ADVANCES IN THE COMPREHENSION OF THE MECHANICAL BEHAVIOR OF STEEL CORROSION PRODUCTS.

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Summary The study presented below aims to develop the actual knowledge on mechanical properties of steel's corrosion products. This material shows a complex pattern at the microscale with various corrosion products and crack-like porosity. As a result, we have chosen to follow a coupled modelling and experimental approach at different scales.

CONTEXT

Accounting for the development of corrosion layers in residual lifetime calculations of reinforced concrete structures requires a good knowledge of the mechanical properties of these products. From literature, it appears that the characterization of the mechanical behavior of such corrosion products still remains to be done. The stakes are high, especially in the nuclear field, as the development of these products at the interface between the reinforcing steel and the surrounding concrete cover leads to concrete cracking. In usual computational models, the corrosion expansion is modelled by a fictitious thermal loading which can reproduce qualitatively the cracking facies of corroded reinforced concrete. However, the lack of knowledge about the kinematics of growth and mechanics of these products limits the prediction capability of such models. Consequently, our study aims to determine the mechanical properties of these products.

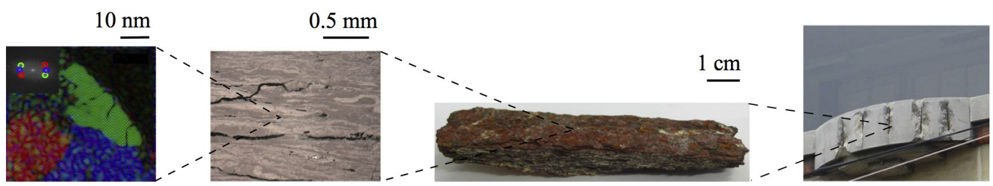

Figure 1. Corrosion products from reinforced concrete at different scales. From left to right: High resolution image by TEM of the crystallite sizes of goethite [1], optical microscope image, corrosion sample, corroded reinforced concrete structure [2].

In figure 1, corrosion from the reinforced concrete structure is an inherently heterogeneous porous material requiring a study on different scales. Hence, our study includes test campaigns and statistical analysis at the microscale, concurrently with homogenization calculations with simplified scheme and effective modulus calculations to obtain the elastic mechanical properties at the mesoscale.

MICROSCALE STUDY

We have performed microindentation tests coupled with Raman microspectrometry analysis to determined the mechanical properties of each products of the sample [3]. It turned out that the mechanical properties are not clearly distinct because of various degrees of mixing of the different products. To assist the interpretation of microindentation tests, we analysed statistically the data by Gaussian mixture models [4] for a mechanical interpretation of the microstructure heterogeneity.

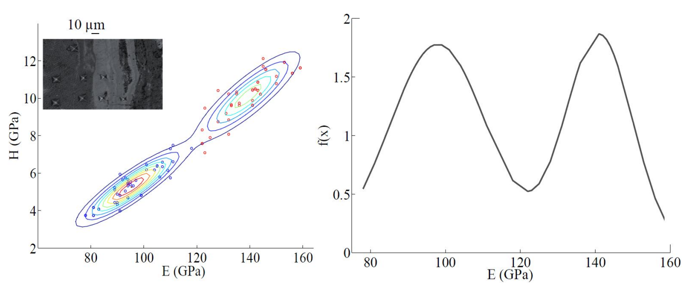

Figure 2. Exploitation of microindentation data by statistical mixture model. Data from the indentation test and Gaussian resulting from the mixture model.

As illustrated figure 2 each indentation point give us access to a local hardness and elastic modulus. From the grid of indents, we collected a set of data. With a statistical mixture model approach, we can determine several clusters that are

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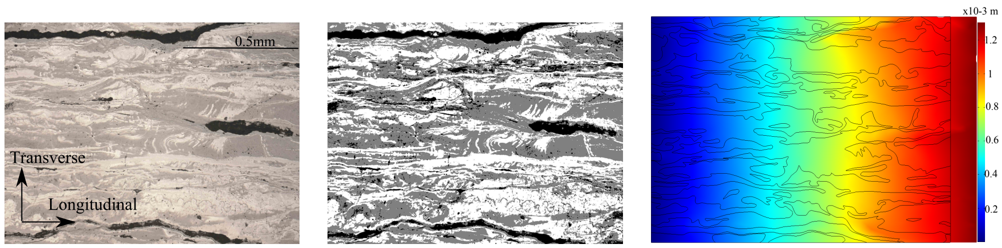
statistically mechanically different and can represent the phases present on the grid [5], [6]. As presented figure 2 the microindentation grid of our sample shows two clusters of respective mean elastic modulus equal to 95 GPa and 139 GPa.

INTEGRATION OF THE MICROSCALE STUDY AT THE MESOSCALE

The microstructure's characterization brings valuable information for homogenization calculations. The first approach has consisted of calculations of random media homogenization by self-consistent and generalized self-consistent schemes [7], [8], [9]. In the second approach, effective modulus calculations were performed with Comsol Multiphysics3.5a using numerical microstructures resulting from 2D images taken with an optical microscope and processed with Matlab2009 software. Those calculations were aimed to identify the mechanical properties at the mesoscale in a more realistic way, without over-simplifying the heterogeneous microstructure.



(a) Optical microscope.

(b) Image processing with Matlab2009b.

(c) Deformed shape and displacements after calculation.

Figure 3. Image of the corrosion sample.

Computation results on 2D images show that the calculated elastic moduli are systematically lower in the transverse direction (31 to 97 GPa), which corresponds to the direction of growth of the oxide layers. The elastic moduli obtained by the approach of random media and the longitudinal elastic modulus calculated by numerical homogenization are of the same order of magnitude, about 100 GPa. However, observations of the microstructure raise the problem of the existence of a Representative Elementary Volume on this type of microstructure which presents heterogeneities (cracks in our case) of significant size in the longitudinal direction, thus calling into question the conditions of separation of scales, a prerequisite for the use of homogenization approaches. To avoid this problem, a third approach has been followed, whereby random structures models are used to create fictive microstructures based on statistical data from 2D optical analysis.

CONCLUSIONS

This study is an important step in the knowledge of the mechanical properties of reinforced concrete corrosion products. From the microscale to the mesoscale, our study shows an elastic modulus which can be a hundred times higher than in actual simulations of reinforced concrete lifetime. Lastly, the mechanical properties identified in our study for the heterogeneous corrosion layers at the mesoscale, are intended to be confronted with ongoing oedometer corrosion tests performed on small concrete samples at the mesoscale.

Acknowledgements

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