

Carole Kaouane^{1,2}, Michel C. Chouteau¹, and Philippe Côte³

(1)Ecole Polytechnique de Montreal, CGM, Montreal, QC, Canada, (2) CEREMA Centre d'Étude et d'Expertise sur les Risques, l'Environnement, la Mobilité et l'Aménagement, (3) IFSTTAR Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux, Bouguenais Cedex, France

CONTEXT

Quality control of compaction work consists of assessing the gravimetric water content and the dry density of the implemented structure. Most of the standardized geotechnical tests are point measurements, destructive, time consuming and may require employing nuclear probes. Also lime and cement treatments may be required to stabilize water-sensitive soils. Lime-cement-fines reactions are not yet full understood and the pore space and water content are affected (Saussaye, 2012). The use of in situ monitoring of the reactions would be of high interest.

Because of its sensitivity to textural parameters of porous media, SIP shows a high potential to assess the condition of building materials (Kruschwitz *et al.*, 2014), the porous network (Florsch *et al.*, 2014) and recent work investigates linkages between geotechnical parameters and the SIP response (Boadu and Owusu-nimo, 2010). The present study was designed to (1) observe characteristics features of a natural and treated soil, and to (2) assess the ability of SIP to discriminate between samples compacted near the Optimum Proctor (OP).

SAMPLE PREPARATION

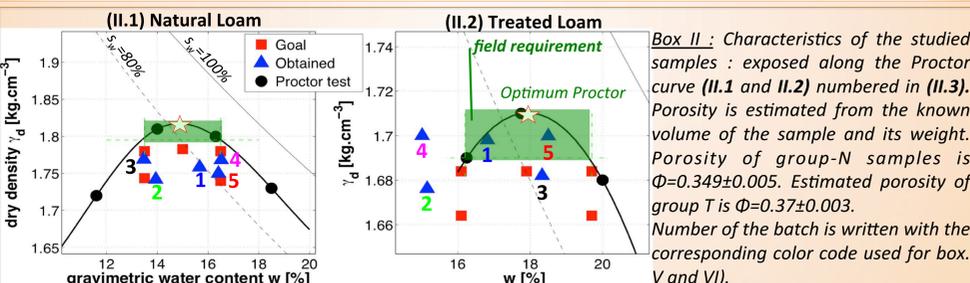
Box I: Preparation of the two groups of samples

Group N samples:
silty loam
20% clay (d<2 μm)
72% silt (d<80 μm)
8% sand (d>80 μm)
sieved at 2 mm
bring to desired water content
→ manual mixing → compaction

Group T samples:
sieved at 2 mm
bring to desired water content + 1%
+ 1% Lime 24 h before compaction
+ 5% CEM II cement
→ mechanical mixing 1 min → compaction

Mixing Mechanical compaction

Samples are mechanically compacted cores (5 cm-diameter and 10 cm-long) according to French standards (NF P 94-230-1). Each group is composed of 5 batches of 3 samples each. Compaction levels were chosen along the Proctor curve (Box II). Initial gravimetric water content is determined per batch, with the oven test using a fraction of material prior to compaction. The objectives of implementation were almost always reached for the N-samples.



(II.3) Properties of the obtained batches

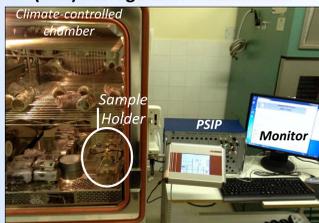
w = gravimetric water content [%]
 γ_d = dry density [kg.cm⁻³]
 ϕ = porosity
 s_w = degree of saturation
A color code is used to designed the batches: (1) blue, (2) green, (3) black, (4) magenta, (5) red.

	Group N				Group T			
	w	γ_d	ϕ	s_w	w	γ_d	ϕ	s_w
1	15.7	1.76	0.35	0.79	16.8	1.7	0.37	0.77
2	13.9	1.74	0.35	0.68	15.2	1.68	0.38	0.67
3	13.5	1.77	0.34	0.69	18.3	1.68	0.38	0.81
4	16.5	1.77	0.34	0.85	15	1.7	0.37	0.68
5	16.4	1.75	0.35	0.81	18.5	1.7	0.37	0.84

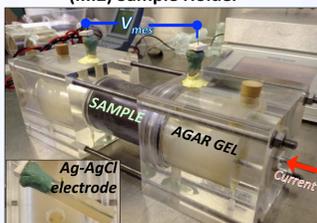
SAMPLE HOLDER

The sample holder is designed after the work of Binley *et al.* (2005). Samples are inserted between two chambers filled with agar gel (tap water at 70 mS/m, 4% (total weight) of Sigma Aldrich noble agar). Slices of agar gel are used to ensure a good and consistent contact between the gel in the chambers and the sample during the experiment. We regularly checked that the contact resistance between the potential electrodes is below 20 kΩ as recommended in Kemna *et al.* (2012). Current electrodes are 5cm-diameter stainless steel plates, attached to the ends of the sample holder.

(III.1) Storage & Measurements



(III.2) Sample Holder



(III.3) Samples & Agar slices



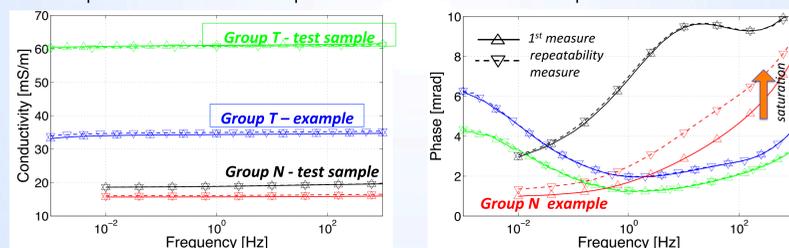
Box III: Installation. The sample holder and the samples are stored in a climate controlled chamber set at 20°C and 50% humidity (A). We conducted preliminary tests with the sample holder filled with agar gel to ensure the measured residual phase is below 1 mrad. The agar gel was renewed between the measurements on group N and group T.

PROTOCOL

For each group the protocol is based on measurements of a test sample from batch #5. The goal is to determined (1) the necessary frequency sweep, (2) the time of equilibrium prior to measurement. SIP measurements are carried out with a Portable Field/Lab SIP Unit (PSIP) system developed by Ontash & Ermac, Inc. (River Edge, USA). We weight the samples before and after the measurements. Repeatability could be obtained for T-samples but not for N-samples (Box IV).

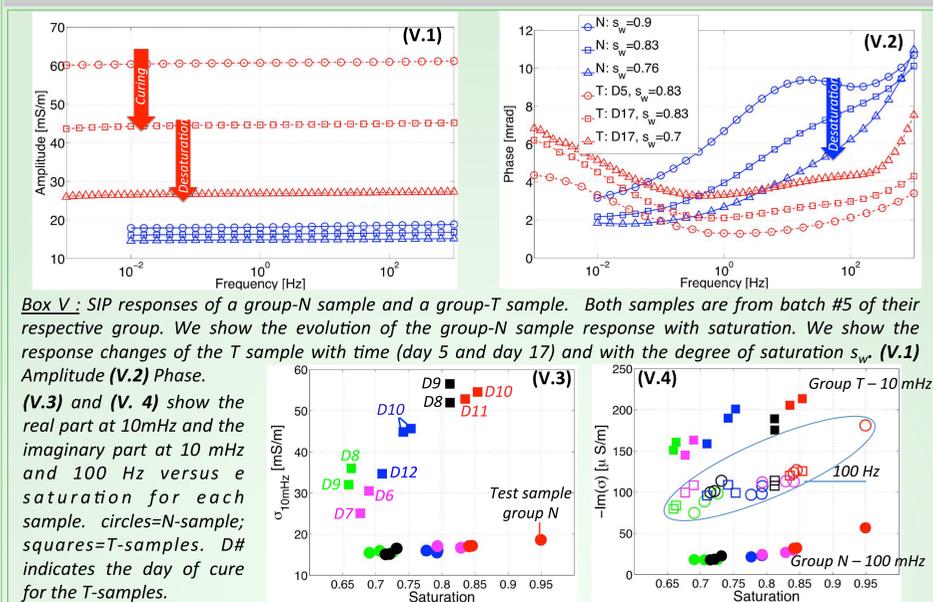
Group N: 10 mHz → 10 kHz, 5 freq/decade (~25 min)
10 measurements (5h)
no equilibrium time in the sample holder

Group T: 1 mHz → 10 kHz, 5 freq/decade (~4h)
2 measurements (1 sample on 2)
3h equilibrium time



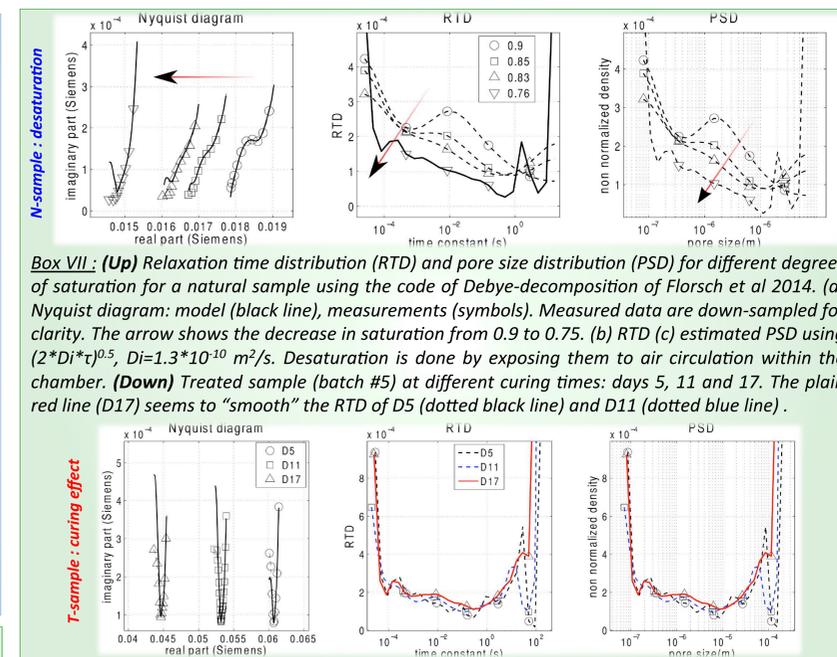
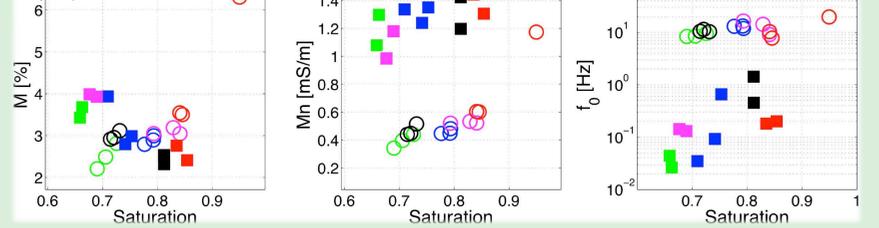
Box IV: Amplitude and the phase of the conductivity for the tests samples of each group. Except for the test sample, phase response of N-samples change over the 5 h in the sample holder. This is associated with an increase in the weight of the samples that translates in a change in the degree of saturation of 4±2 %.

RESULTS



For each batch, we observe very similar results between the samples, which suggests that our core implementation is reproducible. The conductivity spectrums of group-N samples show pronounced differences when compared with those of group-T samples (Box V). During the first week of curing, polarization in group-T samples seems to only occur at low frequency. Beyond the first week, a polarization signature appears between 1 Hz and 100 Hz. Conductivity of the group-T sample decreases over time but it remains always higher than conductivity of group-N samples. Magnitude of the phase increases with increasing saturation for group-N and decreases for group-T. We perform a Debye-decomposition as described by Nordsiek & Weller (2008) to assess total chargeability M , normalized chargeability M_n and mean frequency f_0 (Box VI) and we apply the code developed by Florsch *et al.* (2014) to observe the relaxation time distribution (RTD) considering a Debye-like decomposition. Assuming each relaxation time τ is related to a pore size Λ through a diffusion coefficient D_p , $\Lambda = (2D_p\tau)^{0.5}$, we obtain a pore size distribution (PSD) (Box VII).

Box VI: Total chargeability M , normalized chargeability $M_n=M/\rho_0$ and the mean frequency f_0 obtained with Debye Decomposition versus saturation. Empty circles represent the Group N and full squares represent the Group T. ρ_0 is the amplitude of the resistivity at the lowest measured frequency (1 mHz for T-samples and 10 mHz for N-samples).



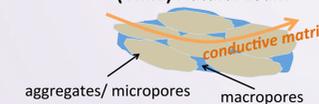
CONSIDERATIONS

We cannot observe the influence of porosity (or dry density) on the SIP response. On one hand, the differences in porosity between the group N samples are very small. On the other hand, the porosity of the group T samples is changing over time while cement hydrates develop into the pore space. Therefore, we can only observe the influence of saturation. The saturation degree estimated for the group T samples may be overestimated because of the lime and cement reaction, which consumes water molecules in the media.

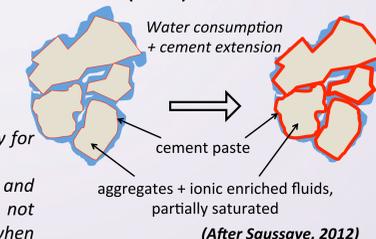
We explain the electrical behaviour of the group N samples by the presence of a conductive matrix formed of mostly saturated clay-silt aggregates in contact with each other. The desaturation process decreases the surface covered by the pore solution and slightly increases its conductivity. The RTDs shown in box VII (N sample) suggest a contribution of grains of smaller dimensions with the decrease in saturation, which was expected (Binley *et al.* 2005).

A diffusion process along the membrane formed by cement hydrates might cause the low frequency effect observed for group T samples. With time, cement hydrates fill the pore space. The evolution of the spectrum at higher frequencies could be representative of those changes in porosity. The RTD of group T samples seems to flatten with time. We speculate that appropriate calibration could allow to monitor the evolution of treated soils and, therefore, to characterize their stabilization.

(VIII.1) Natural Loam



(VIII.2) Treated loam



Box VIII: Conceptual models of the particles assembly for natural and treated loam.

(VIII.1) Natural loam: compacted aggregates of silt and clay particles forms a conductive matrix. We do not expect the water content in the micropores to vary when samples desaturate by exposition to air ventilation.

(VIII.2) Treated loam: water molecules in the main pore space are consumed in the formation of cement hydrates. That could explain the similarities between the effect of desaturation and the effect of the cure on the SIP spectrum.

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