École des Ponts
ParisTech

Imaging of Construction Materials and Geomaterials

7-8 July, 2016

École des Ponts ParisTech
Champs-sur-Marne, France

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Navier

LafargeHolcim

Acknowledgements

This Workshop is organized by Chair *Materials Science for Sustainable Construction*. We wish to thank LafargeHolcim for supporting financially both Workshop and Chair.

The celebration entitled *Five Years of Tomography at École des Ponts* has benefited from a support from the Laboratoire d'Excellence MMCD (MultiScale Modelling and Experimentation of Materials for Sustainable Construction) which is funded by the French government within the frame of the national program Investments for the Future, under grant ANR-11- LABX-022-01.

Thursday, July 7, 2016

8:30 – 9:40	**La Ruche**
Registration & Welcome Coffee	

9:40 – 11:00	**Cauchy**
Introduction	

9:40 Opening
S. Brisard, S. Meulenyzer, F. De Larrard

10:20 30 Years of Imaging and Modeling Building Materials at NBS/NIST: From PIXAR to MICROCHAR
D.P. Bentz

11:00 – 13:00	**Cauchy**
Multimodal Images	

11:00 Hierarchical Segmentation of Multimodal Images
M. Dalla Mura

11:40 Multiscale Imagery of Cement Paste: Relation with the Confined Transport of Water
P. Levitz

12:20 High-Resolution Spectromicroscopy of Cementitious Materials
P. Monteiro

13:00 – 14:00	**Ifsttar restaurant**
Lunch	

14:00 – 16:00	**Cauchy**
Damage and Cracking	

14:00 About Cracks Imaging in Cementitious Materials
D. Bernard

14:40 New Ways to Look at Fracture Processes in Concrete
E. Landis

15:20 On the Use of Digital Volume Correlation for the Identification of the Crushing Behavior of Plaster
F. Hild

16:00 – 16:40	La Ruche
Coffee break	

16:40 – 18:00	Cauchy
Fluid Transport	

16:40 3D Imaging of Moisture Distribution and Transport in Early-age Cementitious Materials
P. Lura

17:20 3D Pore Scale Imaging as a Tool to Understand Multiphase Flow in Porous Media
S. Youssef

Friday, July 7, 2016

9:00 – 9:40	Cauchy
Microscopy	

9:00 Chemical Imaging in Cementitious Systems
K. Scrivener

9:40 – 10:00	La Ruche
Coffee break	

10:00 – 12:00	Cauchy
Algorithmic and Material Developments	

10:00 Optimisation Methods for Tomography
H. Talbot

10:40 Cross-scale 3D Characterization of Complex and Heterogeneous Geomaterials with X-ray Micro-CT
A. Sheppard

11:20 X Ray 3D Imaging of Construction Materials
E. Maire

12:00 – 13:00	Ifsttar restaurant
Lunch	

13:00 – 14:20	**Cauchy**

Synchrotron Tomography

13:00 Realtime 4D Tomographic Microscopy: the SLS Experience
M. Stampanoni

13:40 PSICHE: Synchrotron Tomography and Diffraction for in-situ Experiments
A. King

14:20 – 14:30	**Cauchy**

Closing words
S. Brisard, S. Meulenyzer

14:30 – 16:00	**Cauchy**

Five Years of Tomography at Laboratoire Navier *(Chair: M. Bornert)*

14:30 Birth and growth of a federative multi-scale project
M. Bornert

14:45 3D Detection and Characterization of Damage in Quasi-brittle Heterogeneous Materials
C. Chateau

15:00 Measurement of the Damage Process in Highly Filled Elastomers
P-A Toulemonde

15:15 Measuring grain displacements from X-ray tomography projections: a time-saving method
M.H. Khalili

15:30 X-ray Tomography to Study the Mechanical Behaviour of Structural Materials
N. Guéninchault

15:45 Flows of Suspensions of Particles in Yield Stress Fluids Studied by X-ray Microtomography
N. Lenoir

16:00 – 17:30

Reception and Visit of the Tomography Facility

30 Years of Imaging and Modeling Building Materials at NBS/NIST: From PIXAR to MICROCHAR

Dale Bentz

National Institute of Standards and Technology (NIST)
Gaithersburg, Maryland, 20899, United States

Computer image processing and quantitative image analysis have become mainstays of both the academic and industrial communities during the past 30 years. This presentation will review research conducted at NBS/NIST during this era on polymeric and inorganic materials. In the mid 1980's, NBS developed its first home-built image processing system for the analysis of defects in building materials using both video and infrared cameras. From this initial effort, it was subsequently recognized that digital imaging could be equally applied to computer modeling, with the NBS/NIST cement hydration models being one primary example of this application. Here, computer imaging is critical for providing quantitative phase composition and location information to use as model inputs, while also providing the framework for 2-D and 3-D simulations of microstructure development. These models, initially developed in the late 1980s, continue to be employed worldwide in the present day. More recent research has focused on examining microstructure and water movement in cement-based materials using both X-ray and neutron imaging techniques and the coupling of image analysis/preprocessing with Multiphysics simulations to validate the underlying models and provide real world performance and service life predictions. Throughout this time period, NBS/NIST has also emphasized the distribution of these models and analysis routines to the end-user community. The Visible Cement Data Set will be highlighted as one example of such technology transfer.

Hierarchical segmentation of multimodal images

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This talk deals with the problem of multimodal segmentation, that is how to find a partition starting from images of the same objects acquired by different sensors (modalities).
The availability of images acquired by different sensors is of particular interest since joining diverse information sources allows one to have a more accurate perception of the imaged objects.
However, performing image segmentation jointly on several modalities is a challenging process: how to preserve and exploit the complementarity of the different modalities and how to get rid of their redundancy?
In this work we consider a segmentation approach that deals with hierarchical representations of the image content.
We address the problem of the joint segmentation of images with different characteristics by using the recently proposed structure of braids of partitions, which can be considered as an extension
of the concept of hierarchies of partitions. Specifically, we derive a novel and practical architecture implementing the fusion of hierarchical representations based on braids of partitions.
Formulating the segmentation process in an energetic framework it is possible to obtain segmentation maps, considering joinlty different modalities, that are optimal with respect to some criterion (defined according to the application). The validation of the proposed methodology is conducted using various multimodal data sets.

Multiscale imagery of cement paste: relation with the confined transport of water

Pierre Levitz

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Most of natural or industrial geo-materials like sedimentary rocks, shale or cement pastes are made of an intricate clustering of polydisperse grains. For many of these materials, the particle organization on a length-scale ranging from nanometer to several micrometers is a cornerstone to properly understand transport properties (diffusion-permeation) and mechanical strength. In this context, micro and nano X ray microcopies, small angle X ray and neutron scattering (SAXS and SANS) and soft X-ray ptychography are attractive and no destructive tools for the investigation of the structural evolution of these strongly disordered systems. These experiments have the ability to probe a hierarchical organization on a large length scale ranging from nm to several hundred mm. This multimodal structural analysis offers the possibility to use 3D reconstructions and to build constrained models mimicking the geometrical features observed at different length scales. These models can then be used to compute mechanical and transport properties allowing comparison with the experimental determinations. In this conference, we first present some strategies to image at different length scales the structure and the time evolution (the setting) of the cement paste. Analysis and modeling using a colloidal and/or a ”granular” approach is presented, allowing to test and to discard some microstructure hypothesizes. In the second part and in relation with the geometrical constraints generated by image analysis, we discuss the diffusive transport of water inside the cement paste which is known to be strongly hindered. An intermittent dynamics involving adsorption and relocation inside the pore space is especially emphasized.

High-resolution spectromicroscopy of cementitious materials

Paulo Monteiro

University of California at Berkeley (UCB) – United States

Our research group has been using synchrotron radiation to characterize and optimize the nano and microstructure of advanced construction materials. I will discuss how three-dimensional tomographic images are providing fresh new insights into the complex nature of composite materials and how this information coupled with XANES done at the nanoscale can be used in the design of improved materials. The lecture will also cover the exciting goal of producing x-ray images with a spatial resolution of 1 nm.

About cracks imaging in cementitious materials

Dominique Bernard

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Cracks are omnipresent within cementitious materials, and their characteristics (number, size, density, shape, etc.) are key parameters for estimating any physical properties. X-ray computed micro tomography (XCMT) is an unrivalled technique to image these cracks, mainly because it is a 3D technique, a non-destructive one, at least for the sample, and it provides high-resolution images. Logically, literature contains a huge number of studies where XCMT is used to characterize, in 3D or 4D, crack network in various cementitious materials. The first part of this presentation will consist in different examples of cracks imaging during in situ experiments. Based on these illustrations, the question of sample representativeness will be discussed taking into account the different objectives of the experiments.

New Ways to Look at Fracture Processes in Concrete

Eric Landis

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The Fracture Process Zone (FPZ) is a common device for representing a variety of energy dissipation mechanisms in quasi-brittle materials. As a modeling device, it is a convenient way to represent the many different microstructure features that add toughness in the vicinity of the crack tip. In some applications it is enough for us simply to know the total contribution from all the different mechanisms. However, in other applications it could be extremely useful to better know the relative contribution of the different effects. For example, in the case of fiber reinforced concrete, it may be desirable to have quantitative information on the specific contribution of the fibers. Using x-ray computed tomography, combined with simple micro-mechanical information, we are in a position to measure specific toughening mechanisms in a way we have not been able to before. Quantitative 3D imaging techniques are allowing us to measure characteristics of fiber-crack interactions, pullout, as well as crack branching. Through these measurements, coupled with other interrogation techniques such as acoustic emission, we are able to trace the nature of damage progression through the development of a fracture process zone. Recent work is directed at validating models that are able to explicitly incorporate micro-mechanical information in such a way to enhance predictive simulation tools.

On the Use of Digital Volume Correlation for the Identification of the Crushing Behavior of Plaster

Amine Bouterf, Jérôme Adrien, Eric Maire, Xavier Brajer, François Hild[1], Stéphane Roux

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Compaction of the core of plasterboard is one of the limiting phenomena for its mechanical performance. This mechanism is studied in a (standardized) nail-pull test and an indentation test. A cylinder made of foamed gypsum is indented in-situ in an X-ray lab tomograph with a nail or a sphere of millimeter radius. The experiments show that foamed plaster displays a sharp transition between an undamaged state (with a linear elastic behavior) and a compacted state with collapsed porosity under the indenter. Tomographic acquisitions of the sample under load associated with a global version of Digital Volume Correlation allow displacement fields to be measured at different load levels. However, because of the heterogeneous nature of the tests, a fine spatial resolution of the displacement fields is required to measure the strains at the crushing limit. A dedicated procedure exploiting computed displacement fields within the digital volume correlation procedure is utilized. It allows for the quantification of stress fields that are post-processed to identify the crushing criterion. It is shown that this analysis is consistent with more macroscopic oedometric and compression tests.

References

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Bouterf A., Roux S., Hild F., Adrien J., Maire E., Meille S., Digital volume correlation applied to X-ray tomography images from spherical indentation tests on lightweight gypsum, Strain, 50(5), 444-453 (2014).

Bouterf A., Adrien J., Maire E., Brajer X., Hild F. Roux S., Failure mechanisms of plasterboard in nail pull test determined by X-ray microtomography and digital volume correlation, Experimental Mechanics, submitted (2016).

3D imaging of moisture distribution and transport in early-age cementitious materials

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The presence of water and its temporal and spatial distributions influence several processes that are critical to cementitious materials in the first hours to days after casting, including microstructure development during hydration, drying and autogenous shrinkage (which may lead to early-age cracking) and water-curing of concrete. In all these processes, microstructural changes and fluid transport are coupled phenomena, meaning that the fluid transport will influence the microstructure and at the same time changes in the microstructure (cracking, porosity changes) will affect the transport properties of the cementitious material, thus the water distribution. Novel non-destructive / non-invasive imaging techniques for probing simultaneously the microstructure and the moisture distribution provide data for validating coupled numerical models that consider the mutual interactions of cement hydration and transport.

The first part of this presentation shows examples in which neutron tomography (performed at the Paul Scherrer Institute, Switzerland), alone or in combination with X-ray tomography, was used to investigate moisture transport and distribution during drying of fresh concrete, self-desiccation and curing.

In the second part, first results from Talbot-Lau interferometry-based multi-contrast X-ray micro-tomography are shown. With this method, which has recently been implemented at Empa, it is possible to follow both microstructure changes during hydration (with attenuation-based contrast) and simultaneously also moisture transport (with phase- and small-angle scattering – contrast). Compared to neutron tomography, this laboratory-based setup offers the advantages of being continuously accessible and of providing different types of contrast obtained simultaneously on the same samples.

3D pore scale imaging as a tool to understand multiphase flow in porous media

Souhail Youssef

IFP Energies Nouvelles (IFPEN) – France

Multiphase flow in porous media is central in a wide range of phenomena and applications in geosciences, including hydrocarbon formation, migration and production, water resources management, soil remediation as well as CO2 sequestration. Understanding and predicting fluid displacement mechanisms are one of the big challenge in reservoir engineering. Since pioneer works of Vinegar and Wellington (1984), who modified a medical CT scanner for core analysis, until recent developments in synchrotron based X-ray tomography that allows sub-second temporal resolution with a spatial resolution ranging from 0.5 to 11 μm; X-Ray 3D imaging has emerged as a key technology to study multiphase flow in porous media with a continuous quest for space and time resolution.

We present a workflow combining high speed CT-scan, laboratory based micro-CT and synchrotron x-ray ultra-fast tomography to investigate chemical enhance oil recovery process from the pore scale to core scale. We show how the combination of these multi-scale imaging technics allows to better understand how oil is recovered by surfactant injection and to better access the impact of rock structure on oil trapping and mobilization. Then we propose an adimensional analyses that will help to link pore scale proprieties to macroscopic properties such as the capillary desaturation cure and the relative permeabilities. Finally we discuss how lab scale parameters can be used in a reservoir simulation to predicting the efficiency of an EOR process.

Optimisation methods for tomography

Hugues Talbot

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In this talk we will introduce optimization methods for tomographic reconstruction. In this talk we will cover the following topics:

1. Motivation: tomography as an inverse problem
2. Introduction to optimisation: Objective function; Constraints; Statistical interpretation; Maximum Likelihood (ML) and Maximum a Posteriori (MAP) models.
3. Optimisation and tomography: Inverse problems formulation; Simple solutions: least squares; Filtered Back Projection as a ML formulation; Algebraic methods as a MAP formulation; Regularization functionals; sparsity; Total Variation.
4. Applications: Joint denoising and tomography; Sparse reconstruction; Join segmentation and reconstruction; Local tomography.
5. Software packages : Python, Matlab, C++, Fortran packages for optimization. Dedicated tomography packages.

Cross-scale 3D characterisation of complex and heterogeneous geomaterials with X-ray micro-CT

Adrian Sheppard

The Australian National University (ANU) – Australia

Many construction and geomaterials contain both very fine and coarse structure, so that effective characterisation and modelling of such materials demands information on a large range of length scales. A single 3D image (from e.g. X-ray micro-CT) can only cover a limited range of length scales: for example, a cubic image containing 1 TeraVoxel - larger than any instrument can acquire today and impractical for direct modelling - has only 10,000 pixels per side, insufficient for more complex or heterogeneous materials. We present recent advances in 3D imaging capabilities, particularly X-ray micro-CT, considering the overall state of the art and focussing on developments in our laboratory. We discuss methods for cross-scale 3D characterisation, including (a) acquiring individual images with the highest fidelity and resolution, (b) acquiring multiiple images of a particular sample at multiple scales, (c) using image registration to build spatial maps between micro-CT and complementary 2D and 3D techniques such as SEM and SEM-EDS, and (d) developing workflows for modelling that combine the information from these sources.

X Ray 3D imaging of construction materials

Eric Maire

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Construction materials exhibit a complex microstructure and understanding this microstructure is key in optimising the properties. 3D imaging techniques are today available to analyse this microstructure and are becoming more and more useful in the case of complex microstructure. X Ray Computed Tomography (XRCT) is probably one of the most interesting of these techniques as it is multiscale and non destructive. In this lecture we will present a review of qualitative images that our group has obtained over the years for different construction materials. We will also give examples of in situ experiments of different natures (compression, indentation, double torsion, setting). Finally we will also examplify microstructurally faithfull simulations based on these images and Digital Volume Correlation to measure displacement fields.

Realtime 4D tomographic microscopy: the SLS experience

Marco Stampanoni

Swiss Light Source, Paul Scherrer Institute (SLS) – WBBA/216 5232 Villigen-PSI, Switzerland

The TOMCAT beamline of the Swiss Light Source operates multiple imaging end-stations, covering three orders of magnitude in spatial resolution (0.1-10 um) and enabling dynamical 3D acquisitions within a fraction of a second. The talk presents the latest achievements obtained in terms of instrumentation development and results, with particular emphasis on material science and biomedical applications. I will review some of the technical challenges which have been addressed in the recent past enabling dynamical, tomographic microscopy of flying insects and the alveolar visualization of the breathing mouse lung. I will further discuss the limitations of present setups and propose options to improve spatio-temporal resolution. Our future work will focus on the optimization of the acquisition protocols for ultrafast imaging (introducing the GigaFROST detector to users). I will present a few examples from material science applications (foaming processes) and geo-science (bubbling in volcanic rocks) where the ability of collecting 3D data within a short time (subseconds) over a longer period (a few minutes) is demonstrated. Consequently, real-time data interrogation becomes the next hurdle in modern, synchrotron-based tomographic imaging and calls for new, paradigm-shifting approaches. Examples from bone research will be illustrated and discussed.

PSICHE: Synchrotron tomography and diffraction for in-situ experiments

Andrew King

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PSICHE (Pressure, Structure and Imaging by Contrast at High Energy) is the high energy beam line of the SOLEIL synchrotron, located outside Paris. It can perform both tomography and diffraction measurements. The tomograph is optimised for in-situ materials science experiments, while diffraction is used for investigating samples at extreme conditions. A natural progression for the beam line is to combine imaging and diffraction techniques to obtain a more complete description of a sample or process. This talk will present the beam line, and describe the latest developments in these multimodal experiments.

3D detection and characterization of damage in quasi-brittle heterogeneous materials

Camille Chateau[1], Thanh Tung Nguyen[1,2], Yang Chen[3], Michel Bornert[1], Lionel Gelebart[3], Julien Yvonnet[2], Patrick Aimedieu[1], Andrew King[4]

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Detailed experimental characterization of cracking under mechanical loading is necessary to understand damage in many quasi-brittle materials, whose mechanical description is still an open issue. Moreover, it is required for the development, the identification and/or the validation of 3D damage models. Such a characterization is made available through X-Ray Computed Tomography (XRCT), making possible the direct observation of crack networks within the material under in situ mechanical loading. In order to quantify the precise location and the extension of micro-cracks, and to detect early-age cracking, a method based on Digital Volume Correlation (DVC) has been developed. After running DVC routines, the difference between the deformed image (containing cracks) and the reference image (without cracks) is computed. This so-called "subtracted image" reveals the path of cracks which is clearly visible. Segmentation of cracked areas is thus possible, while it would have been very difficult to extract them from the heterogeneous microstructure in the deformed XRCT images. Moreover, very tiny cracks can also be detected and their sub-voxel opening evaluated. This DVC-assisted subtraction has been used to analyze the crack network and its evolution in lightweight concrete, lightweight plaster and SiC/SiC composite tubes. In situ compressive tests on lightweight concrete and plaster were performed on the XRCT laboratory scanner available at Laboratoire Navier. Because of very small crack openings, synchrotron XRCT (PSICHE beamline, SOLEIL) was necessary to characterize damage in SiC/SiC composites tubes under in situ tensile loading.

Measurement of the damage process in highly filled elastomers

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Solid propellants are made of elastomers filled with rigid polyhedral particles up to 75% volume fraction. Their mechanical behaviour needs to be understood and predicted in order to use them in rocket motors. Upon loading two damage mechanisms appear in these composites: matrix/filler debonding and matrix cracking. Since both the particles and the elastomer are incompressible materials, the damaging process can be directly related to the volume variation of the composite upon loading. In this contribution, the volume variations of a model highly filled elastomer upon uniaxial loading are measured with three techniques: gas dilatometry, video-extensometry and tomography. The settings and the results interpretation method of the tomography measurements are emphasized. The results obtained with the three techniques are compared and the complementary information yielded by the three measurement techniques on the two damaging processes is discussed.

Measuring grain displacements from X-ray tomography projections: a time-saving method

Mohamed Hassan Khalili, Sébastien Brisard, Michel Bornert, Jean-Michel Pereira, Jean-Noël Roux

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A small number of tomographic projections contain enough information to solve rigid body motions of particles in a granular material even if it does not allow for an accurate 3D image reconstruction. In this work, we present the Discrete Digital Projections Correlation method (D-DPC). This new technique aims to determine the individual grain displacements directly from the projections of the deformed state with no need of its reconstruction. Using D-DPC considerably reduces the time required to scan the sample at its deformed state and hence, allows studying faster evolutions of the sample.

The method is formulated as an inverse problem. Digital projections are generated from the reconstruction of the initial state by means of a projection model. Grain displacements are then estimated by minimizing the discrepancy between the digital projections and the acquired experimental projections.

The projection model will be presented, next to some applications of the method.

X-ray tomography to study the mechanical behaviour of structural materials

Nicolas Gueninchault

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The increasing popularity and capability of X-ray tomography to image cracks and damage in three dimensions in a non destructive fashion brings forward a new way to validate the mechanical behaviour of structural materials including deformation and failure. Several examples, covering a wide range of materials, inspected by laboratory X-ray tomography and conducted at Laboratoire Navier, will be presented. The development of an original tension machine adapted to the tomograph will also be described and the first results discussed.

Flows of suspensions of particles in yield stress fluids studied by X-ray microtomography

Guillaume Ovarlez[1], Stéphanie Deboeuf[2], Nicolas Lenoir[3], Sarah Hormozi[4], Xavier Chateau[5]

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Suspensions of noncolloidal spheres dispersed in yield stress fluids are good model systems for understanding the rheology of fresh concrete or debris flows, and more generally, the behavior of particles dispersed in any nonlinear material. The particle distribution in space is a key element of their behavior. At the particle level, they display anisotropies under shear, which can be characterized by pair distribution functions. At the macroscopic level, they tend to develop concentration inhomogeneities. In this talk, we will show how such information can be obtained by coupling a flow device and X-ray tomography. We will discuss briefly some new insights brought by these coupled measurements. We will also show that simple 2D X-ray imaging can be used to provide time-resolved concentration fields.

List of participants

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De Larrard François
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Derluyn Hannelore
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Duc Myriam
Dufresne Alice
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