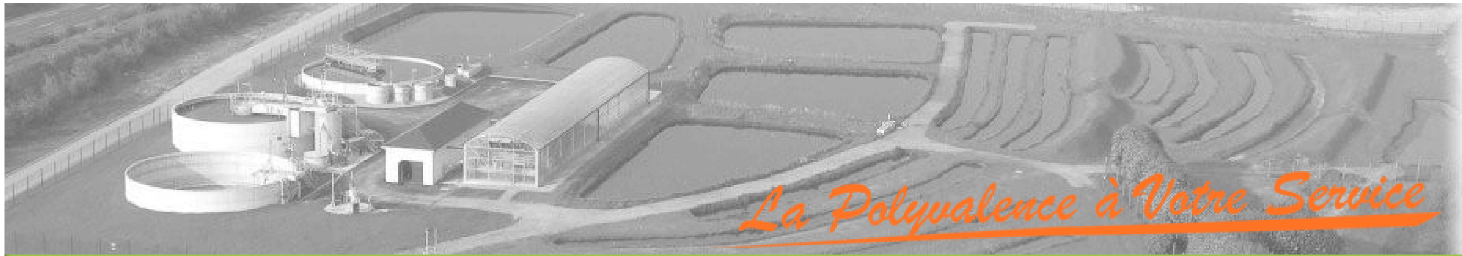

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Paris, le 08/04/2013

UTILISATION DES SOLS TRAITES A LA CHAUX ET AU CIMENT POUR LE RENFORCEMENT DES SOLS AVEC INCLUSIONS RIGIDES

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Use of lime and cement treated soils as pile supported load transfer platform

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A R T I C L E I N F O

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A B S T R A C T

Soil treatment on site is an economical and environmental solution for many engineering applications. The technique has been widely used in construction of roads and railways. In recent years, the interest in soil treatment for foundations has significantly increased. In this context, treated soils are used under structure foundations in order to homogenize settlements and establish a resistant base layer called earth platform. An application of this technique is the use of treated soils between foundations of structures and vertical piles. Load transfer mechanisms occur in the earth platform and loads are transferred to the piles head. The mechanical characteristics of the treated soils are then important due to the fact that it is the place where load transfer mechanisms occur.

In this context, an experimental study was performed in order to obtain the mechanical properties of lime/cement treated soils. Firstly, physical properties of the Goderville silt were examined. Then different quantities of lime/cement were added to soil and compacted at the optimum water content. Stabilized specimens were tested at 7, 28, 90, and 350 days after the treatment in order to observe the evolution of mechanical resistance in time. Finally, the experimental results were used in a numerical analysis in order to understand the load transfer mechanisms in the piled earth platforms depending on the type of soil treatment, pile spacing and height of earth platform.

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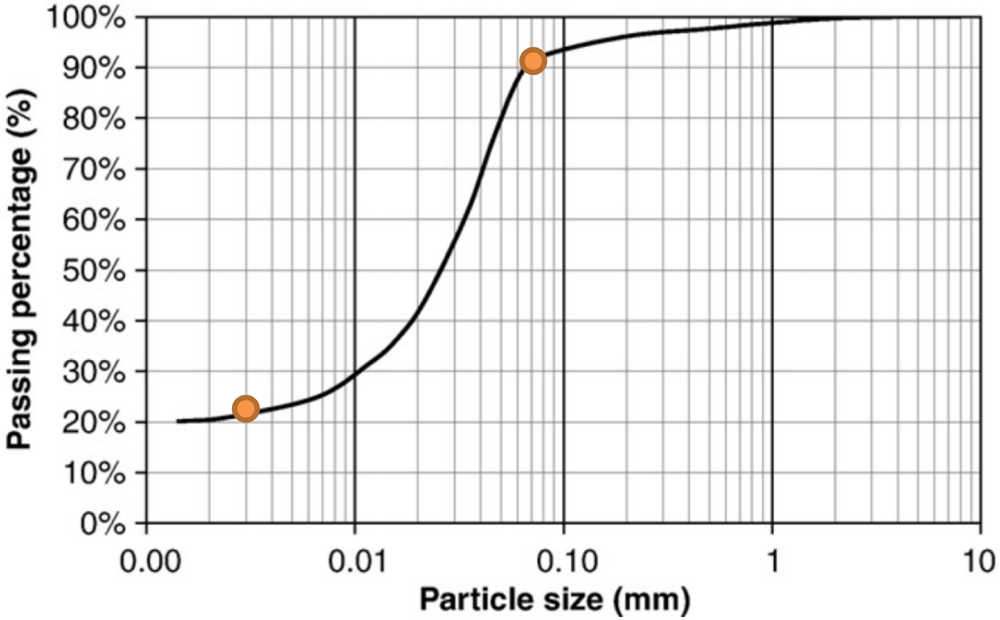
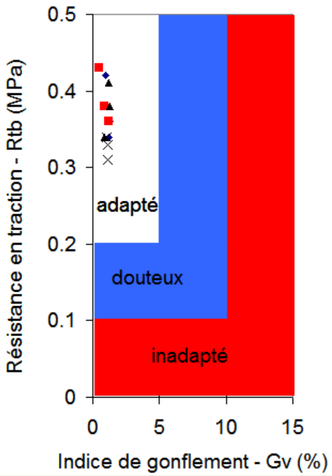
3 Tons of Goderville silt



- Particles smaller than 0.063 mm and larger than 0.002 mm constitute 70% of the soil.
- 25% of the particles are smaller than 0.002 mm.



Liquid limit	LL (%)	30	NF P 94-051
Plastic limit	PL (%)	20.4	NF P 94-051
Plasticity index	PI (%)	9.6	NF P 94-051
Specific gravity	Gs	2.65	NF P 94-054
Clay fraction	(%)	20	NF P 94-057
Organic content	(%)	2	NF P 94-047
$CaCO_3$ content	(%)	2.12	NF P 94-048
Maximum dry density	(g/cm^3)	1.80	NF P 94-093
Classification		A1	NF P 11-300
Unified soil classification		ML	ASTM D2487
AASHTO soil classification		A-4	ASTM D3282

Gravel	Sand	Silt	Clay
>2	2 to 0.06	0.06 to 0.002	<0.002

Soil

Lime

Cement

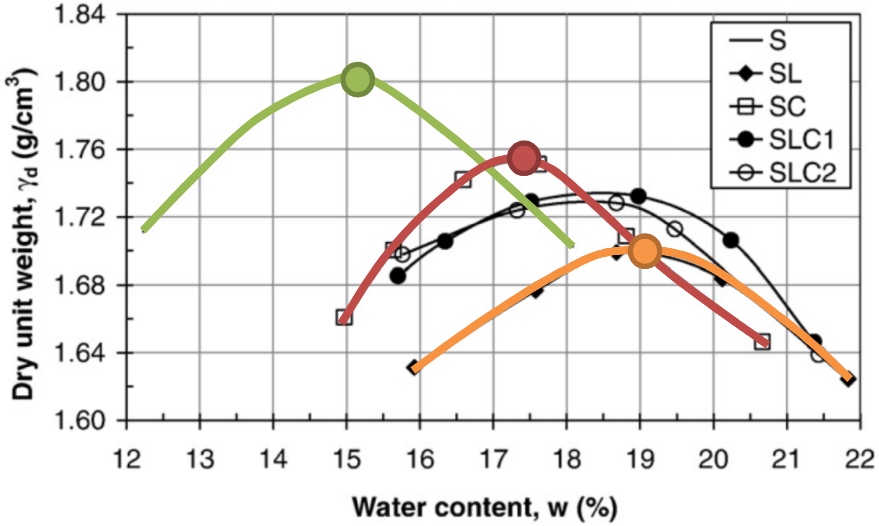
SL 3%

SC 6%

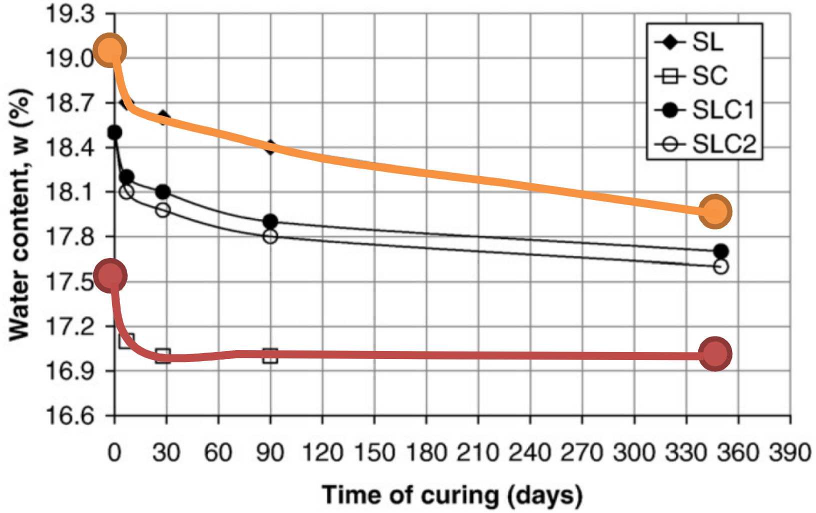
SLC1 3% 2%

SLC2 5% 2%

Proctor tests & Treatment formulations



The addition of cement/lime has an influence in increasing the optimum water content and decreasing the maximum dry unit weight of the naturel soil.



Variation of reduction in water content due to hydration at different curing time

Notation of the tested materials and optimum Proctor values

	Notation	Lime	Cement	wopt	γd (g/cm^3)
Soil	S	–	–	15.2	1.80
Soil + lime	SL	3%	–	19.0	1.70
Soil + cement	SC	–	6%	17.5	1.75
Soil + lime + cement	SLC1	2%	3%	18.5	1.73
Soil + lime + cement	SLC2	2%	5%	18.5	1.73

Mechanical performance of treated soil : Laboratory tests

In the experimental program, the Goderville soil was characterised by laboratory tests and appropriate treatment formulations were chosen.

Mechanical soil tests were conducted to deduce the strength characteristics of soils at **7, 28, 90 and 350 days** after treatment.

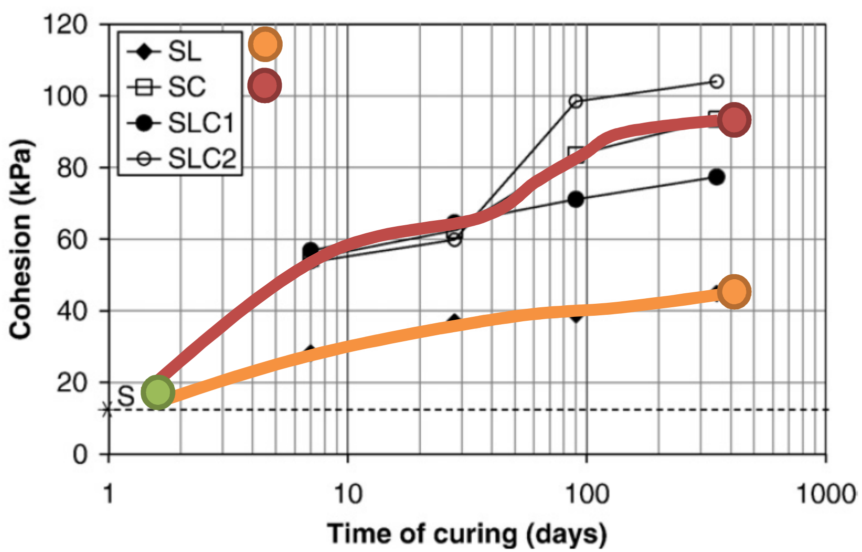
Test name	S	SL	SC	SLC1	SLC2
Proctor	5	5	5	5	5
Uniaxial compression	4	12	12	12	12
Direct shear	4	16	16	16	16
Indirect tension	4	12	12	12	12
Bending	4	8	8	12	12

Direct shear tests

The shearing tests were carried on normal stress range from 50 to 100 kPa.

- The value of the cohesion reaches at least 25 kPa at the first week treatment and above 60 kPa at 28 days after the treatment in presence of cement.
- The evolution of cohesion for the soil treated with lime is quite slow and the cohesion does not exceed 45 kPa in long term.

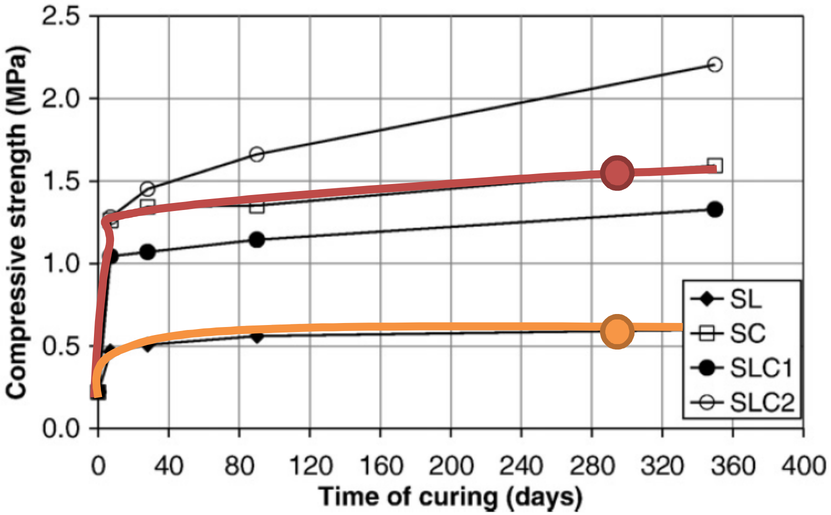
Evolution of cohesion



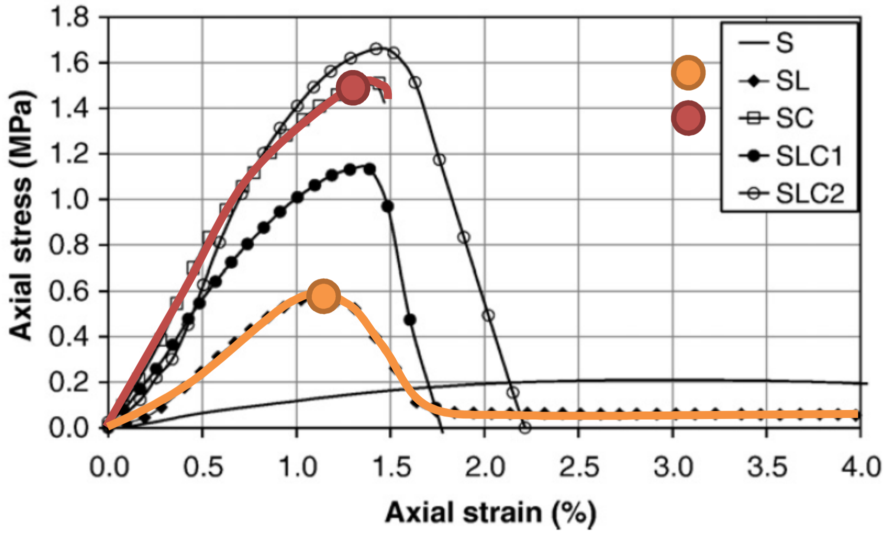
The tests were performed with 50mm height and 60 mm diameter cylindrical specimens at constant shearing speed (0.1 mm/min).

Unconfined compressive strength test : uniaxial compression

Evolution of compressive strength



Stress vs strain @ 90 days

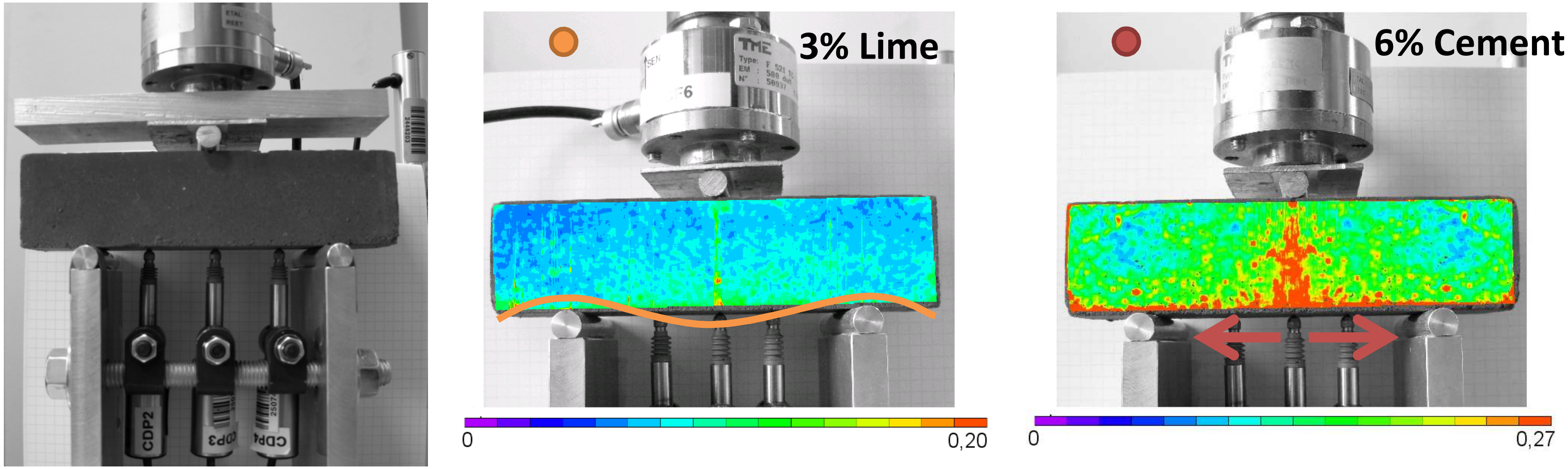


In presence of cement, more than 80% of the final compressive strength was obtained at 90 days after the treatment. This ratio is 70% for the treatment with only lime. The highest strength value is obtained with the combined treatment SLC2.

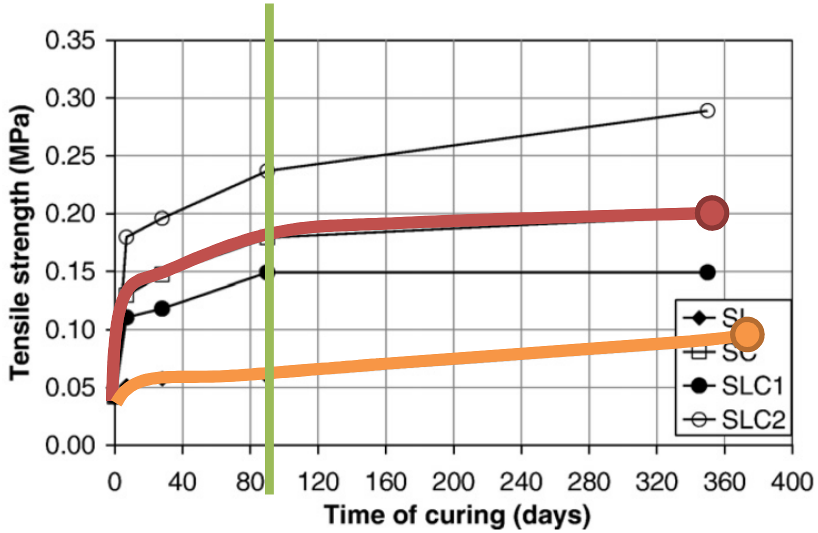
- The untreated soil (S) has ductile strain hardening failure behaviour.
- On the other hand, ductile strain softening behaviour is observed for lime treated soil (SL).
- Addition of cement ----- specimens become more brittle.
- For the cement treated soil (SC), the failure occurs suddenly at the end of the test.
- The addition of lime to the treatment provides a residual resistance at the end of the test and the specimens behave in a more ductile manner.

The tests were carried out with 100 mm height and 50 mm diameter cylindrical specimens at a constant loading speed of 0.1 mm/min.

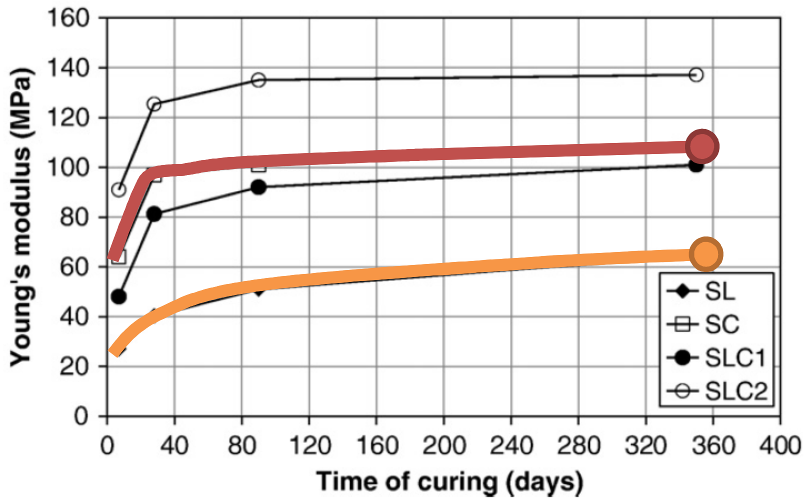
Bending test on 4 x 4 x 16 cm specimens



Evolution of tensile strength



Evolution of Young's modulus



Bending resistance of the specimen is equal to $3FL/2a^3$ where a is the section of the specimen. Then the Young's modulus of the specimen is calculated $E=FL^3/48I_y$ where I is the second moment of area and y is the deflection at the centre of the beam.

Summary of the results at 90 days after the treatment and comparisons

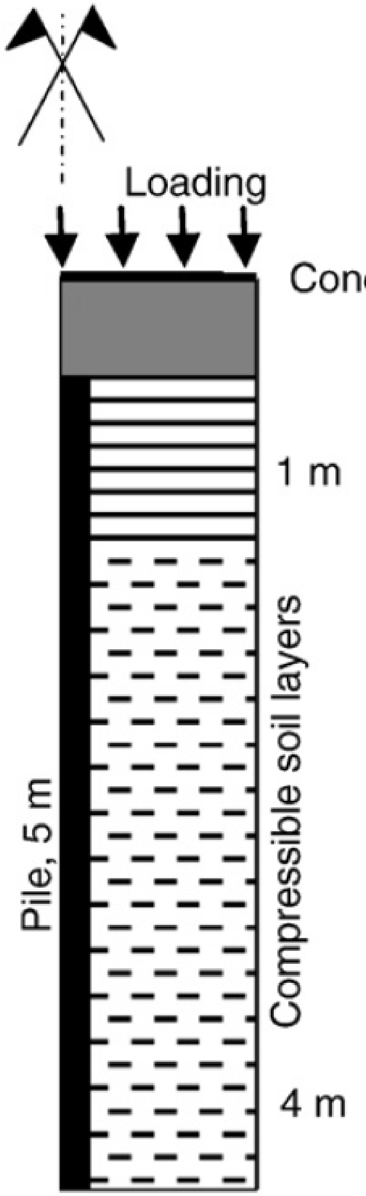
		S	SL	SC	SLC1	SLC2	Test type
Rc	MPa	0.39	0.56	1.35	1.14	1.66	Unconfined compression
Rt	MPa	0.028	0.06	0.18	0.15	0.24	Tensile strength
Rb	MPa	0.25	0.39	1.02	0.74	1.06	Bending
Es	MPa	9	53	106	100	145	Unconfined compression
Et	MPa	10	64	114	99	170	Unconfined compression
E	MPa	9	51	101	92	135	Bending
c'	kPa	12.5	38.9	83.5	71.1	98.4	Direct shear
ϕ'	°	10.8	18.0	22.4	20.1	31.0	Direct shear
ν	–	0.303	0.310	0.296	0.307	0.300	Tensile strength

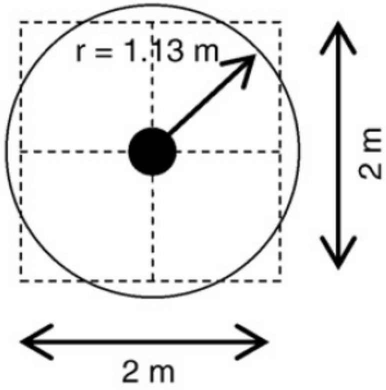
Comparisons

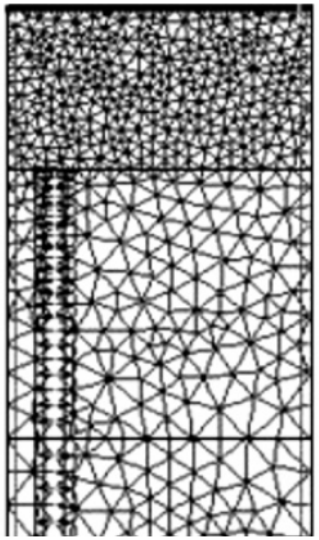
Rt/Rc	–	0.07	0.11	0.13	0.13	0.14	Comparison 1
Rt/c′	–	2.24	1.54	2.16	2.11	2.44	Comparison 2

The tests indicate that almost 90% of total resistance is gained at 90 days of curing after treatment.

Numerical analysis of treated soils with rigid piles







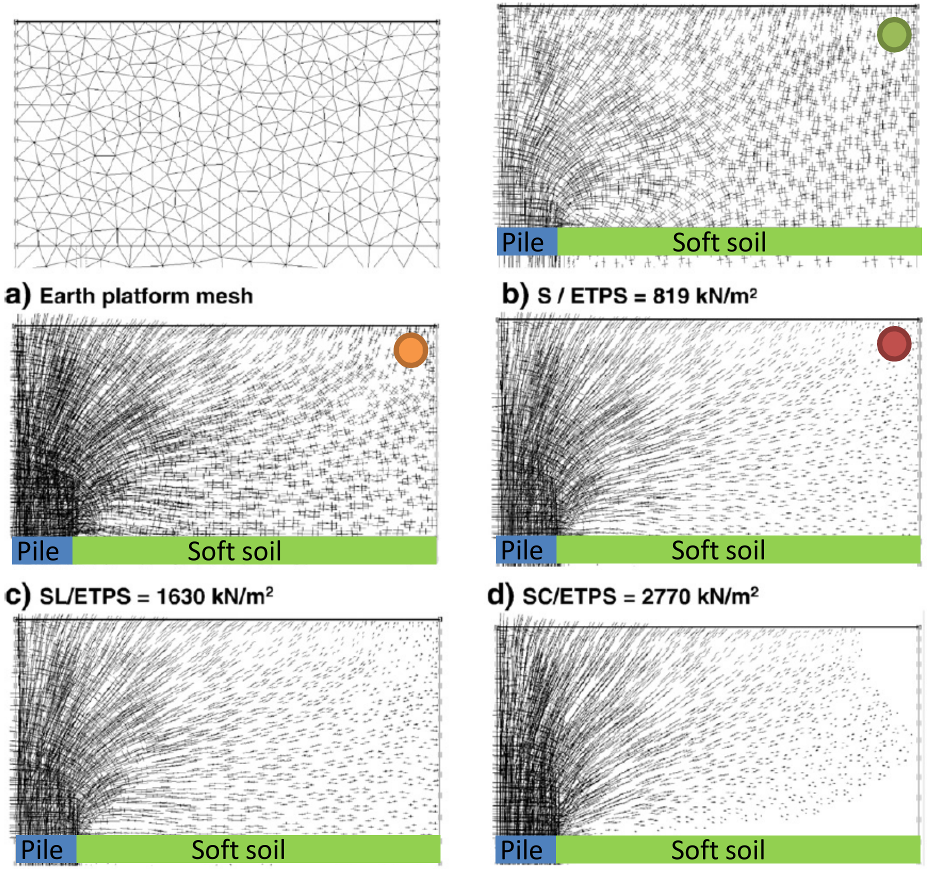
Model parameters for the treated soils.

			S	SL	SC	SLC1	SLC2
Young's modulus	E	MPa	10	50	105	95	140
Effective cohesion	c'	kPa	12.5	35	85	70	100
Effective angle of friction	ϕ'	°	10.8	18	22	20	30

Model parameters for the clay of Cubzac-les-Ponts.

	λ	κ	M	$e = N - 1$	ν
Compressible soil	0.53	0.048	1.2	4.11	0.35
Surface layer	0.12	0.017	1.2	1.47	0.35

Total principal stresses under 60 kPa of loading on the foundation



a) Earth platform mesh

b) S / ETPS = 819 kN/m²

c) SL/ETPS = 1630 kN/m²

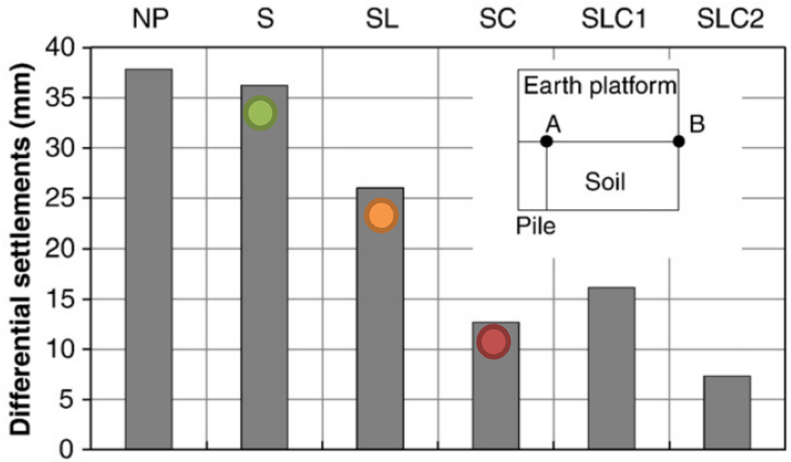
d) SC/ETPS = 2770 kN/m²

e) SLC1/ETPS=2580 kN/m²

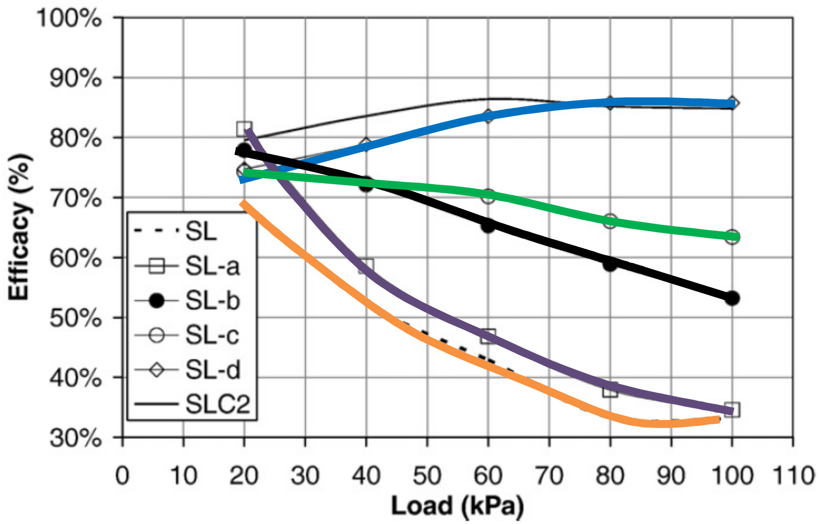
f) SLC2/ETPS=2930 kN/m²

			SL	SL-a	SL-b	SL-c	SL-d
Young's modulus	E	MPa	50	150	50	50	150
Effective cohesion	c'	kPa	35	35	115	35	115
Effective angle of friction	ϕ'	°	18	18	18	36	36

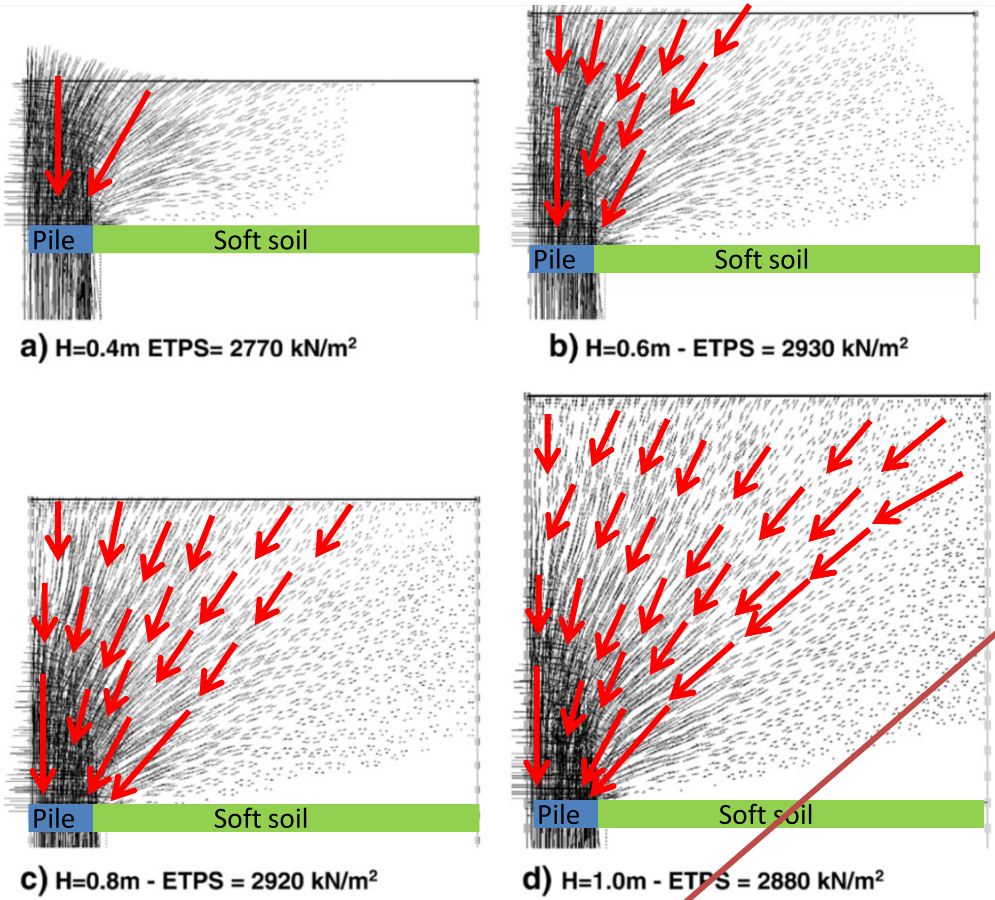
Differential settlements



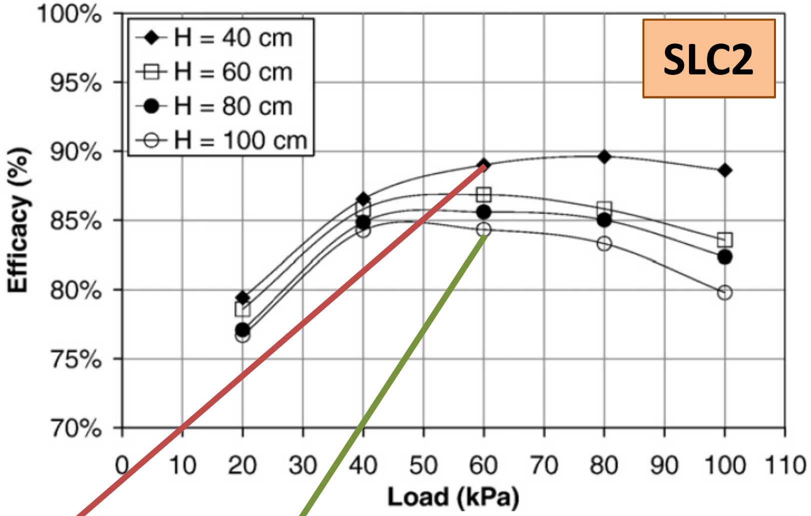
Variation of the material characteristics



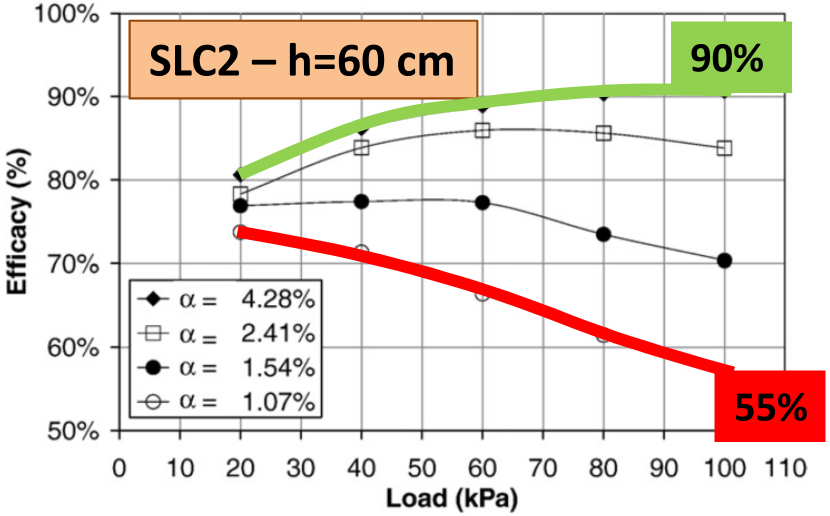
Total principal stresses for 60 kPa of loading on the foundation.



Influence of platform height



Influence of pile spacing

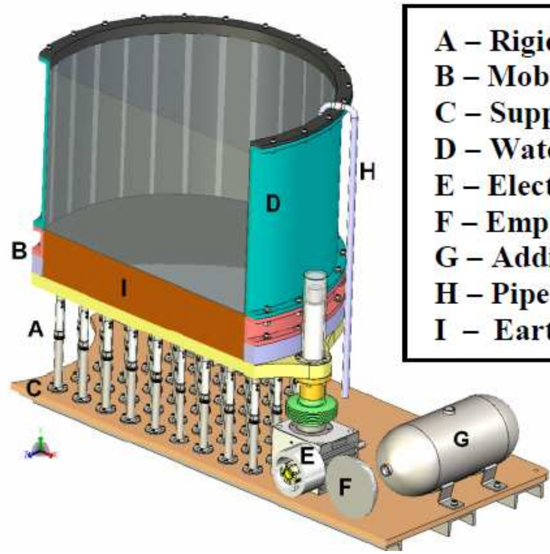


Bending moments and shear forces in the foundation.

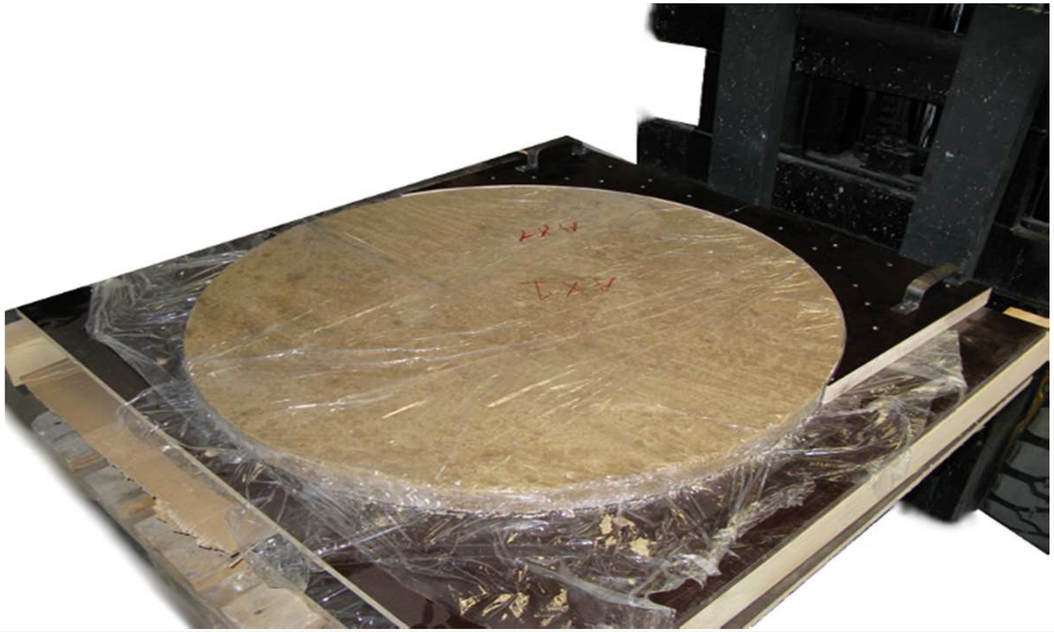
Earth platform	m	0.4	0.6	0.8	1.0
Maximum moment	kN m	17.2	9.6	5.2	3.0
Shear force	kN	59.6	30.6	17.2	9.9
Efficacy	%	89.0	86.8	85.6	84.3

Geotechnical centrifuge of LCPC Nantes

Experimental Apparatus



A – Rigid piles
B – Mobile tray and adjustment rings
C – Supporting deck
D – Water tank
E – Electric jacks
F – Emptying pump
G – Additional water tank
H – Pipes for filling and emptying
I – Earth-platform



Fabrication des galettes du sol traité :

MALAXAGE

TRAITEMENT

COMPACTAGE

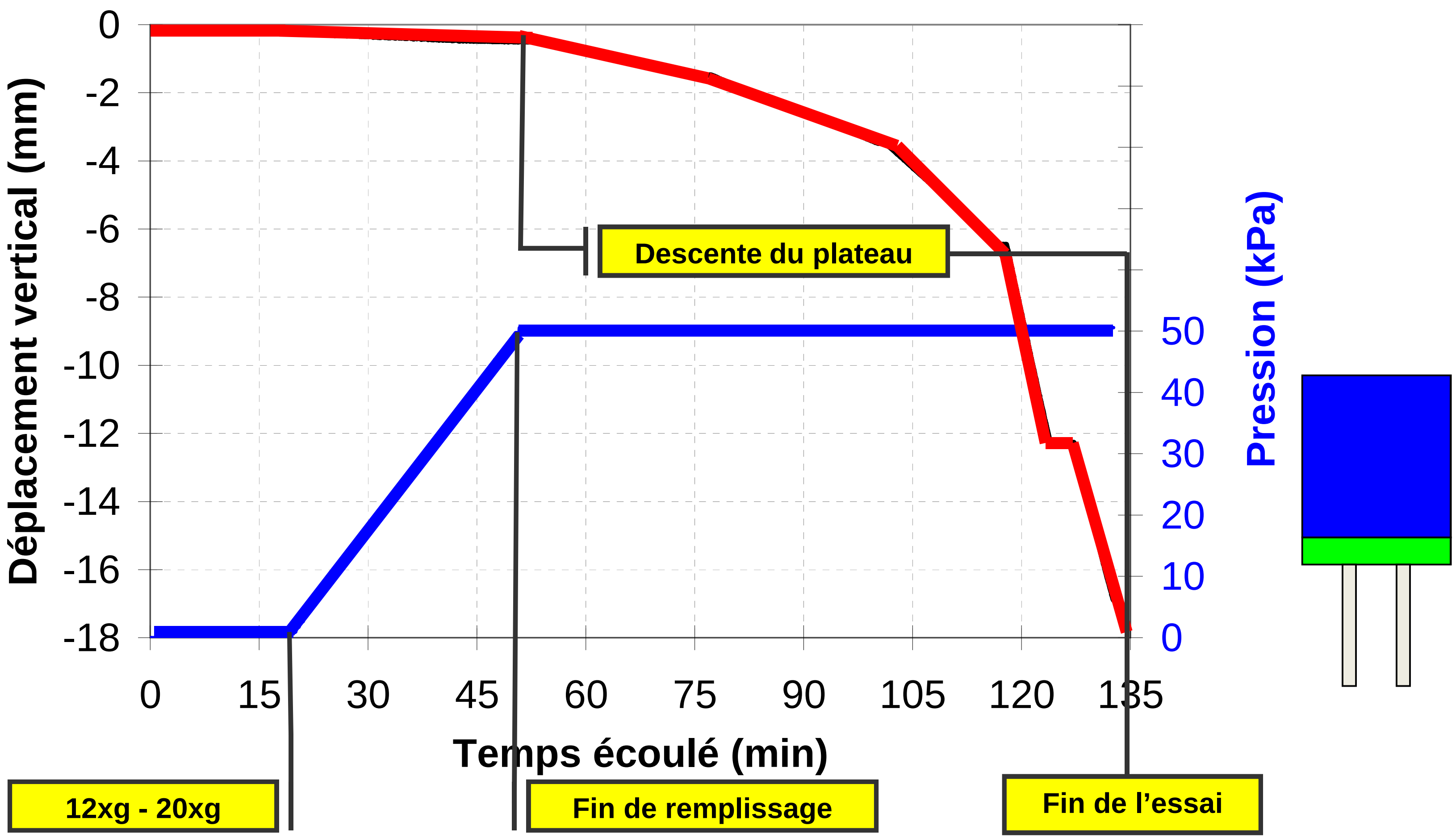
COMPACTAGE

STOCKAGE

TRANSPORTATION

SL & SC **Diamètre = 90 cm** **Hauteur = 42 cm – 60 cm**

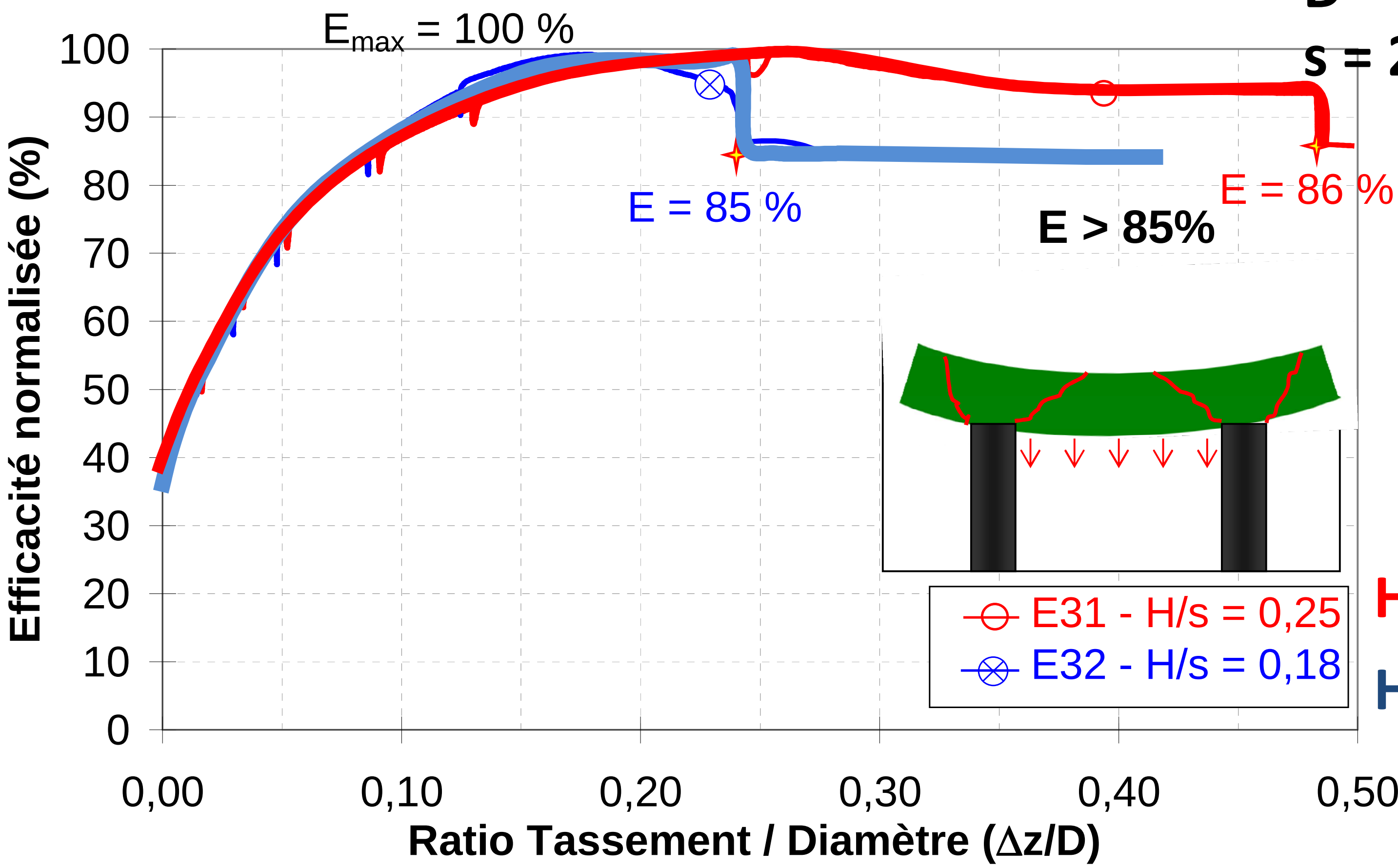
ESSAI TYPE : Déroulement d’un essai



Efficacité avec un matelas traité à la chaux (α = 1,23%)

12 x g

D = 30 cm
s = 240 cm



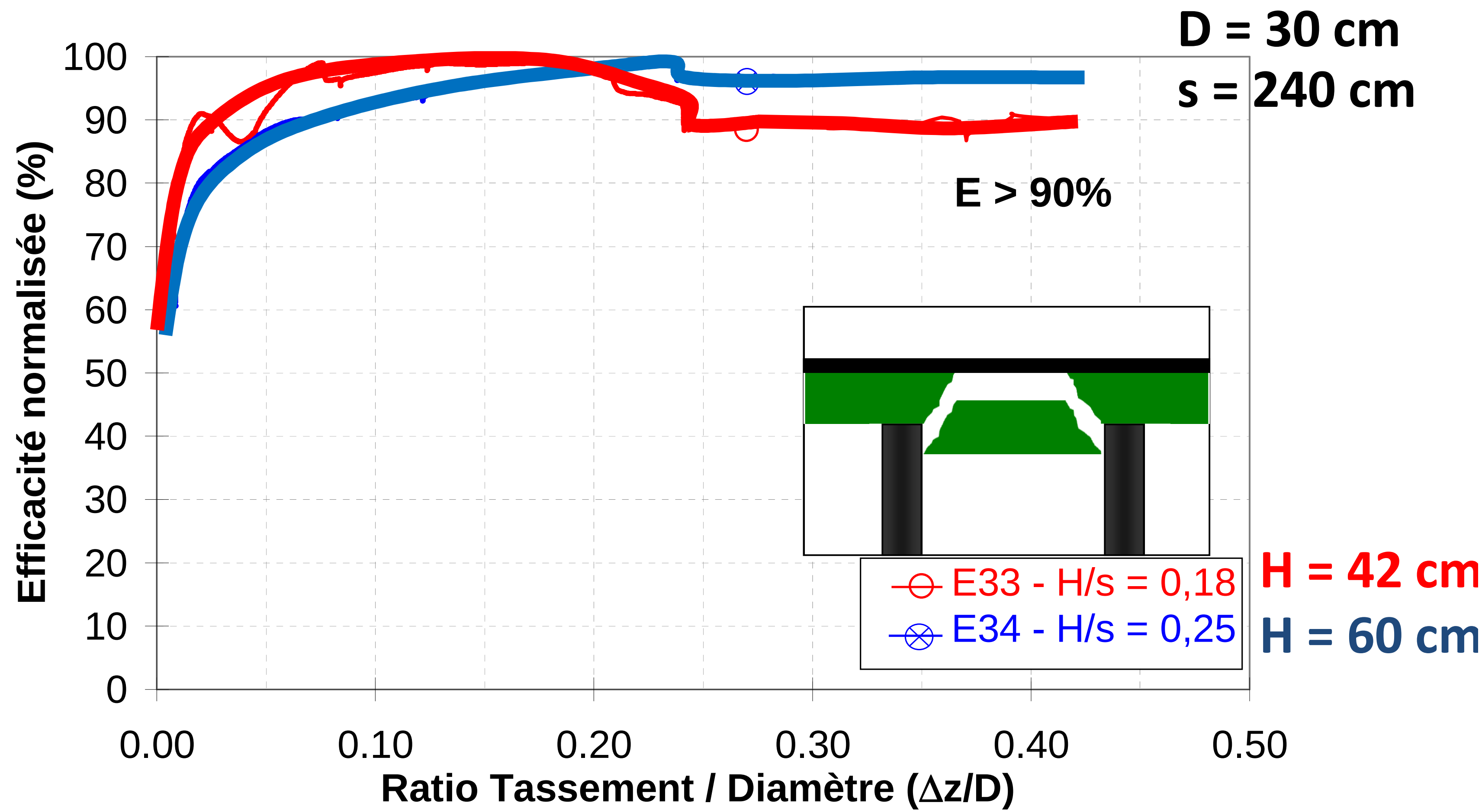
H = 60 cm

H = 42 cm

- La valeur d'efficacité ne descend pas en dessous de 85% pour les 2 hauteurs de matelas testées.
- La baisse d'efficacité s'effectue plus tôt avec une hauteur de matelas faible qu'avec une hauteur de matelas plus importante.

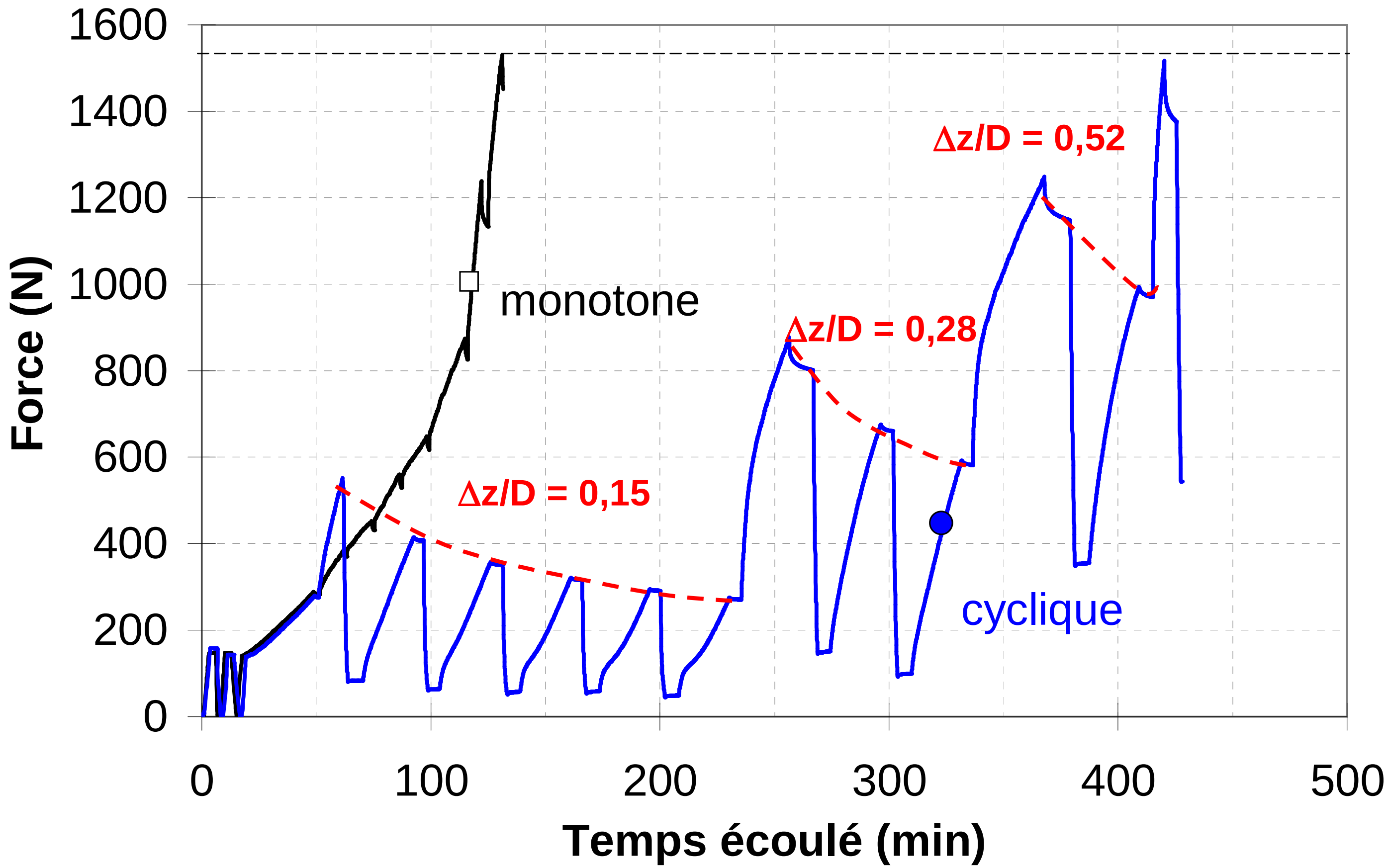
Efficacité avec un matelas traité au ciment(α = 1,23%)

12 x g

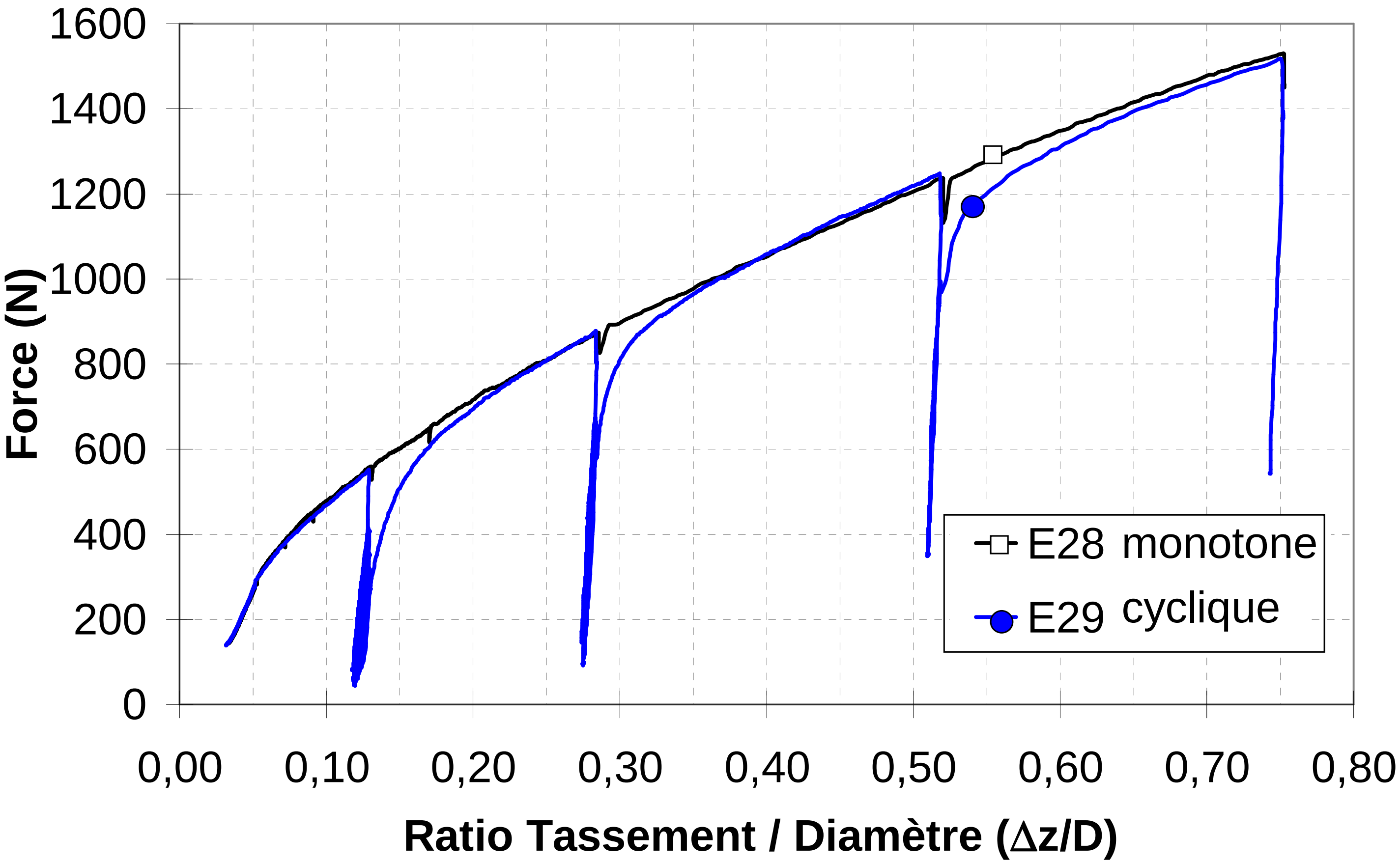


- Pour les deux hauteurs de matelas testées, l'efficacité maximale de 100% est atteinte au cours des essais.
- L'efficacité maximale est atteinte rapidement pour une hauteur de matelas faible.
- La moyenne des contraintes en tête des inclusions rigides est d'environ 6 MPa.

Cycles de chargement / déchargement



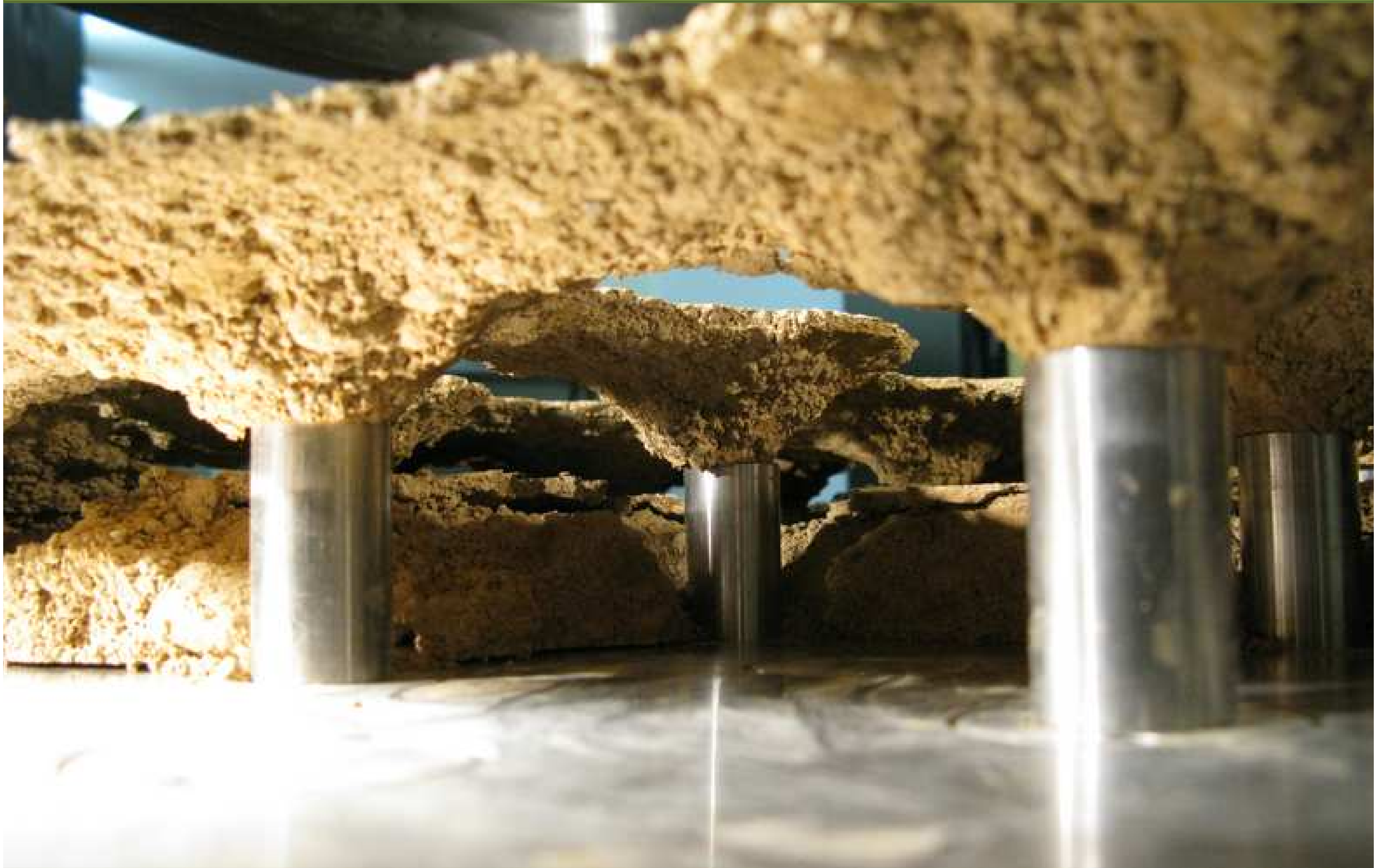
Cycles de chargement / déchargement



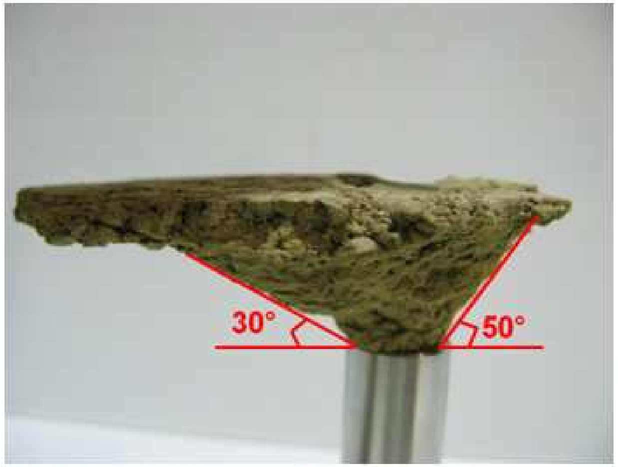
- D’un point de vue global, la courbe de chargement cyclique présente la même allure que celle du chargement monotone.
- A la fin de chaque série, les valeurs d’effort issues d’un chargement cyclique finissent par atteindre les valeurs d’effort de l’essai monotone.

Rupture dans le matelas

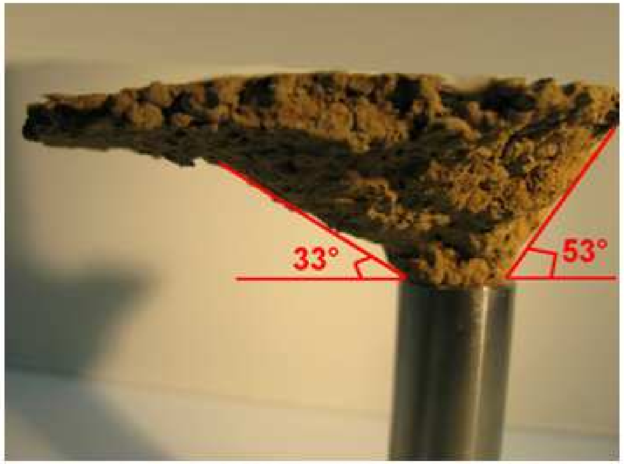
Effet de voûte



Chapiteaux en tête des inclusions rigides

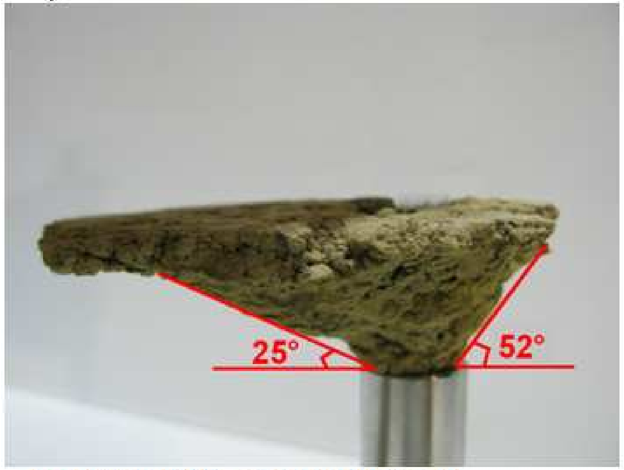


a) Essai E18 – Echantillon A



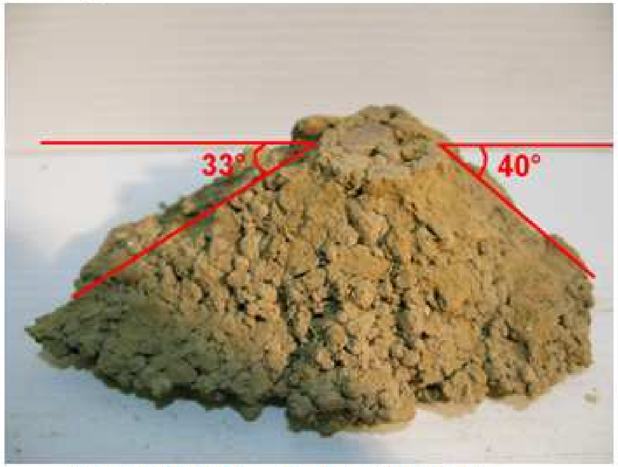
c) Essai E19 – Echantillon A

e) Essai E21 – Echantillon A



b) Essai E18 – Echantillon B

d) Essai E19 – Echantillon B



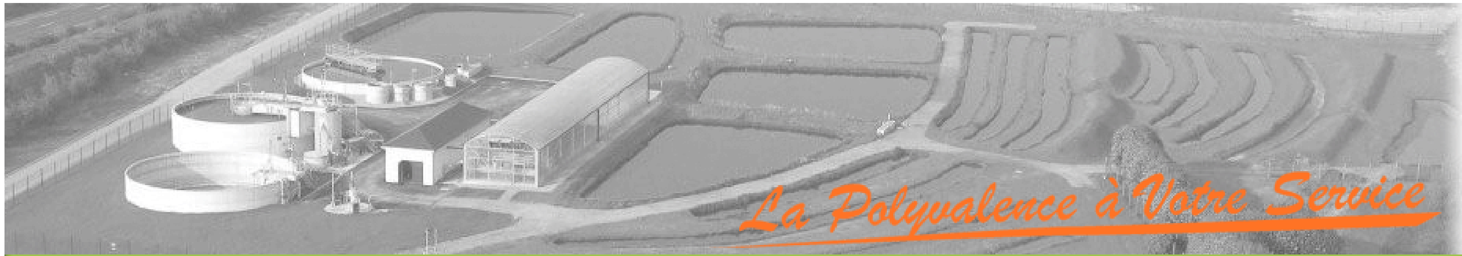
f) Essai E21 – Echantillon B

Surfaces de rupture sur les chapiteaux en tête des inclusions rigides

Décollement entre les couches de compactage

Conclusions

- **Chaux : comportement mécanique souple et radoucissant**
  - **L'efficacité augmente progressivement**
  - **Les contraintes sont réparties entre les inclusions rigides et le sol compressible par flexion du matelas**
- **Ciment : comportement mécanique fragile et cassant**
  - **L'efficacité augmente rapidement**
  - **Comme une dalle sur les têtes des inclusions rigides**
- **E > 85% après la rupture**
- **Le matelas de faible hauteur se fissure et se détruit plus facilement qu'un matelas épais.**
- **Malaxage et compactage**



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Merci pour votre attention.

Paris, le 08/04/2013

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