GdR MBGS
MATÉRIAUX de CONSTRUCTION
BIO et GÉO SOURCÉS

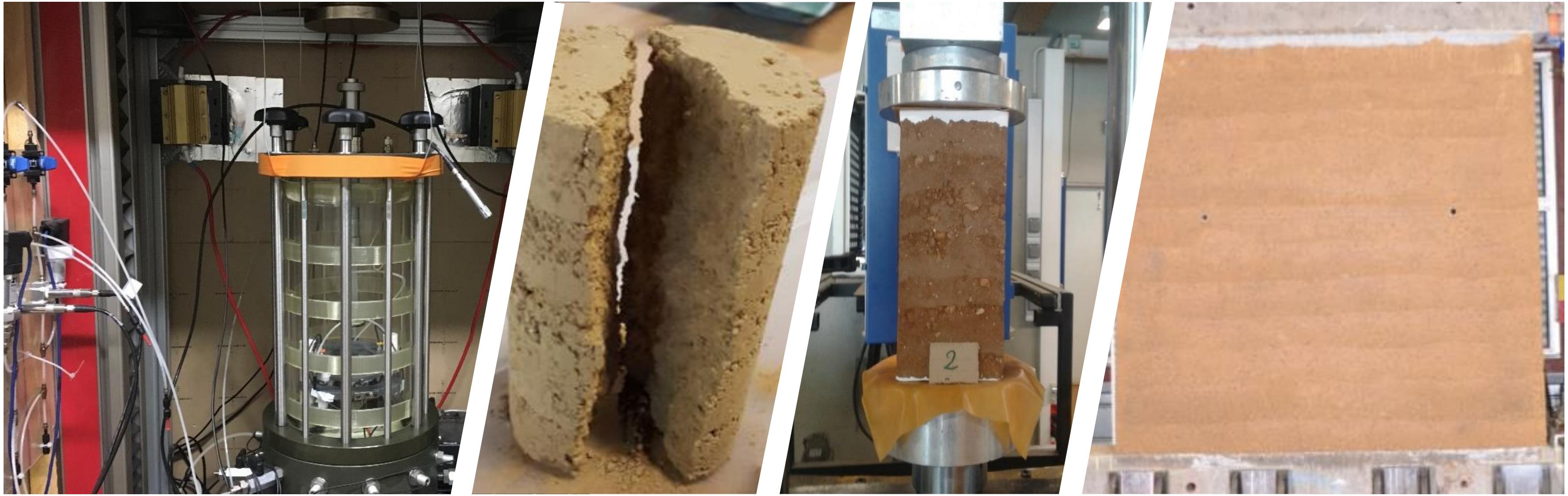
cnrs

UNIVERSITÉ DE LYON

ENTPE
L'école de l'aménagement durable des territoires

LTDS
Tribologie et Dynamique des Systèmes
UMR 5513

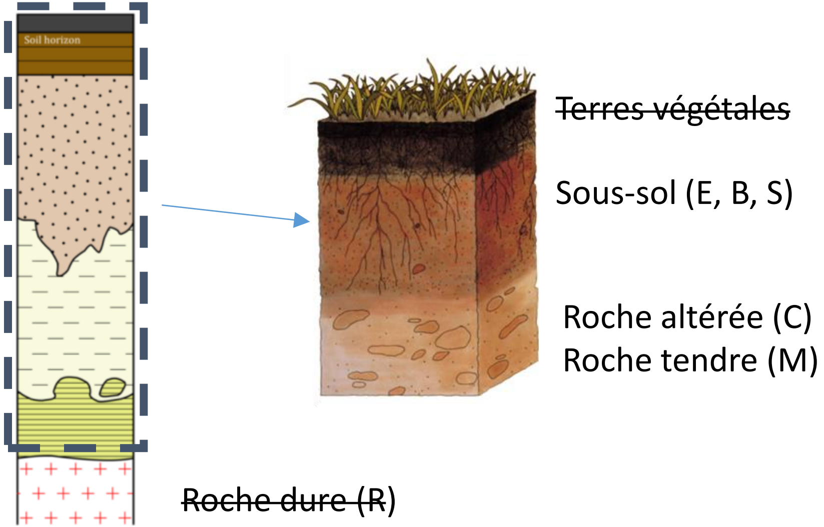
Comportement mécanique de la terre crue



Antonin Fabbri – antonin.fabbri@entpe.fr

Terre crue ?

Matériau naturel issu du sol ou du sous-sol, utilisé cru, et dont la cohésion est assurée par la présence d’argiles.



~~Terres végétales~~

Sous-sol (E, B, S)

Roche altérée (C)
Roche tendre (M)

~~Roche dure (R~~)

(Hamard, PhD Thesis, ENTPE, 2017)

Bâtiments neufs

Exemples de constructions en terre crue dans la région Auvergne Rhône-Alpes

Les ateliers de la danse, Lyon 8ième
Dominique Coulon & associés (architectes); Donato Construction (Maçon-e-s), Batiserf (BET structure) ©

L'Orangerie, Confluence, Lyon
Clément Vergely (architectes); Nicolas Meunier Le pisé (Maçon-e-s)
Batiserf (BET structure) ©

Quels sont les problèmes ?


@ Pascal Scaratto


@ Pascal Scaratto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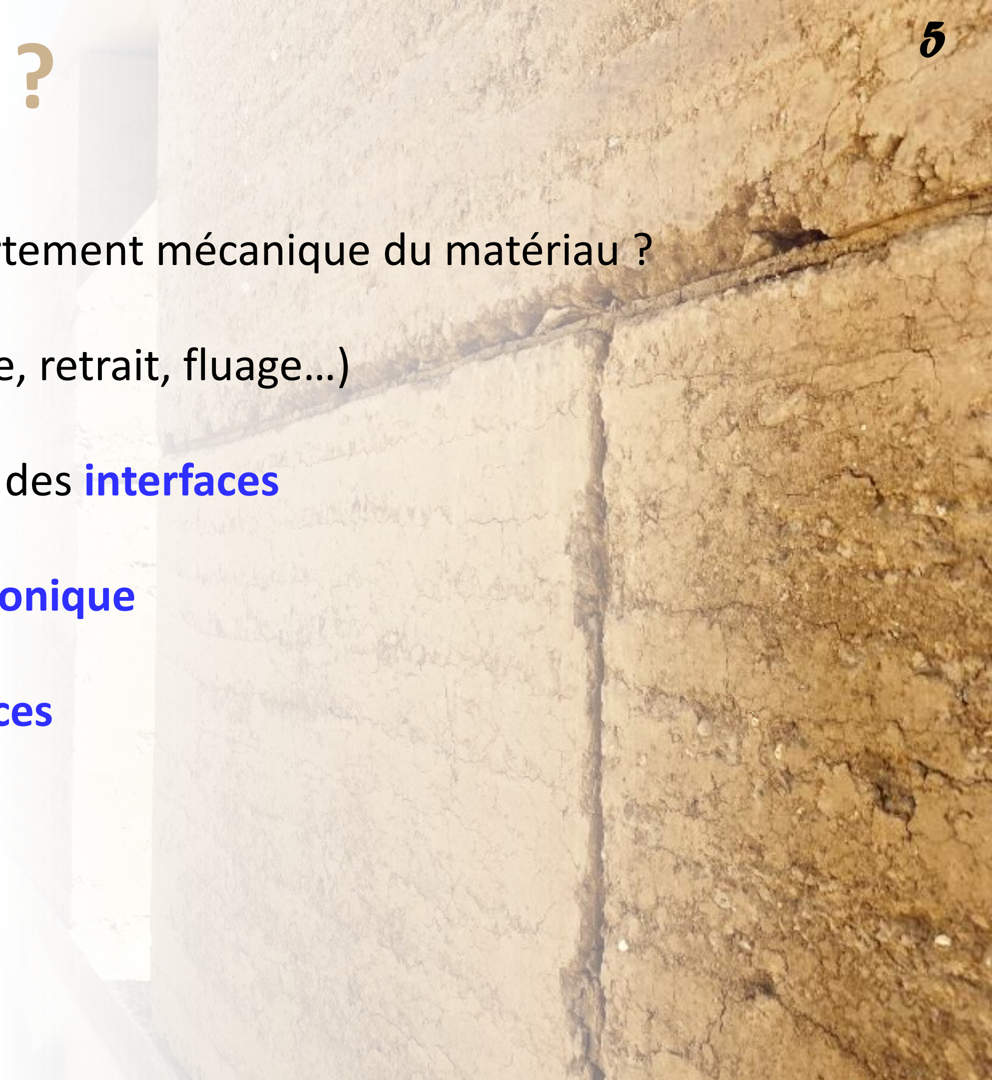
Quels sont les enjeux ?

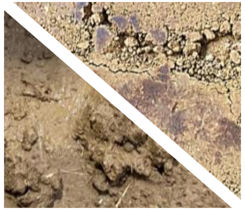


- Comment **tester / quantifier** le comportement mécanique du matériau ?
- Comportement au **jeune à âge** (séchage, retrait, fluage…)
- Problématique des **reports de charges**, des **interfaces**
- Comportement **parasismique, paracyclonique**
- Manque général de **retours d’expériences**

PNTERRE

Quels sont les enjeux ?

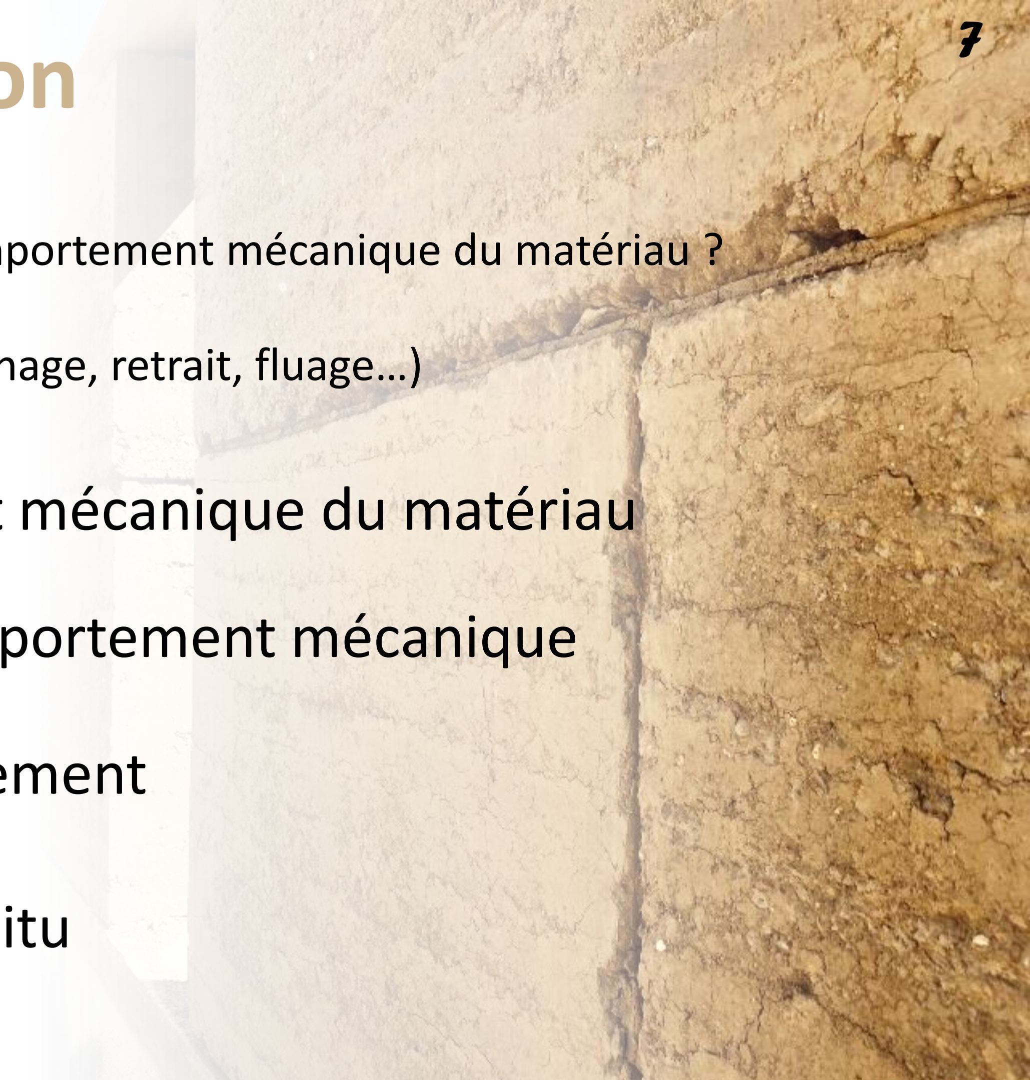
Matériau et méthodes de fabrication non standardisés



Dont les propriétés/performances varient au cours du temps (**teneur en eau**)

Qui possède différents **niveaux d'hétérogénéité**

Plan de la présentation



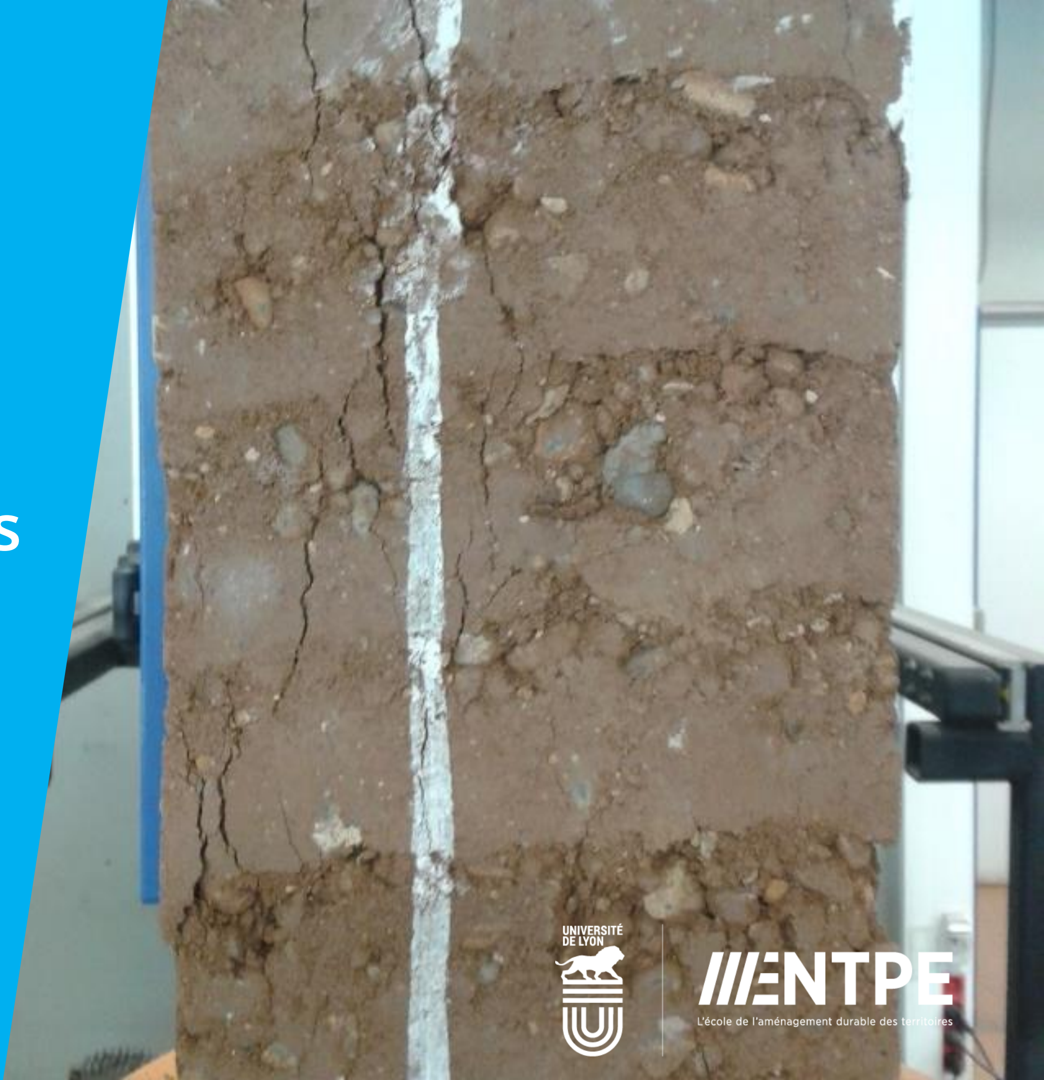
- Comment **tester / quantifier** le comportement mécanique du matériau ?
- Comportement au **jeune à âge** (séchage, retrait, fluage…)

1/ Mesure du comportement mécanique du matériau

2/ Impact de l’eau sur le comportement mécanique

3/ Modélisation du comportement

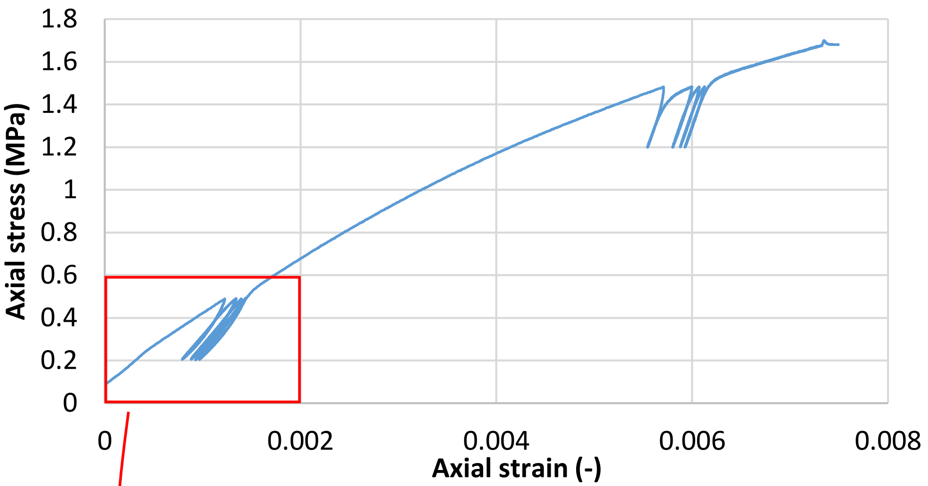
4/ Méthodes de contrôle in-situ

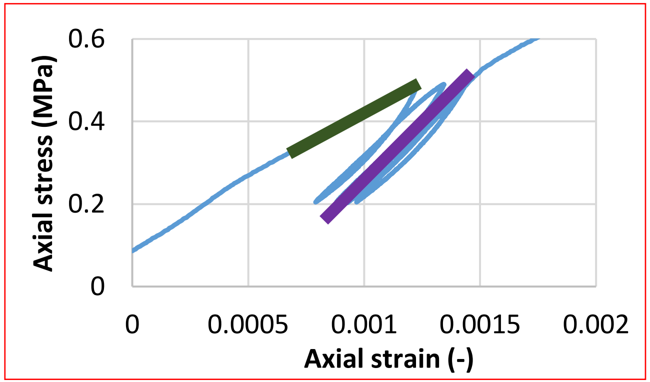


01

Assessment of the mechanical performances

Uniaxial compression test : Young’s modulus

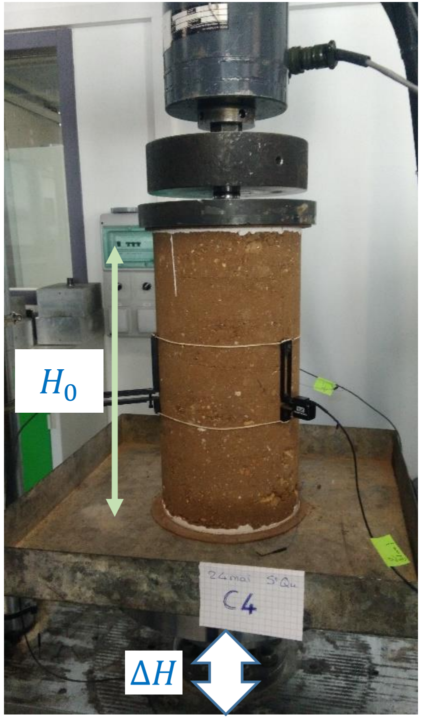




Total strain = $\frac{\Delta H}{H_0}$

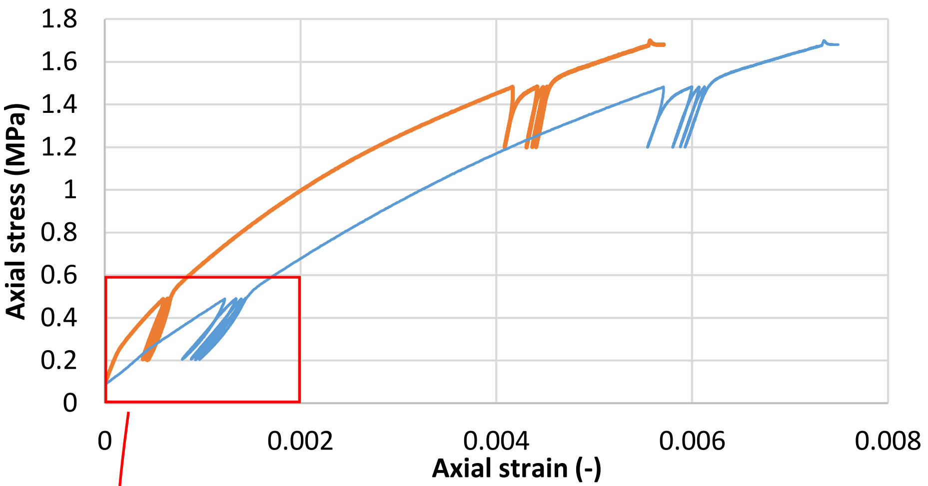
$E_0 = 0.30\ \mathrm{GPa}$

$E_{cycle} = 0.57\ \mathrm{GPa}$



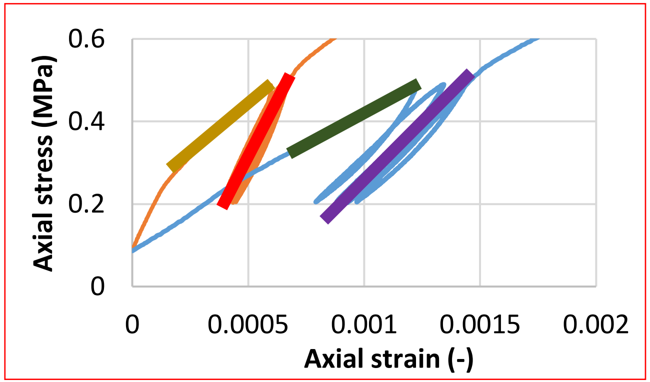
Data from M.S. Force thesis, ENTPE

Uniaxial compression test : Young's modulus



Total strain = $\frac{\Delta H}{H_0}$

Local strain = $\frac{\Delta L}{L_0}$

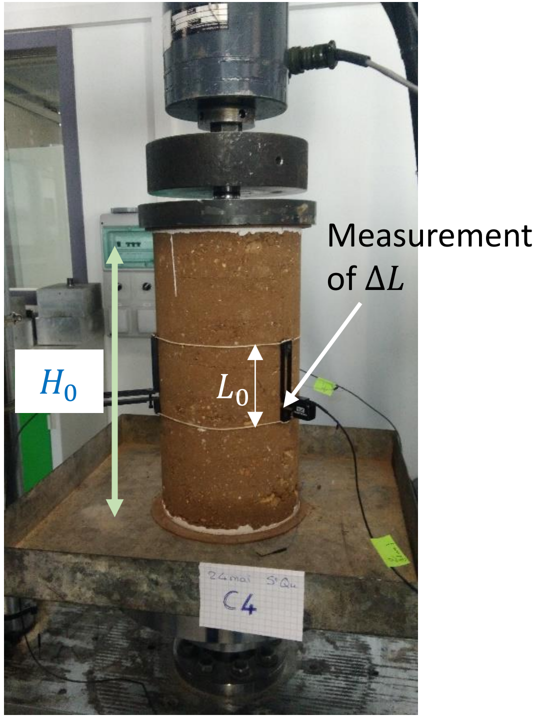


$E_0 = 0.30\ \mathrm{GPa}$

$E_{cycle} = 0.57\ \mathrm{GPa}$

$E_0 = 0.50\ \mathrm{GPa}$

$E_{cycle} = 1.20\ \mathrm{GPa}$



Data from M.S. Force thesis, ENTPE

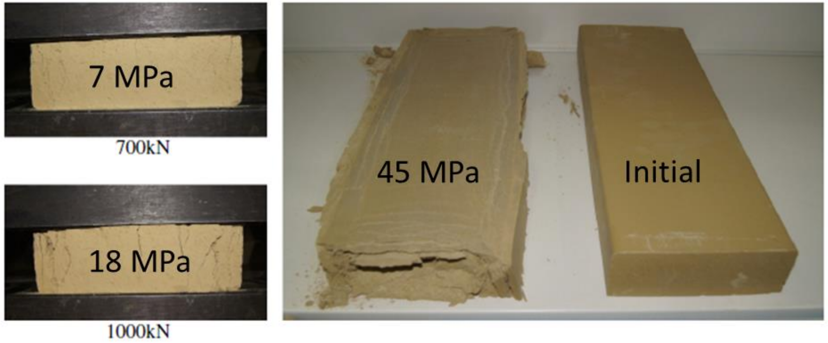
Uniaxial compression test : Shape ratio

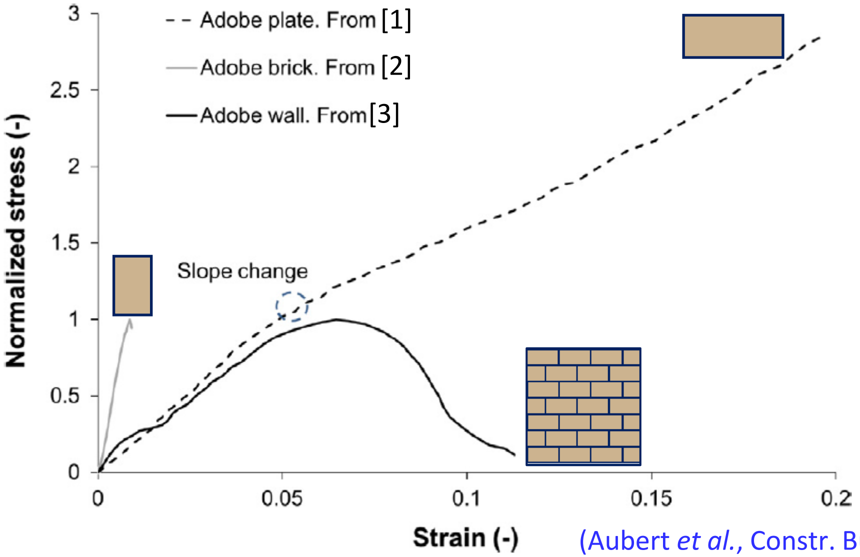
Main direction of the mechanical solicitation

© Macélaré

?

/// Uniaxial compression test : Shape ratio





(Aubert *et al.*, Constr. Build. Mat., 2013)

(Zenou, 2013)

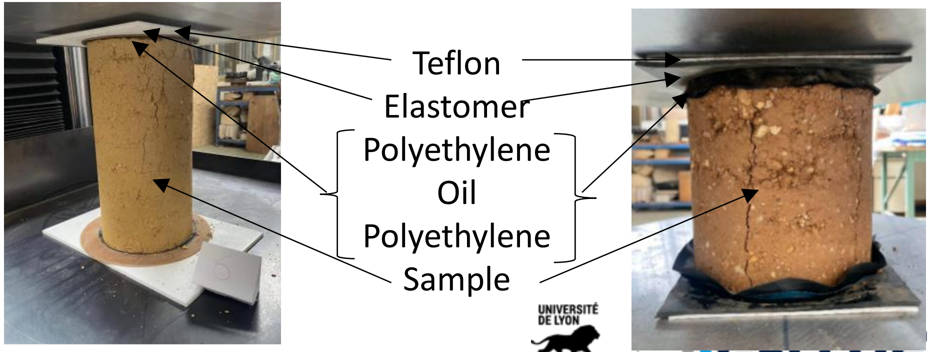
[1] Eslami A, Ronagh H, Mahini S, Morshed R. Experimental investigation and non linear FE analysis of historical masonry buildings – a case study. Constr Build Mater 2012;35:251–60.
[2] Kouakou C, Morel JC. Strength and elasto-plastic properties of non-industrial building materials manufactured with clay as a natural binder. Appl Clay Sci 2009;44:27–34.
[3] Quagliarini E, Lenci S, Iorio M. Mechanical properties of adobe walls in a Roman Republican domus at Suasa. J Cult Herit 2010;11:130–7.

Uniaxial Compression test : Work in progress

Definition of protocol for uniaxial compression test for RE samples and masonry units.

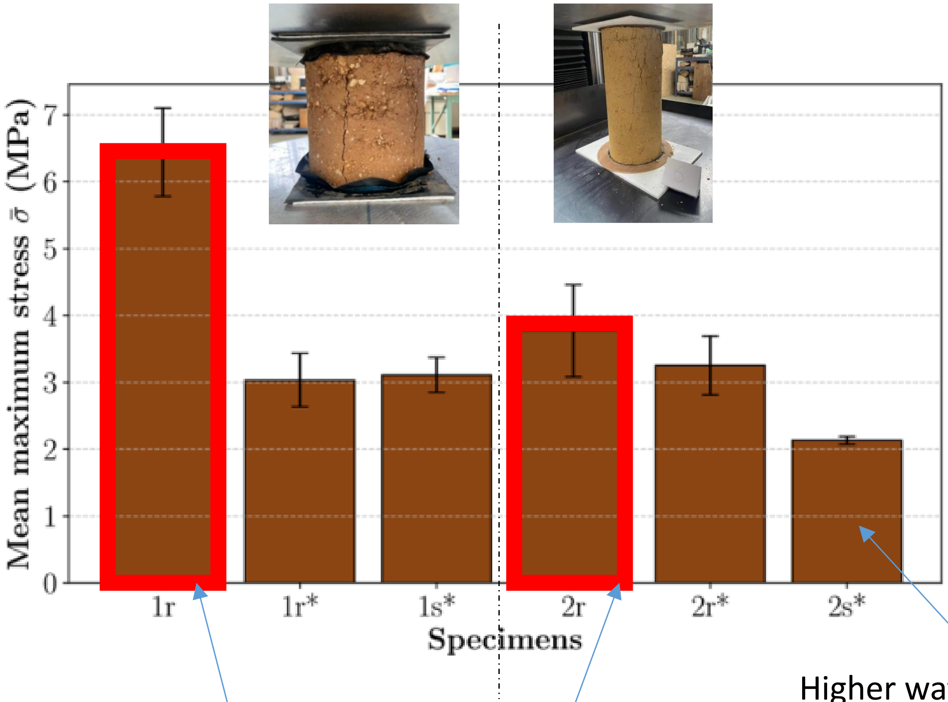
For rammed earth samples, it consists in :

- Manufacturing method based on **Proctor compaction**
- **Surfacing protocols**: either by trowelling or sanding and **use of a novel anti-fretting device**.
- **Drying condition prior to testing**: 60°C in an oven with <5% RH until constant mass
- **Test control conditions** : in displacement, at 1.2mm/min, test stopped after a 10% drop in measured force.



(Durhône *et al.*, Rilem Tech. Letters, 2026)

/// Uniaxial Compression test : Work in progress



Without anti-fretting device

Higher water content of 1.07%
Instead of 0.31% to 0.46% for
other samples

- This systems seems to provide quite simple and reproductible laboratory sample manufacturing and testing protocol for compressive strengh
- But limitations for the stiffness determination
- Results to be confirmed through RRT (in progress)

(Durhône *et al.*, Rilem Tech. Letters, 2026)

02

Impact of water on the mechanical behavior

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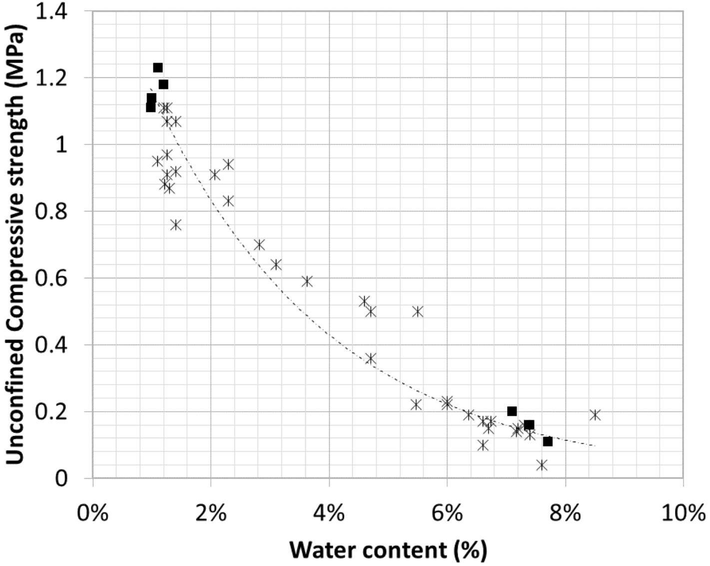
/// Hydromechanical behavior



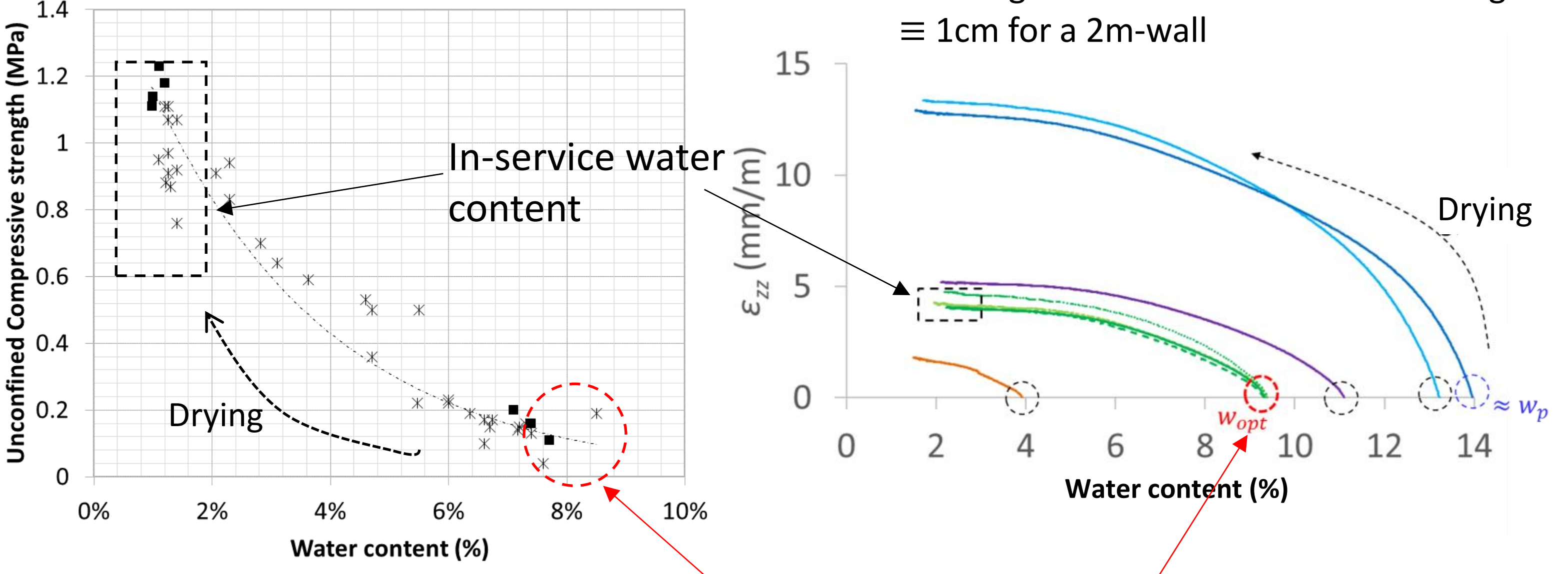
Mass of water within on unit of material dry mass

Tests on rammed earth samples

(Peltier et al., Case Stud. Constr. Mater., 2022)

Hydromechanical behavior

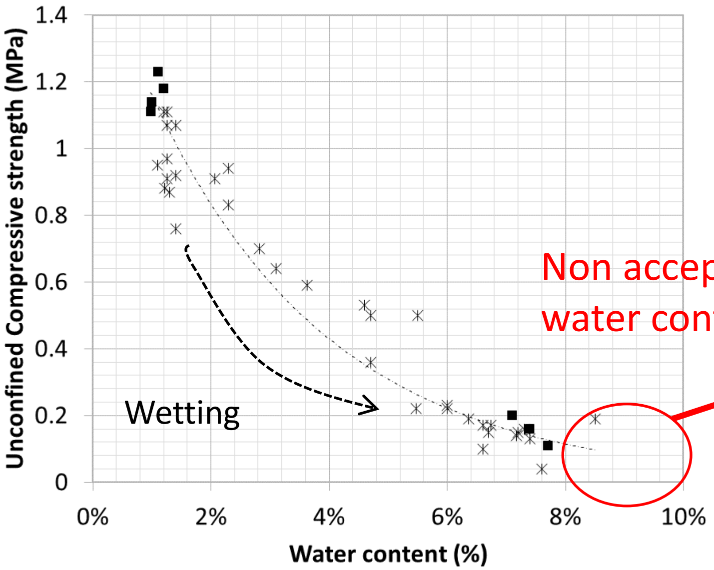
Non neglectable value of linear shrinkage
≡ 1cm for a 2m-wall



Water content of fabrication

Major challenge of controlling the
« early-age-drying » of the material.

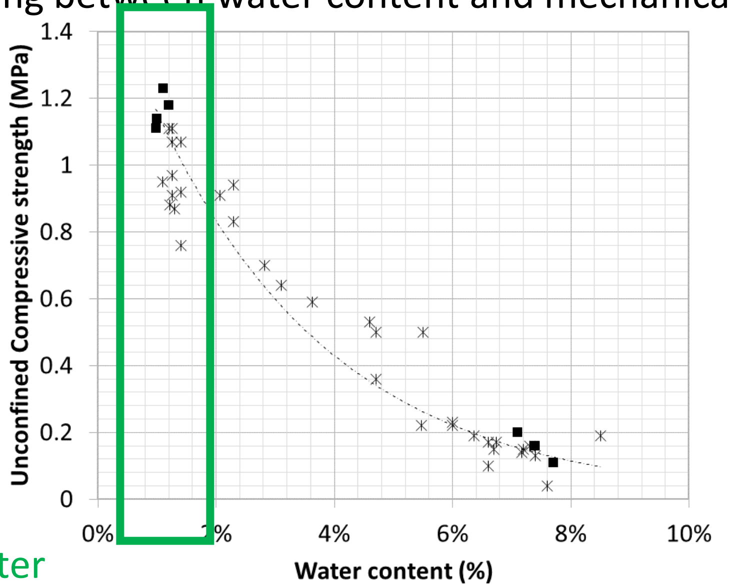
/// Hydromechanical behavior



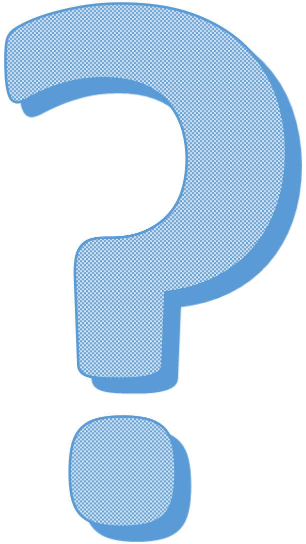
Non acceptable water content

Hydromechanical behavior

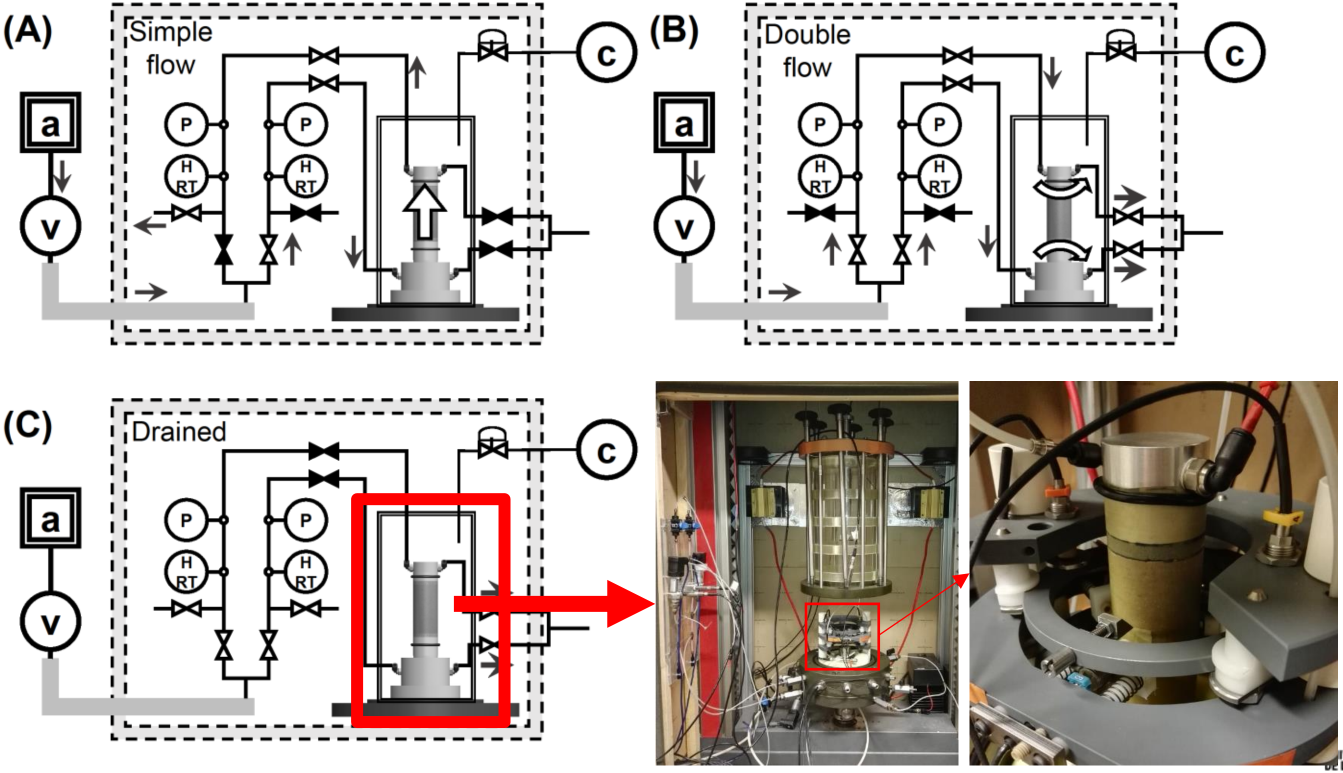
✓ Coupling between water content and mechanical behavior



Normal in-service water content



/// Triaxial behavior at constant temperature and relative humidity



(Champiré, PhD Thesis, ENTPE, 2017)

Triaxial behavior at constant temperature and humidity

Lim

35%

clay content

+

Hostun HN31 sand

clay content

17%

26%

clay content

Testing conditions :

23°C

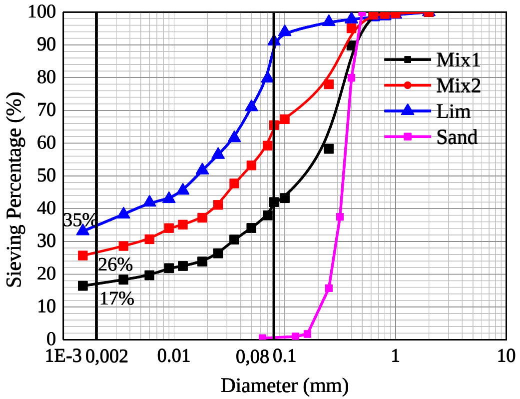
0 bar , 1 bar & 6 bar confinement pressure

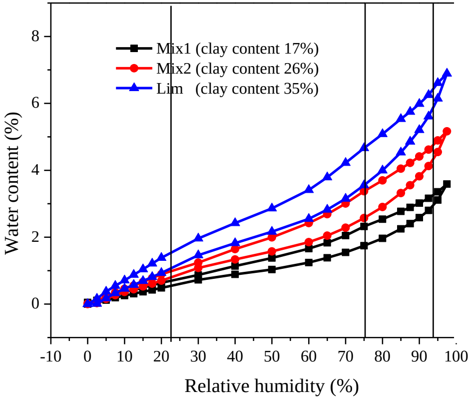
Kelvin’s law :

$$s = -\frac{\rho_L RT}{M_{\mathrm{H_2O}}} \ln(RH)$$

RH (%)
23
75
97

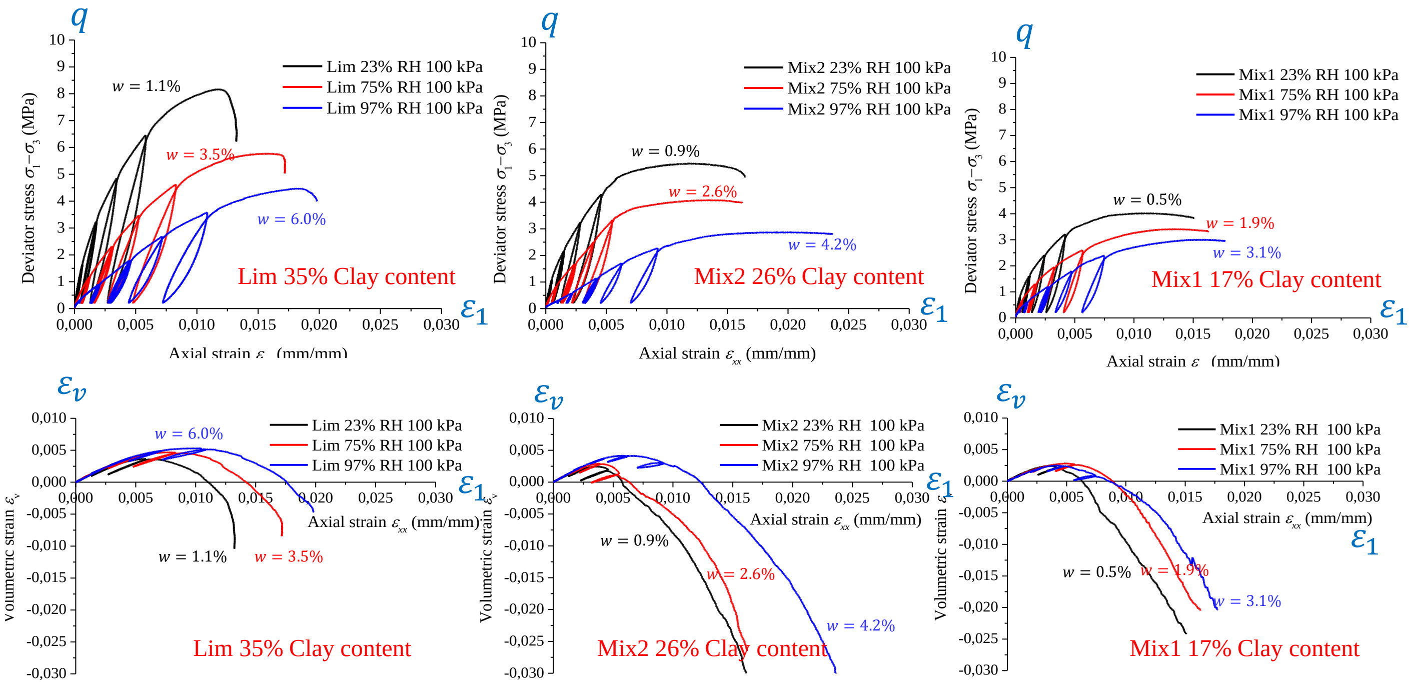
(Xu et al., Soils and found., 2018)





Triaxial behavior at constant temperature and humidity

Stress-strain and volumetric behavior (100 kPa confining pressure)



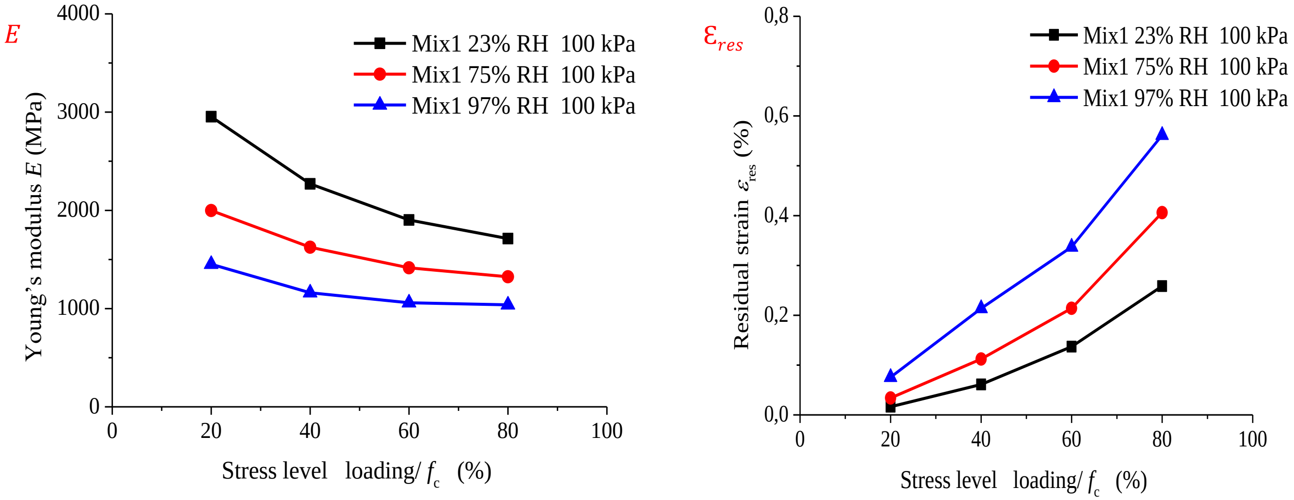
Complex volumetric evolution: contraction to dilation

A certain brittleness for Lim at low RH (high suction)

(Xu et al., Soils and found., 2018)

/// Triaxial behavior at constant temperature and humidity

Influence of stress level on loading-unloading shear behavior



At constant relative humidity and confining pressure, a progressive degradation of Young's modulus *E* is observed with increasing applied stress. (providing us inspiration of taking into account damage into modeling)

An obvious increase of residual strain is also observed from lower stress level to higher stress level

(Xu et al., Soils and found., 2018)

03

Modeling the hydro-mechanical behavior

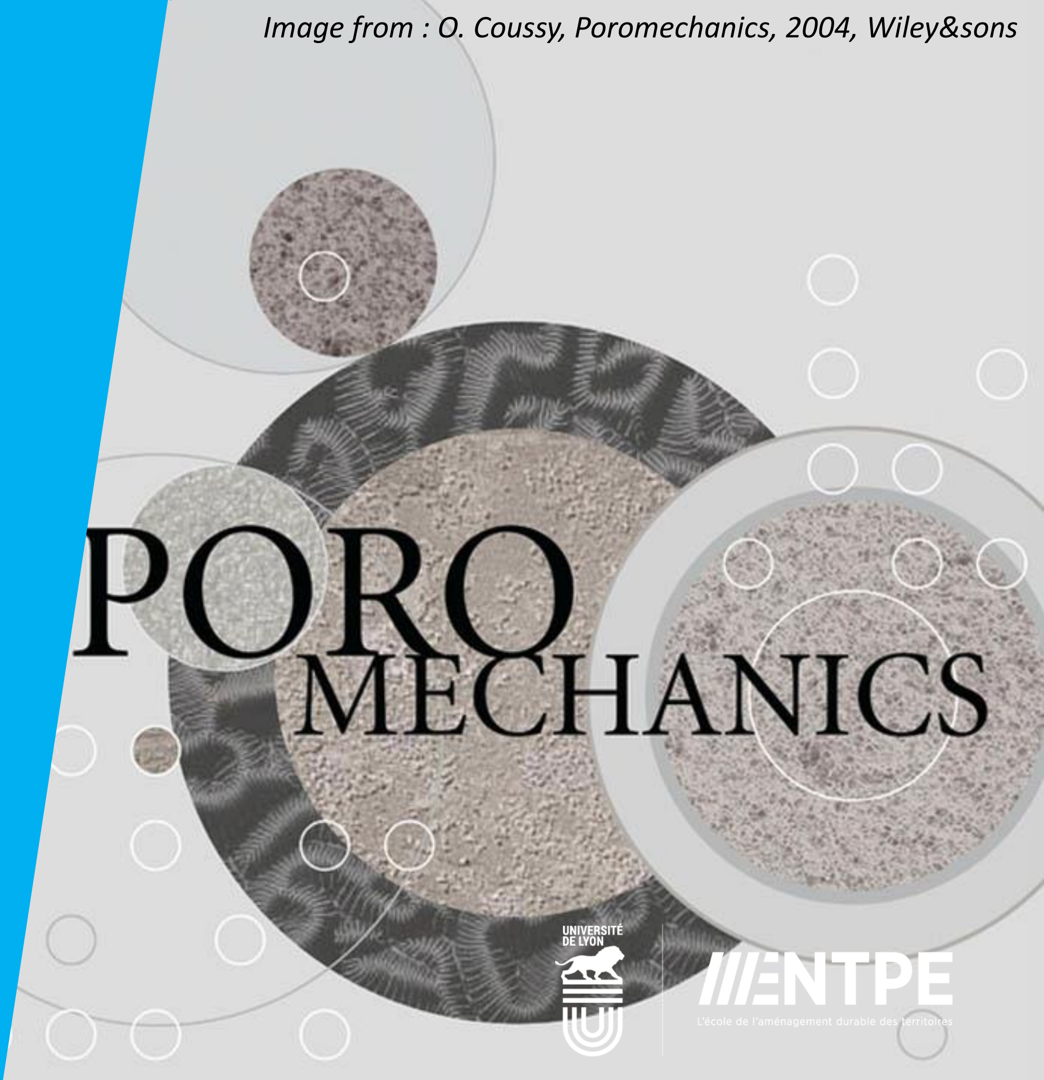


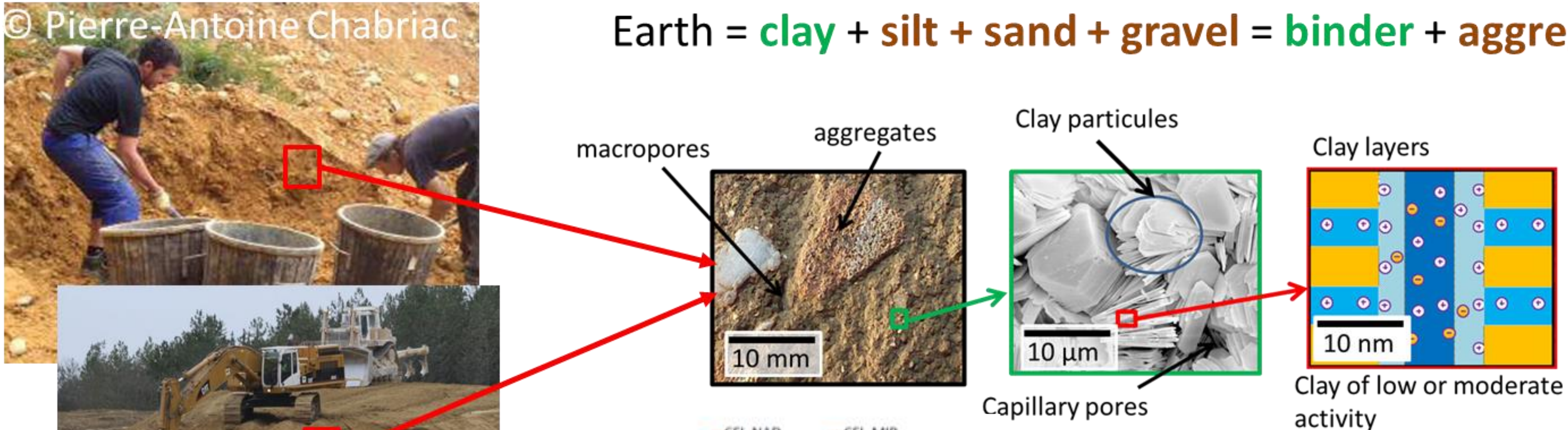
Image from : O. Coussy, Poromechanics, 2004, Wiley&sons

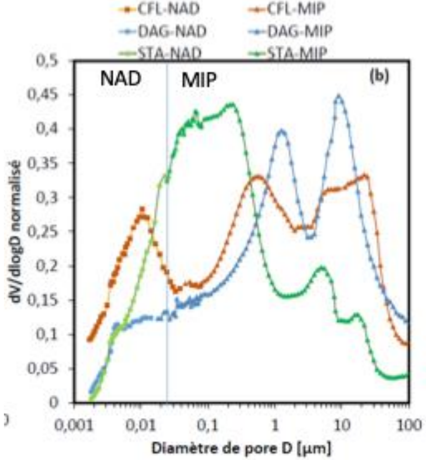
/// Concept of suction

Origin of the Hydromechanical coupling ?

/// *Concept of suction*

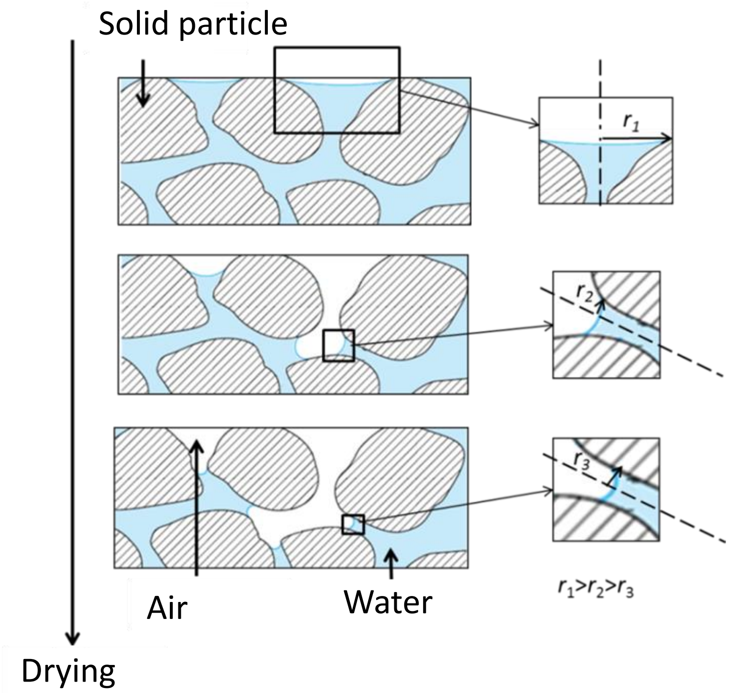
Earth = **clay** + **silt + sand + gravel** = **binder** + **aggregates**

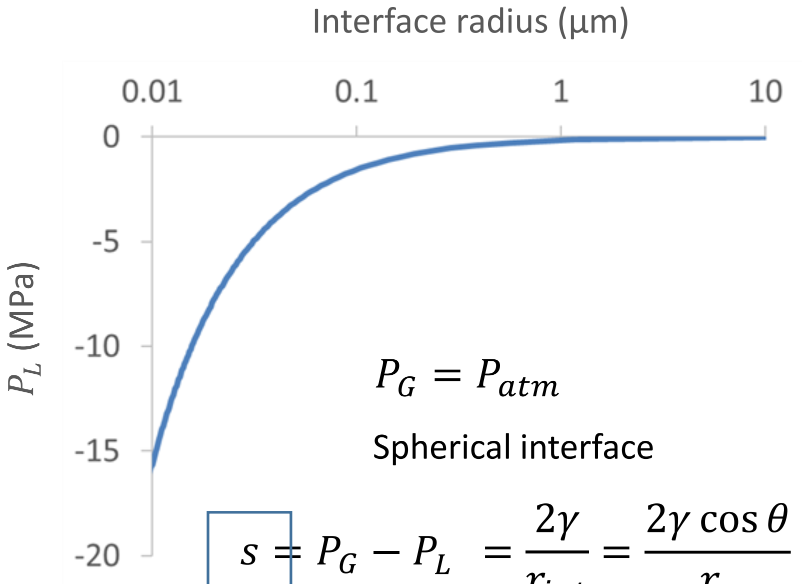




Pore size distribution obtained my MIP and NAD on 3 different earths

Concept of suction





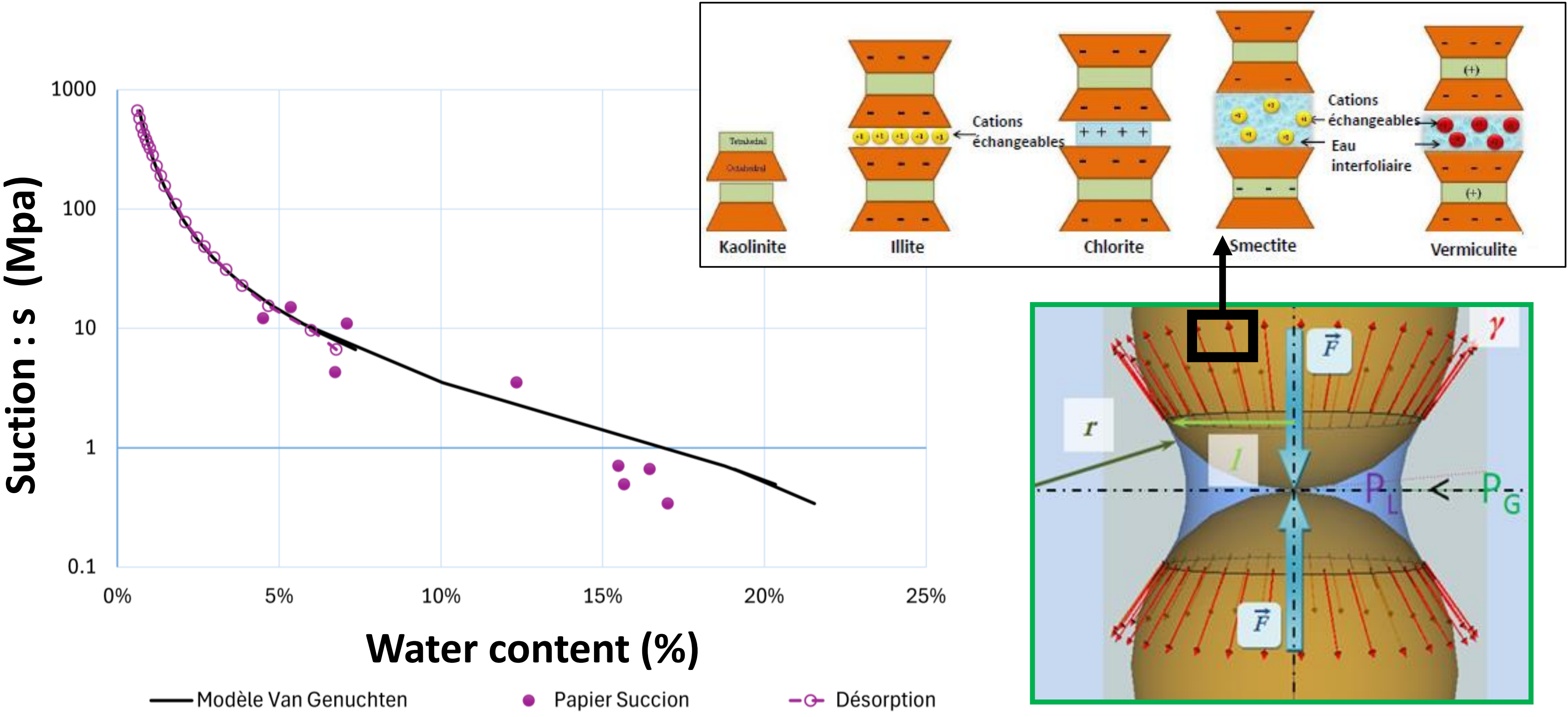
$$P_G = P_{atm}$$

Spherical interface

$$\boxed{s} = P_G - P_L = \frac{2\gamma}{r_{int}} = \frac{2\gamma\cos\theta}{r_p}$$

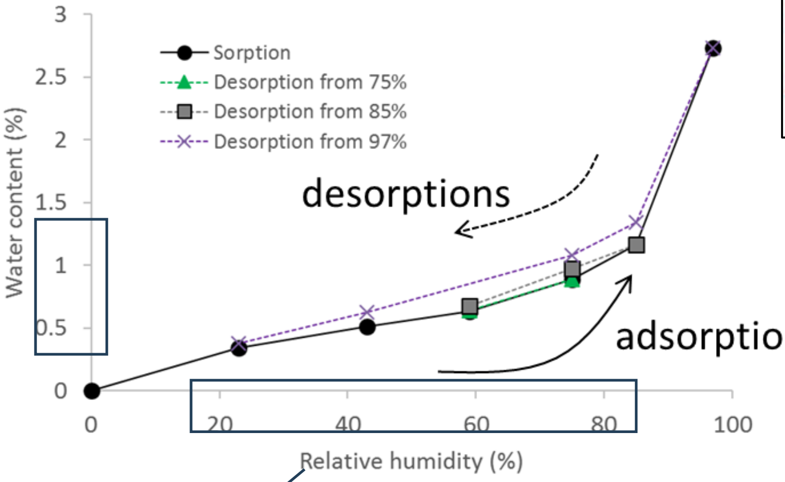
Matric suction or capillary pressure

/// Concept of suction

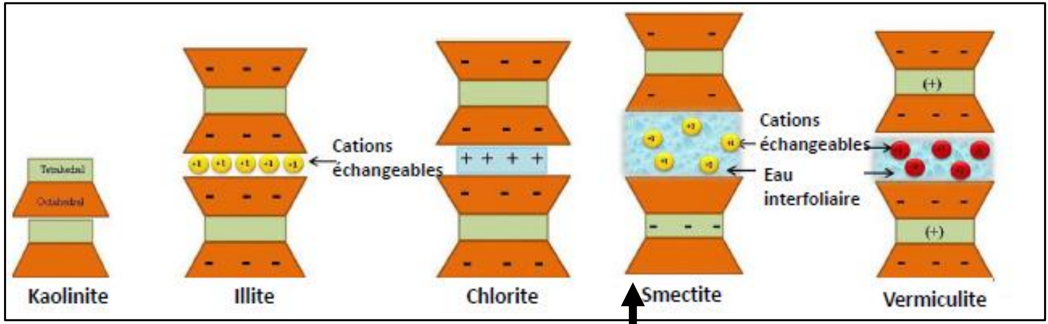


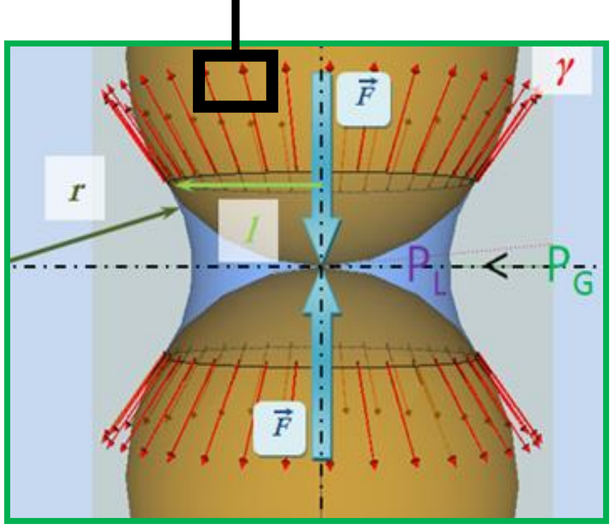
$s = P_G - P_L > 0$: matric suction

/// Concept of suction



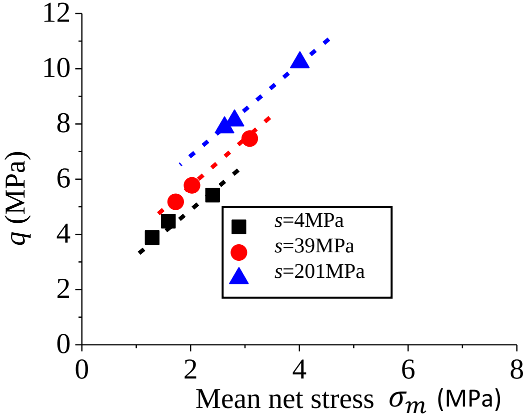
$$RH = \frac{p_v}{p_v^{sat}} \qquad s = -\frac{\rho_L RT}{M_{\mathrm{H2O}}}\ln(RH)$$



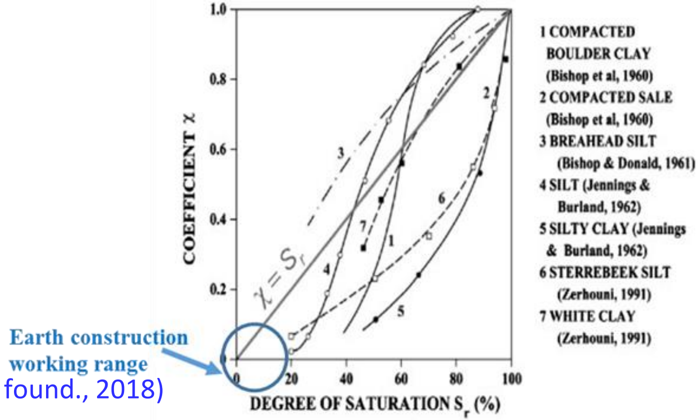


$s = P_G - P_L > 0$: matric suction

Example of effective stress definition



Notations : $\sigma_m = \frac{1}{3}(\sigma_1 + 2\sigma_3)$; $q = \sigma_1 - \sigma_3$



(Xu et al., Soils and found., 2018)

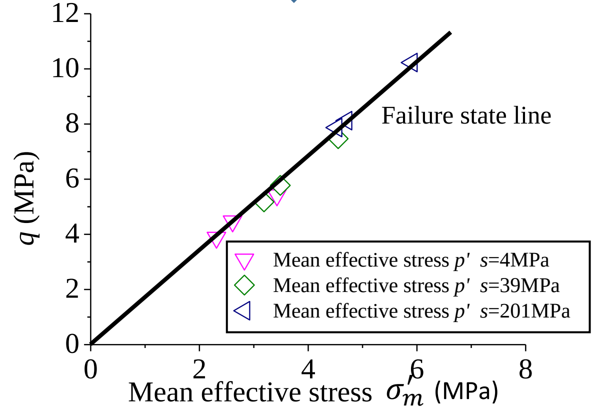
Mean effective stress p'

$$\sigma'_{ij} = (\sigma_{ij} - u_a\delta_{ij}) + \chi s\delta_{ij}; \quad \sigma_m{}' = \sigma_m + \chi s$$

$$\chi = \left(\frac{s_e}{s}\right)^{\alpha}$$

Adapted from(Khalili 1998)

	Clay content (%)	Coefficient α
Mix1	17	0.85
Mix2	26	0.85
Lim	35	0.85



Example of elasto-plastic modelling with damage

Assumptions: Isotropic damage by a scalar D

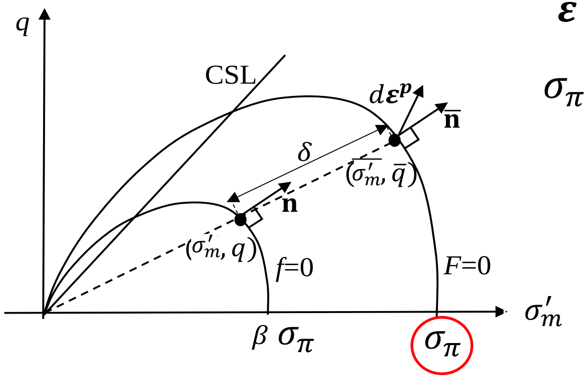
Triaxial stress state $(\sigma_1, \sigma_2 = \sigma_3)$

Constant suction : $ds = 0$

Suction effect

Damage criterion: $f_D(Y_D, D, s) = Y_D - r(D, s) \leq 0$

Bounding Surface Plasticity (BSP)



$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p$$

$$\sigma_\pi(\varepsilon_v^p, s, D) = (1 - D)\big(1 + k_1 \times l(s)\big)\sigma_p\big(\varepsilon_v^p\big)$$

damage effect suction hardening plastic hardening

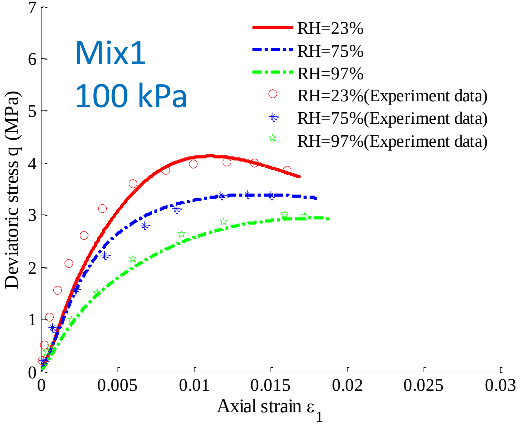
$$\sigma'_m = \frac{1}{3}\,(\sigma'_1 + 2\,\sigma'_3) = \sigma_m + \chi s$$

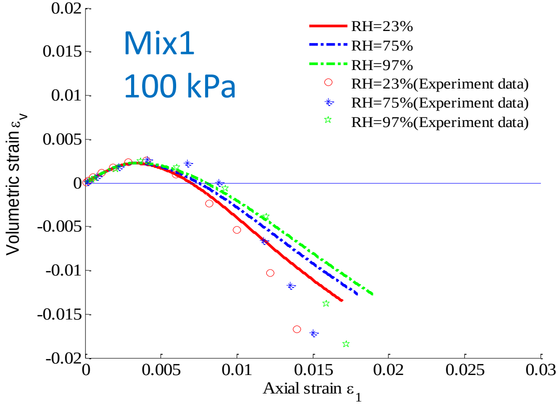
$$q = \sigma_1 - \sigma_3$$

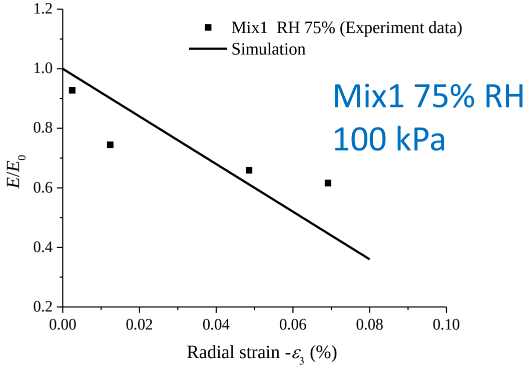
$$\chi = \begin{cases} \left(\dfrac{s_e}{s}\right)^{0.85} & \text{if } s > s_e \\ 1 & \text{if } s \leq s_e \end{cases}$$

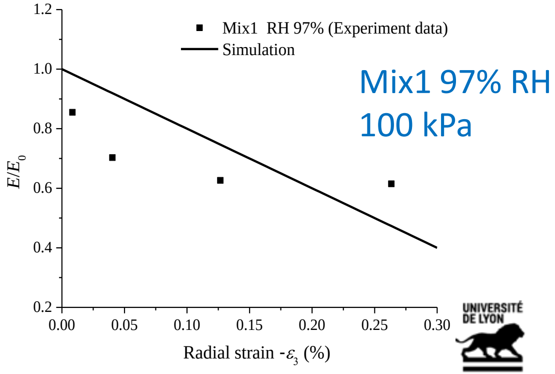
(Xu et al., Mat. & Struct., 2018)

/// Example of elasto-plastic modelling with damage



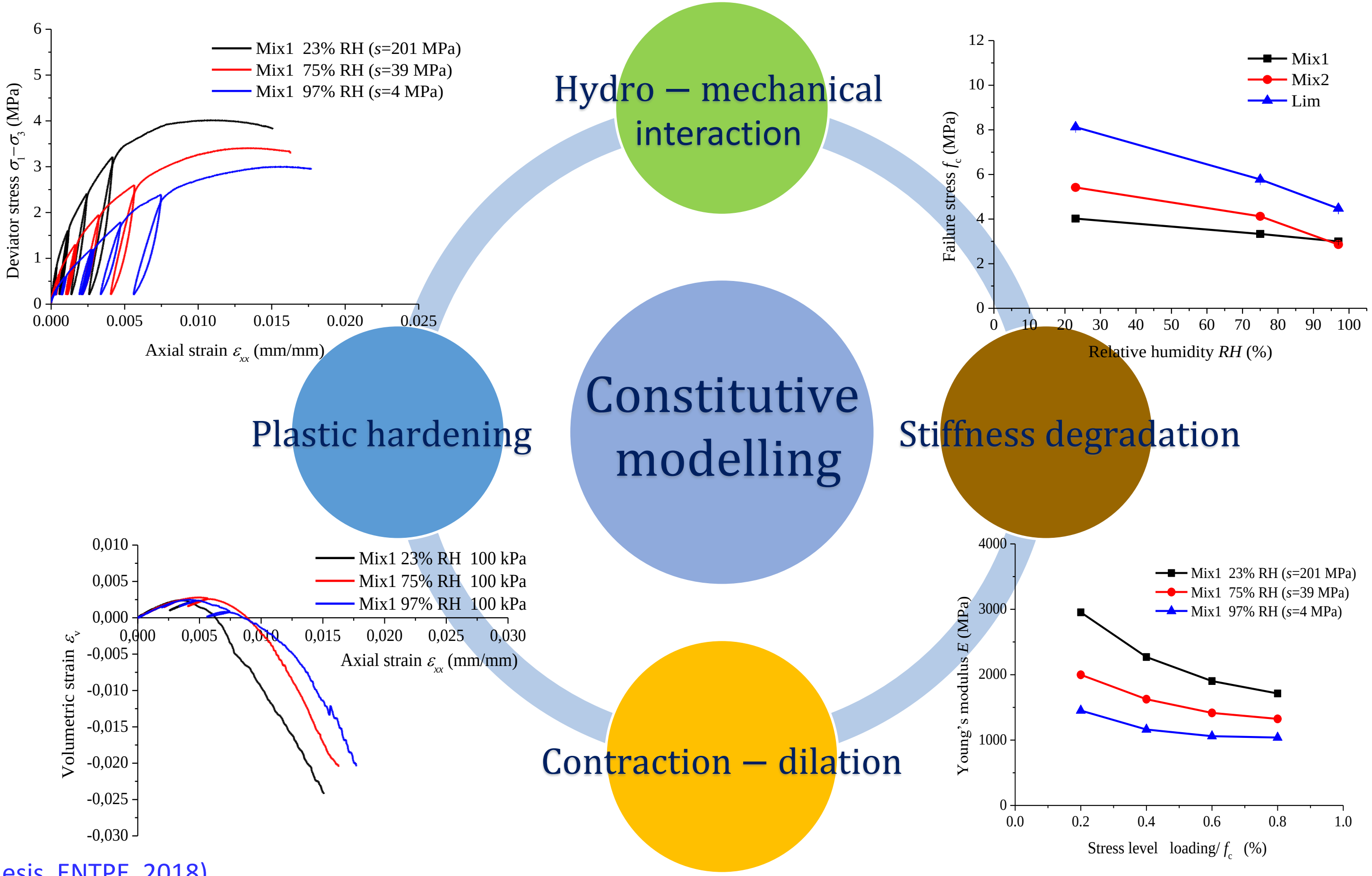






(Xu et al., Mat. & Struct., 2018)

Summary of HM behavior and modelling



Hydro – mechanical interaction

Plastic hardening

Constitutive modelling

Stiffness degradation

Contraction – dilation

(Xu, PhD Thesis, ENTPE, 2018)

04

On site assessment

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Non destructive assessment

Mise en **œuvre**

Contrôle qualité |
Identification défaut de mise en œuvre

Mise en **service**

Suivi du bâtiment |
Attestation des performances finales

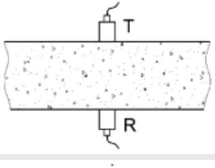
Phase **réhabilitation**

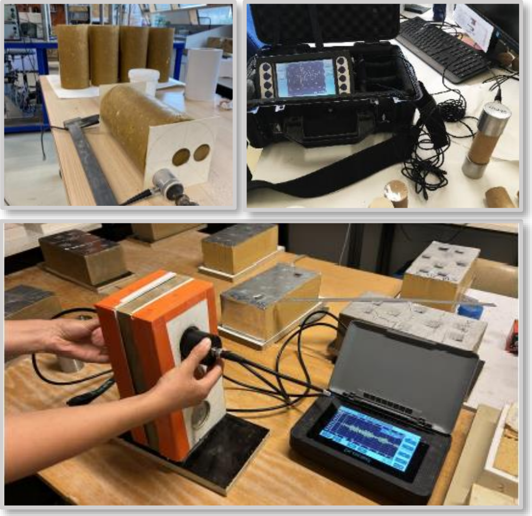
Estimation des performances |
Identification de pathologie

Non destructive assessment

- Example of ultrasonic waves velocities

Méthode directe[1]





Estimation des propriétés élastiques d’un milieu à partir des mesures de vitesse de propagations d’ondes ultrasoniques.

Onde de compression et de cisaillement

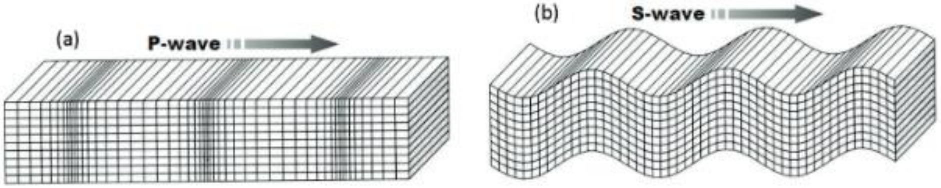


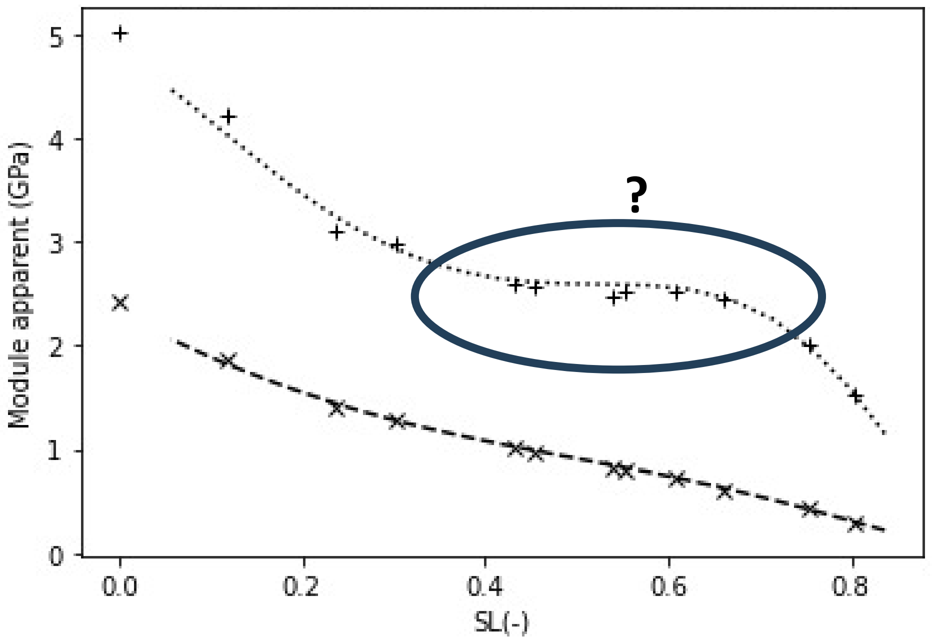
Figure 2.7. Particle motions characteristic of body waves propagation: (a) P-waves; (b) S-waves (Shearer, 1999).

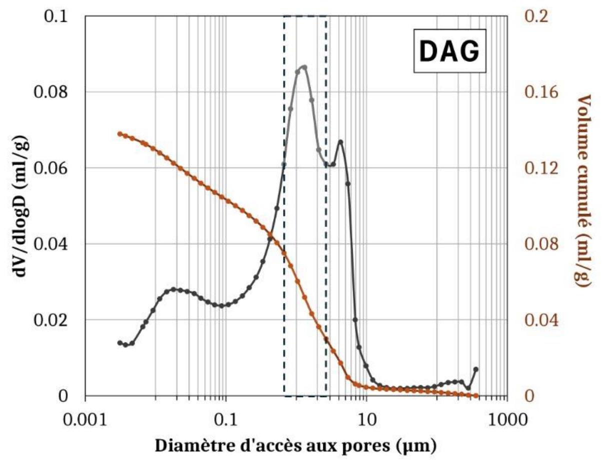
$$V_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \qquad V_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2\rho(1+\nu)}}$$

(Force, PhD Thesis, ENTPE, In progress)

Non destructive assessment

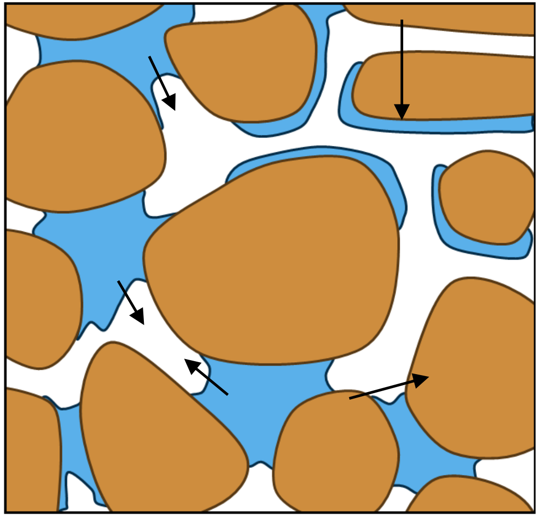
Evolution of confined (M) and shear (G) moduli with liquid saturation on CEB



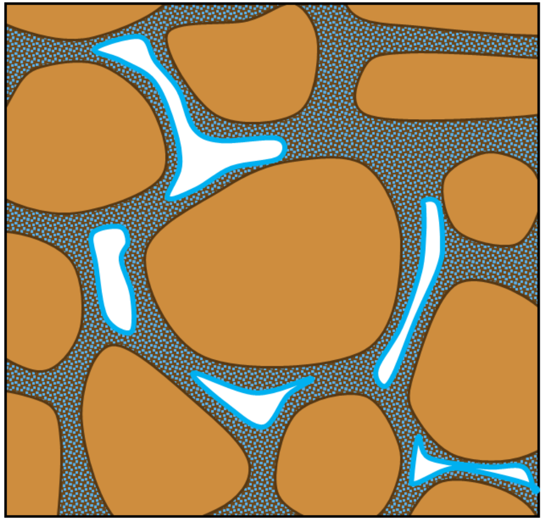


/// Non destructive on site assessment

Impact of liquid water on stiffness ?



At several dozen of kHz, water can participate to material stiffness



Solid clayey matrix is soften by the presence of water

(Force, PhD Thesis, ENTPE, In progress)

/// Non destructive on site assessment

Isothermal poro-elastic law of behaviour, with null gaz pressure

Skeleton

$$\mathrm{d}\sigma_m = K\mathrm{d}\varepsilon_m - b_L \mathrm{d}p_L$$
$$\mathrm{d}\boldsymbol{s} = 2\,G\,\mathrm{d}\boldsymbol{e}$$
$$\mathrm{d}\phi_L = b_L \mathrm{d}\varepsilon_m + \frac{\mathrm{d}p_L}{N_{LL}}$$

Liquid water

$$\frac{\mathrm{d}\rho_L}{\rho_L} = \frac{\mathrm{d}p_L}{K_L}$$

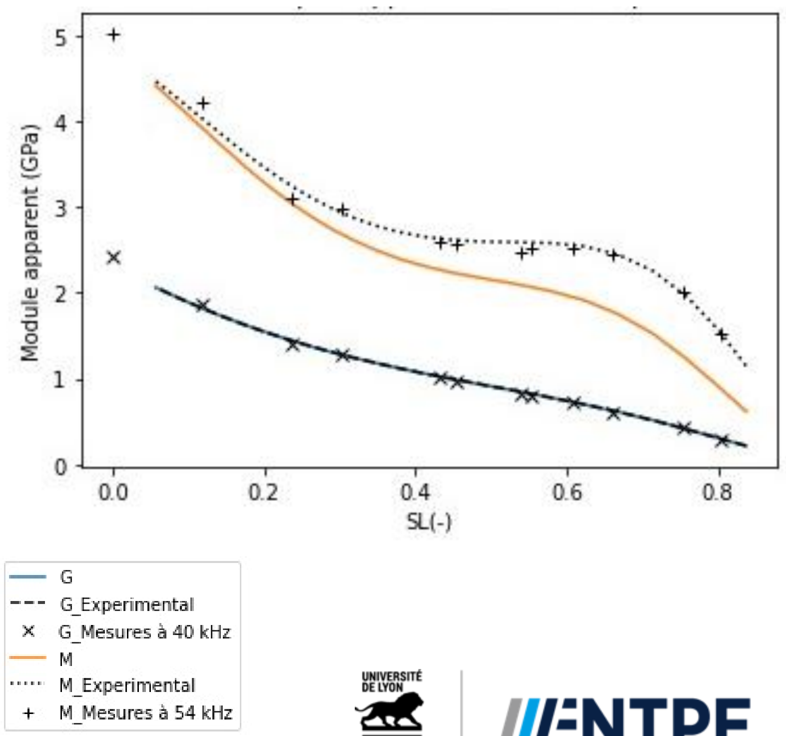
Mass conservation of liquid phase with undrained condition

$$\frac{\mathrm{d}m_L}{\rho_L} = \mathrm{d}\phi_L + \phi_L \frac{\mathrm{d}\rho_L}{\rho_L} = 0$$

$$\Rightarrow \quad V_p = \sqrt{\frac{\widetilde{M}}{\rho}} = \sqrt{\frac{\widetilde{K} + 4G/3}{\rho}}\,; \qquad V_s = \sqrt{\frac{G}{\rho}}$$

where

$$\widetilde{M} = M + b_L^2 \left(\frac{1}{N_{LL}} + \frac{\phi_L}{K_L}\right)^{-1}$$
$$\widetilde{G} = G$$



(Force, PhD Thesis, ENTPE, In progress)

/// On site applicability

Qualit' ère

Suivi séchage sur Bloc

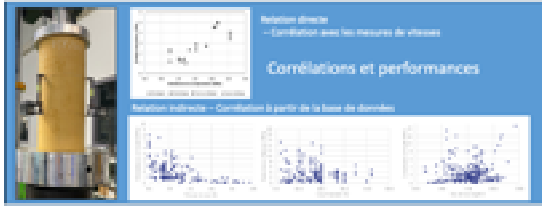
Validation sur Atelier de la danse

Mesure vitesse de propagation sur site

Validation sur démonstrateur

+ Atelier de la danse

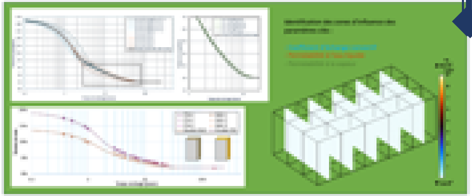
◆ Déterminer la Résistance à la compression



Déterminer teneur en eau sur site

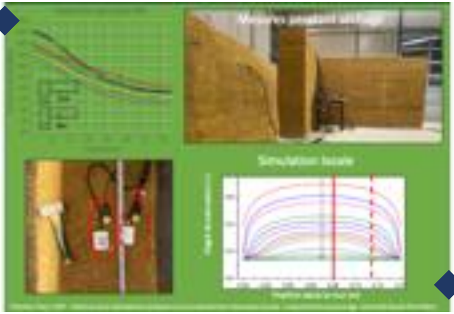
Mesure sur site

Mesure laboratoire



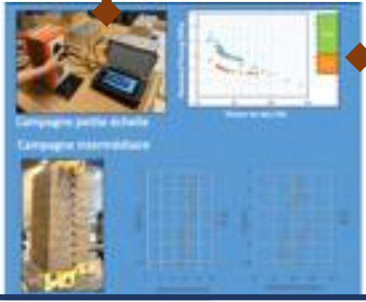
Paramètre hygrothermique

Déterminer cinétique de séchage



Validation sur démonstrateur

Distribution teneur en eau



Lien vitesse et propriétés mécanique

Etalonnage sur échantillon

Vitesse
-
Propriétés mécaniques
Teneur en eau

Relation en milieu hétérogène

Comportement au séchage

(Force, PhD Thesis, ENTPE, In progress)

Batiserf
Ingénierie structure tous matériaux

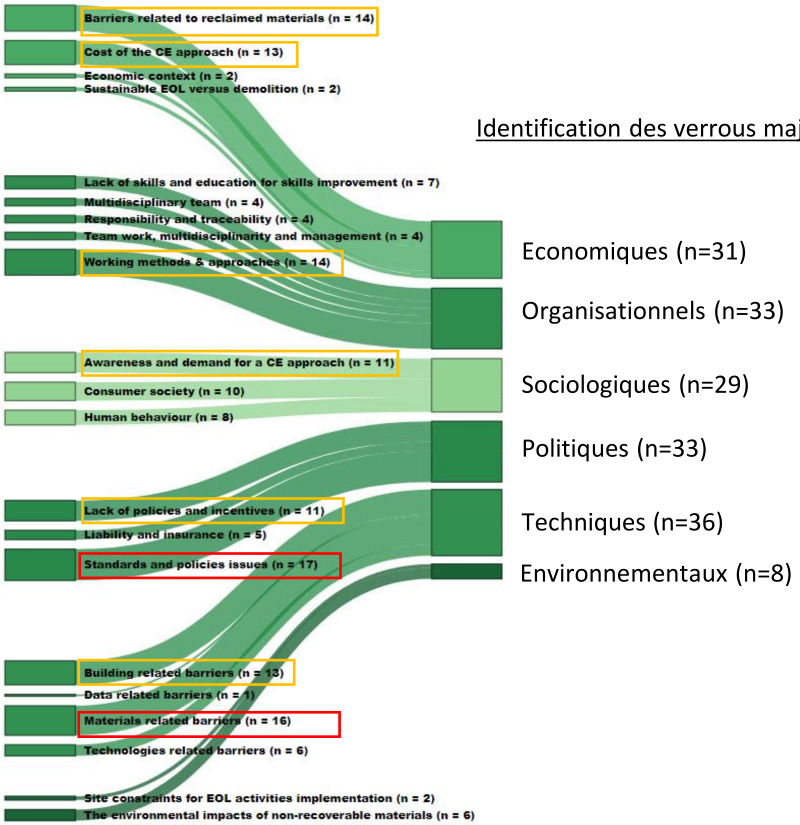
CSTB
le futur en construction

Université Gustave Eiffel

PNTERRE

/// Conclusion

Les verrous actuels au développement

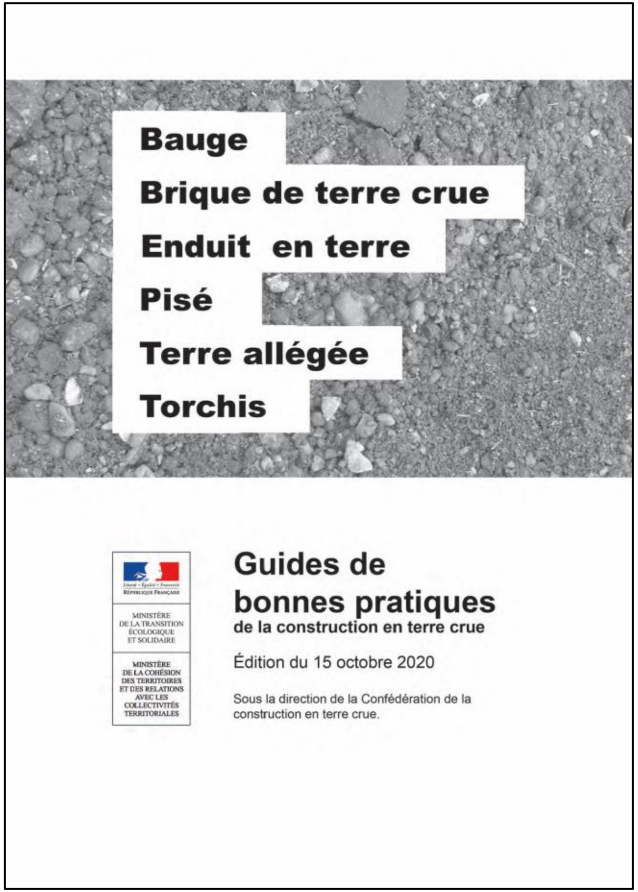


Identification des verrous majeurs

Identification des verrous basée sur des entretiens avec 20 personnes ayant des expériences internationales reconnues dans les champs de l'architecture, de l'éco-construction et de l'économie circulaire.
(Morel et al., Ph. Trans. B, 2021)

- ✓ Une grande partie de l'histoire de la terre crue moderne est encore à construire
- ✓ Cette construction ne pourra se faire que par une approche couplée combinant les différents aspects (techniques, sociologiques, politiques…)

/// Conclusion



Bauge
Brique de terre crue
Enduit en terre
Pisé
Terre allégée
Torchis

MINISTÈRE DE LA TRANSITION ÉCOLOGIQUE ET SOLIDAIRE

MINISTÈRE DE LA COHÉSION DES TERRITOIRES ET DES RELATIONS AVEC LES COLLECTIVITÉS TERRITORIALES

Guides de bonnes pratiques
de la construction en terre crue

Édition du 15 octobre 2020

Sous la direction de la Confédération de la construction en terre crue.

Approche **performantielle** retenue

Pas de prescription des moyens permettant d’atteindre les performances mais :

- identification des performances attendues (en fonction de la technique constructive) et
- description des méthodes permettant d’évaluer correctement les performances

Ils facilitent l’assurabilité des constructions MAIS ne suffisent pas à faire entrer les constructions en terre dans les techniques courantes

ENTPE

L'école de l'aménagement durable des territoires