/paste debonding, cracking in the aggregate and paste). These observations have been confirmed by other authors who worked on in situ and laboratory concrete samples^{38,39}. They have shown that the velocity wave propagation decreased very slightly with the concrete expansion which (in the studied case of ASR) varied from 0 to 0.2%. However, the results obtained on in situ cores are less convincing than those in the laboratory. Two explanations are proposed: the heterogeneity of in situ concrete is larger and uncontrolled as compared to laboratory concrete, and the non-representativeness of the core sampling, because concrete of the samples may have evolved once extracted from the structure^{38,39}.

(Figure 7)

An other technique of data processing, namely the measure of the wave attenuation, seems relevant. The spectral response of the concrete specimen, subjected to an ultrasonic pulse, is measured in order to calculate the loss of

spectral gain (i.e. the attenuation). All the studies in this domain confirm the significant reduction of volume waves in the presence of ISR, which means the attenuation increasing with the structure expansion⁴⁰⁻⁴³.

3.2. Resonant frequency method

The resonant frequency method is one of the most interesting techniques for structural health monitoring applied to civil engineering structures⁴⁴⁻⁴⁶. The changes of the physical properties of the structure cause the variations of the modal parameters (mode shapes, resonant frequencies, modal damping)⁴⁷. Nevertheless, the capacity to detect a reduction of the stiffness resulting from ISR-induced damage depends on the environmental variability of the modal properties⁴⁸.

The principle of this method is to check periodically the structure by the impact of the force hammer. The transmission of the wave is initiated on one side of the structure and the reception takes place on the opposite side by using an accelerometer positioned directly opposite the force hammer. The resonant frequencies caused by the force hammer allow characterizing the mechanical condition of the structure. Thus, this method relies on the feasibility of vibration based health monitoring in controlled conditions.

An experimental study was performed on six beams subjected to ISR⁴⁷. Possible ISR influence on the resonance frequencies of ultrasonic waves caused by a force hammer was checked. The six beams (reinforced and unreinforced) had been manufactured with reactive and non-reactive aggregates and had been equipped with a series of accelerometers⁴⁹. The interpretation of the signals was carried out thanks to an analysis of the spectral density of acceleration measured⁴⁷ (Fig. 8).

(Figure 8)

Fig. 9 shows the evolution of ultrasonic waves frequencies with time. Before immersion in water, the resonant frequencies of concrete beams (reinforced and unreinforced) manufactured with non-reactive aggregates have turned out relatively constant and higher than those of beams with reactive aggregates (Fig. 9). Resonant frequencies of beams made with reactive aggregates show an early decrease that has reached 6 to 10% of initial values and then an increase with time. These results correspond to a loss of about 12 to 20% of stiffness for beams affected by ISR. After partial immersion in water, the values of the resonant frequencies increase and remain higher for beams with non-reactive aggregates. As previously well known, the presence of water in concrete increases the resonant frequencies⁴⁷. A thorough and careful interpretation is thus required to avoid artefacts due to moisture when monitoring structures affected by ISR.

In sum, the dynamic evaluation of structures is therefore a possible method of monitoring the development of damage caused by ISR in the structures, but there are still many issues to be clarified before its operational application.

(Figure 9)

3.3. Seismic tomography

The overall objective of this last type of investigation method is to produce an image describing the distribution of materials and/or their properties (based on mechanical vibratory response) in the structure. The different zones investigated correspond to the variations in the propagation velocity of compression waves, called “primary waves”, through the concrete⁵⁰. The tomographic image is based on three steps: data acquisition, simulation of these data in a synthetic model and finally the definition of solutions. The experimental data are the travel times of the seismic waves between each source point and each sensor location. The model is defined by the wave velocity considered in each node of a grid covering the whole tested structure.

Fig.10 shows an example that illustrates the type of seismic tomography visual output which can be obtained on a real structure⁵⁰. The variations observed in the velocities are very important and indicate a significant alteration of the material for the upper zones of the dam. The velocities measured vary between 2000 and 4500 m/s. Low velocities are assumed to be caused by cracks in the concrete, rather than by a simple reduction in the modulus of elasticity. When the velocity values are higher than 3000 m/s, the concrete is considered of good quality⁵⁰.

(Figure 10)

The application of this method in the case of real structures, with repeated investigations over time, is clearly possible and allows differentiating the zones affected by ISR from the non-affected ones⁵¹ (even though there may be artefacts due to distribution of moisture supply).

4. Discussion

This review has aimed to explore the applicability of some NDT of investigation to delimit the structure zones affected and not affected by ISR for different exposure conditions. As is clearly known, the ISR evolution generates micro-cracking and thus an increase in porosity and water content of concrete. This reduces the amplitude of the radar signal due to the increase of the attenuation by adsorption (dielectric polarization and electrical conduction). The attenuation by diffusion (diffraction of radiation on heterogeneities of dimensions comparable to the wavelength) can also intervene in this case due to the presence of cracks and thus an increase in the heterogeneity of the material. So all these phenomenon explain the effect of damage caused by ISR on the amplitude attenuation of the radar signal.

This GPR technique can be implemented in a complementary manner with the capacitive method. Since the capacitive technique can provide accurate results with respect to cover concrete, prior to extensive GPR investigations.

The resistivity measurement for on site concrete damage characterisation, in the frame of the non-destructive evaluation methods, can be complementary to the GPR and capacitive methods. This technique, easier to use and adapted to on site constraints, is also sensitive to the moisture degree and presents an interesting ability to characterise concrete damage and more particularly its cracks (the ability to assess cracks depth and opening). In any way, the coupling between the three methods may help engineers to give an original response to their problems of assessing damage degree of structures.

However, it has been shown that the sensitivity of pulse velocity method is too low to establish damage criteria associated with ISR whereas the attenuation variation associated only with ISR increase highly with the structure expansion. The variability of the reduction of the volume waves would make the ISR-structures characterization semi-quantitative (e.g. no damage, very low damage, low damage, high damage, etc...).

The applicability of the wave attenuation method can be effective if the investigated area of the damaged structure is reduced. In this case, the use of another ND method, namely the seismic tomography, can be helpful. In fact, in addition to its interest in allowing full accounting of the whole structure (and enabling a major tensile crack in the gallery to be located⁵⁰), this method can help in determining the more damaged areas on the structure by targeting zones of different quality.

Finally, the dynamic evaluation of structures seems to be a possible method of monitoring the development of damage caused by ISR. However, this method has to be applied with another ND technique for more accurate results (and identification of possible artefacts due to moisture distribution).

5. Conclusion

Six non-destructive methods were compared to assess their applicability regarding ISR damage in concrete structures. The following conclusions can be drawn:

- The use of the radar technique does not distinguish the presence of the ISR from other ageing phenomena, but it may delimit suspicious zones in the structures. The affected zones are characterized by a decrease in the amplitude of the radar wave according to the level of concrete expansion. The radar allows determining the zones with higher water content which is an indicator of ISR risk.
- The capacitive method could complement the radar technique and give information about the water content evolution with depth in the structures.

- The electric resistivity is very sensitive to different parameters such as moisture content and presence of chemical agents in the interstitial solution. Application of this technique could differentiate the more or less affected zones.
- The ultrasonic waves attenuation has been one of the most important techniques used for our purpose. It allows locating the zones where the mechanical properties decrease with the concrete expansion.
- The use of dynamic evaluation can inform about the stiffness reduction of the structures affected by ISR. Nevertheless, this method has to be applied combined with another technique due to sensitivity to moisture.
- The seismic tomography is one of the methods which permits full coverage of the whole structure and can locate a major tensile crack and its estimated depth.

All these conclusions give confidence in using non-destructive methods to detect the ISR-damaged areas in a structure suspected to be affected. However, all studies that could be used as references in the present review show that ND method described for the purpose are not effective when used alone to assess the damage of structures caused by ISR. Monitoring of structures affected by these pathologies should only be carried out by combining two or more techniques (acoustic, electric and seismic) for an accurate detection of damaged areas.

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Figure 8. Tested beam in the climatic chamber (38°C)
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