International school on

RECENT TRENDS IN THE ECOCONSTRUCTION OF BUILDINGS

Université de Pau et des Pays de l'Adour, Anglet/Biarritz, France

Thursday 28 Sept (afternoon) – Friday 29 Sept (all day) 2017

TERRE

Hypercompacted raw earth for load bearing and air conditioning

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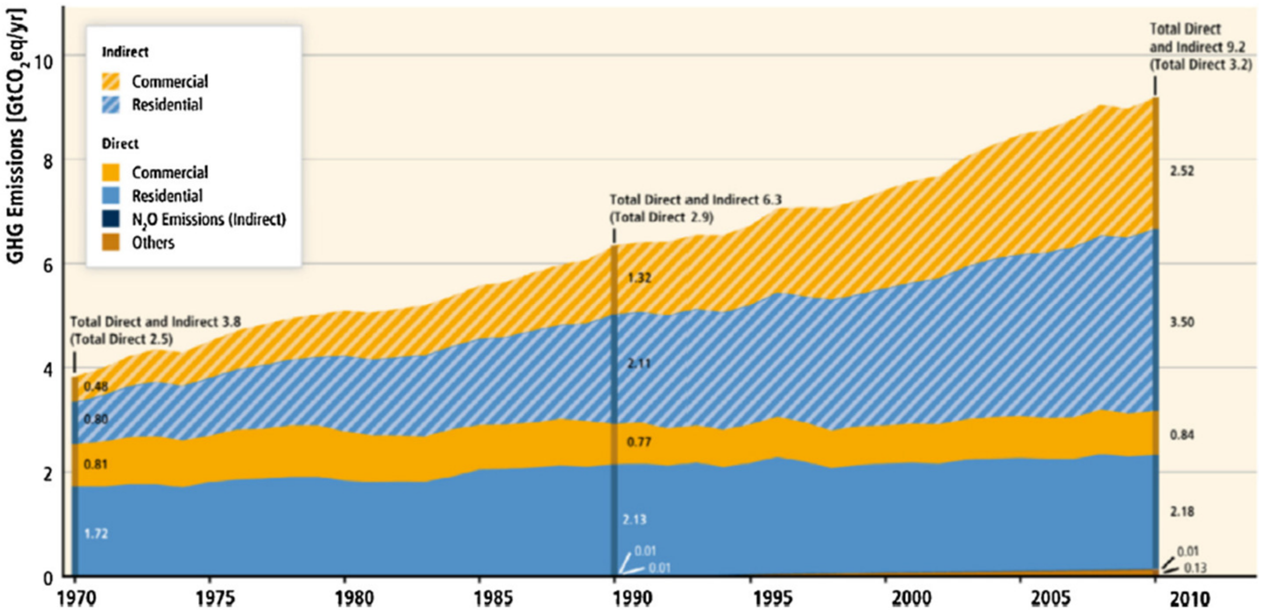
Outline

- Background on raw earth construction
- Hygro-mechanical behaviour of hypercompacted earth
- Durability against water erosion
- Recommendations for future work

Background

Building sector: energy consumption and GHG emissions

- "The global contribution from buildings (residential and commercial) towards energy consumption has steadily increased reaching figures between 20% and 40% in developed countries, and has exceeded the other major sectors: industrial and transportation" *(Pérez-Lombard et al., 2007)*

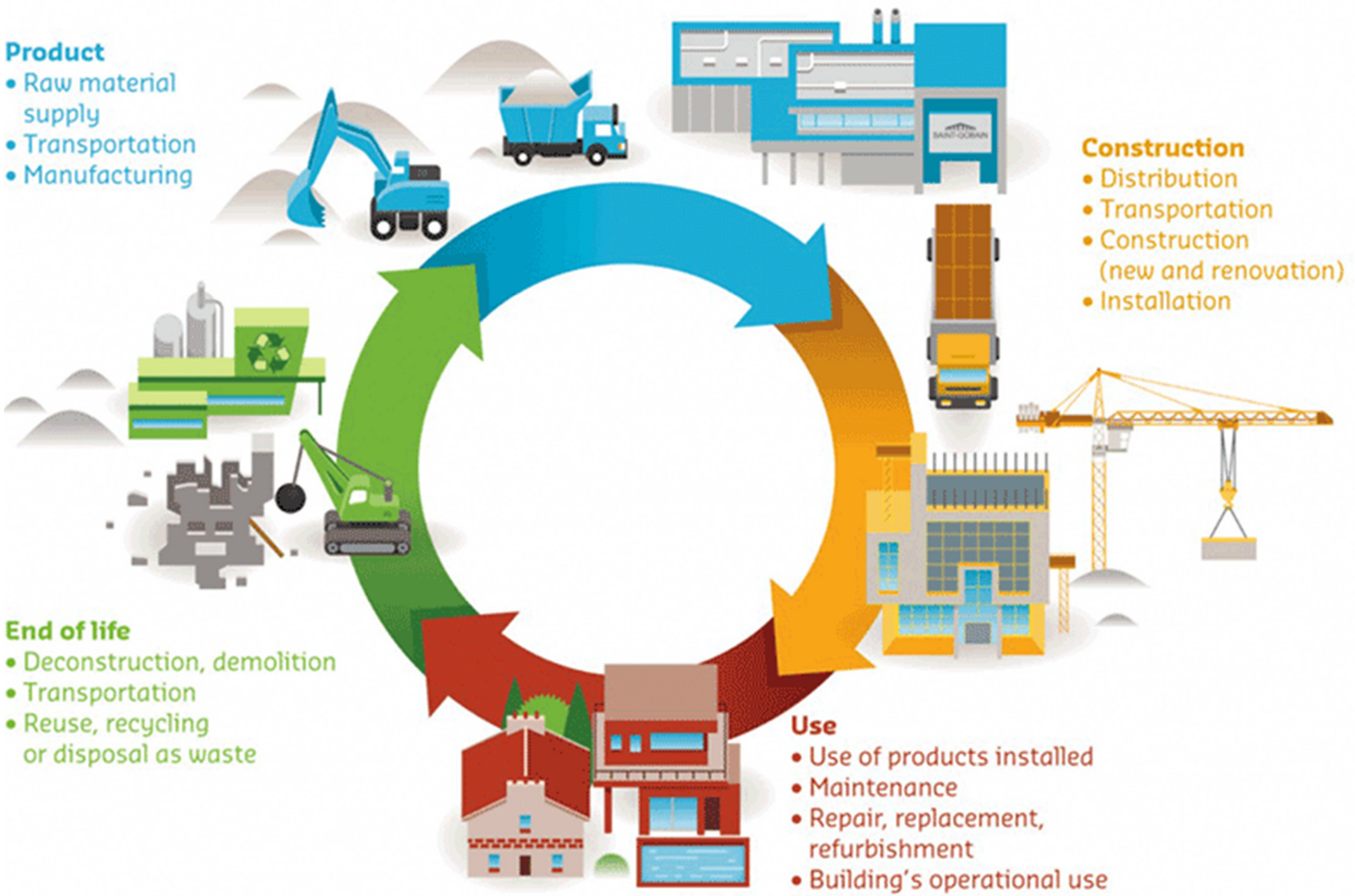


(IPCC, 2015)

- Buildings are responsible for 40% of energy consumption and 36% of CO_2 emissions in EU (2017). Source: http://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

Background

The life cycle of a building material



Background

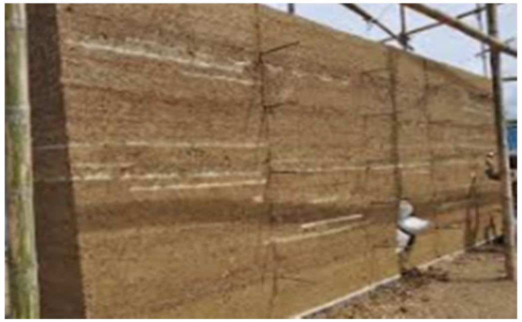
Raw earth as a building material

- The expression **raw earth** describes a construction material consisting of a mix of soil and water subjected to the least possible transformation before being put in place.
- Various construction techniques

Adobe

Cob

Compressed earth bricks



Rammed earth

Background

Raw earth construction

- Ancient building material - (Jéricho, Syria - 8000 BC)

Alhambra, Granada
(Spain, 10th century)

Great Wall, Jiayuguan, Gansu,
(China, 14th century)

Haus Rauth , Weilburg an der Lahn
(Germany, 1828)

- After the Second World War, raw earth construction was almost completely abandoned

- Since the 1970s, studies have quantified the environmental costs of construction

- More details about history of raw earth construction in *Jaquin (2008), Jaquin and Augarde (2012)* and website: <u>*www.historicrammed.co.uk*</u>

Background

Raw earth construction: advantages

- Local material– reduction of environmental impacts *(Morel et al., 2001)*

- Comparison: stone masonry VS concrete
- Materials: stones, timber and soil mortar
- The impact of construction assessed by:
  1. Energy to manufacture walls and floors
  2. Amount of transported material to the worksite

	Stone masonry	Concrete
Energy (GJ)	97	239
Transport (tkm)	1390	6707

Background

Raw earth construction: advantages

- Manufacturing process - low consumption of energy *(Minke, 2000; Little and Morton, 2001)*

  - Commonly used construction materials (e.g. fired earth bricks, cement, gypsum) require:
    1. Mining in a restricted number of geographical locations
    2. Significant levels of transportation
    3. High firing temperature

  - To prepare, transport and construct earth materials requires about 1% of the energy required by cement based alternatives

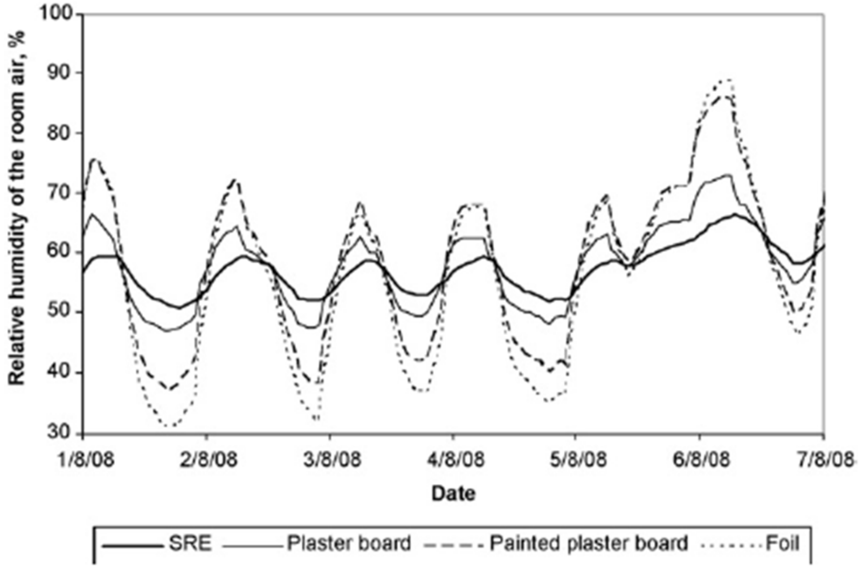
  - Earth bricks necessitate about a third of the energy required to produce fired earth bricks, i.e. 440 kWh/m^3 compared to 1300 kWh/m^3

Background

Raw earth construction: advantages

• Hygro-thermal regulator effect *(Allinson and Hall, 2010; Pacheco–Torgal and Jalali, 2012; McGregor et al., 2016; Soudani et al., 2016; Gallipoli et al., 2017; Soudani et al., 2017)*

- <u>Hygroscopic regulator effect.</u> The open network of nanopores in earth materials facilitates absorption/release of moisture depending on the current ambient humidity



(Allinson and Hall, 2010)

- <u>Thermal regulator effect.</u> Evaporation (endothermic process) takes latent heat from the atmosphere during hot times. Condensation (exothermic process) releases latent heat during cool times.

Background

Raw earth construction: advantages

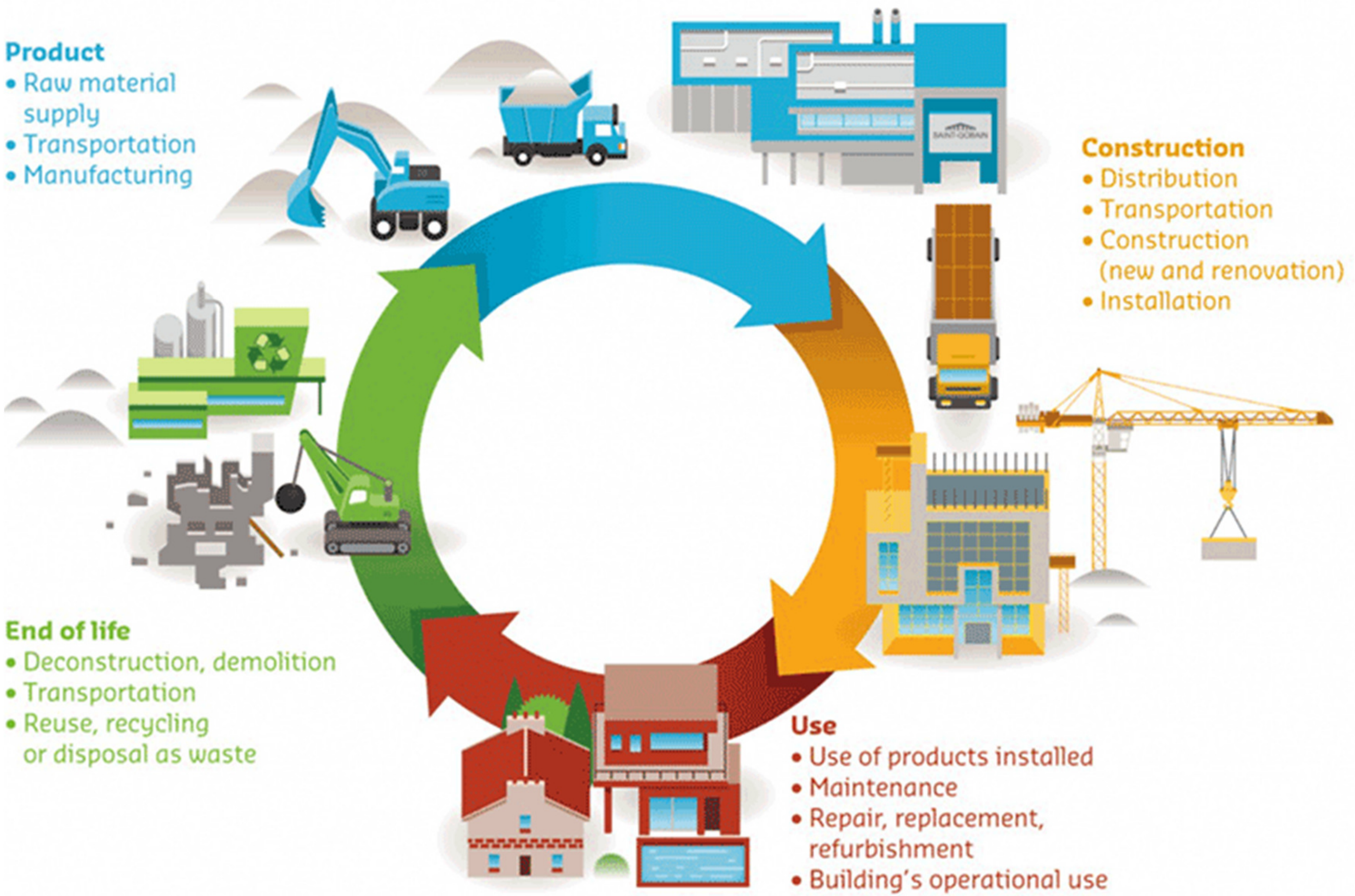
- Recycling, disposal and demolition waste

- "At the end of a building life, earth materials can easily be re-cycled or returned to the ground" *(Little and Morton, 2001)*

- "Earth materials exhibit some environmental advantages at the end-of-life due to its ease of re-use" *(Arrigoni et al., 2017a)*

Background

The life cycle of a building material



Background

Raw earth construction: limitations

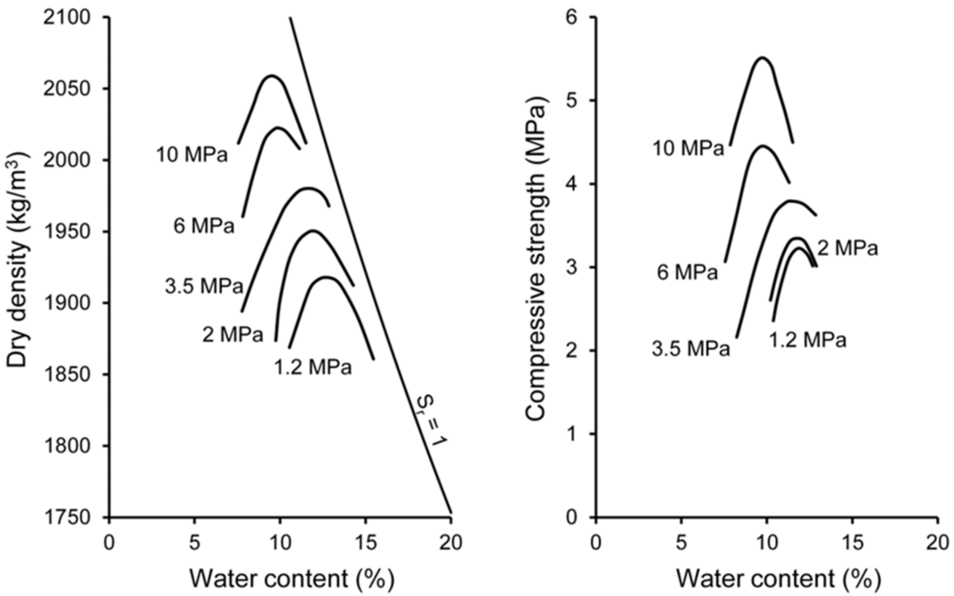
- Low strength and stiffness
- Mostly qualitative assessment of hygro -thermal performance
- Weak durability against water erosion

Background

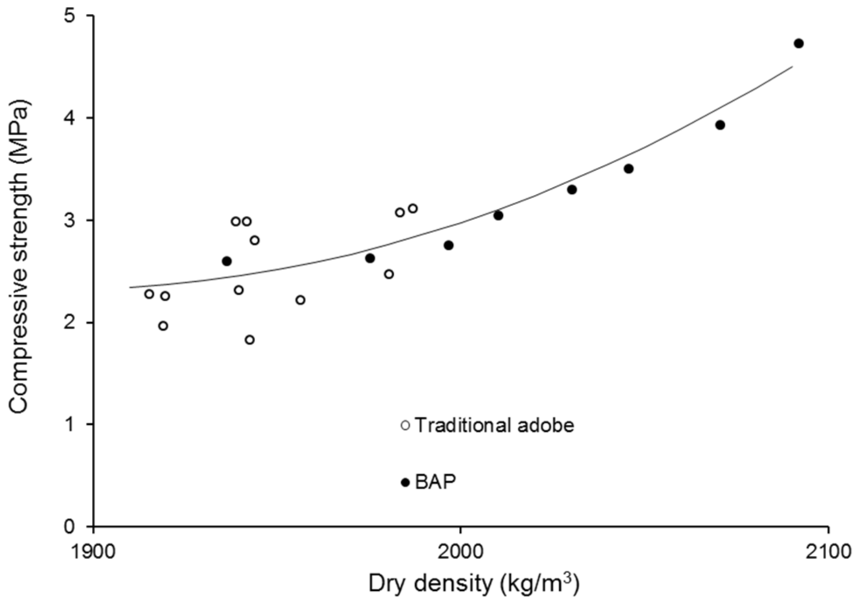
Raw earth construction: limitations

Low strength and stiffness → Increase of compaction pressure

(Olivier and Mesbah, 1986; Venkatarama Reddy and Jagadish, 1993; Attom, 1997; Mesbah et al., 1999; Kouakou and Morel, 2009)



(after Olivier and Mesbah, 1986)



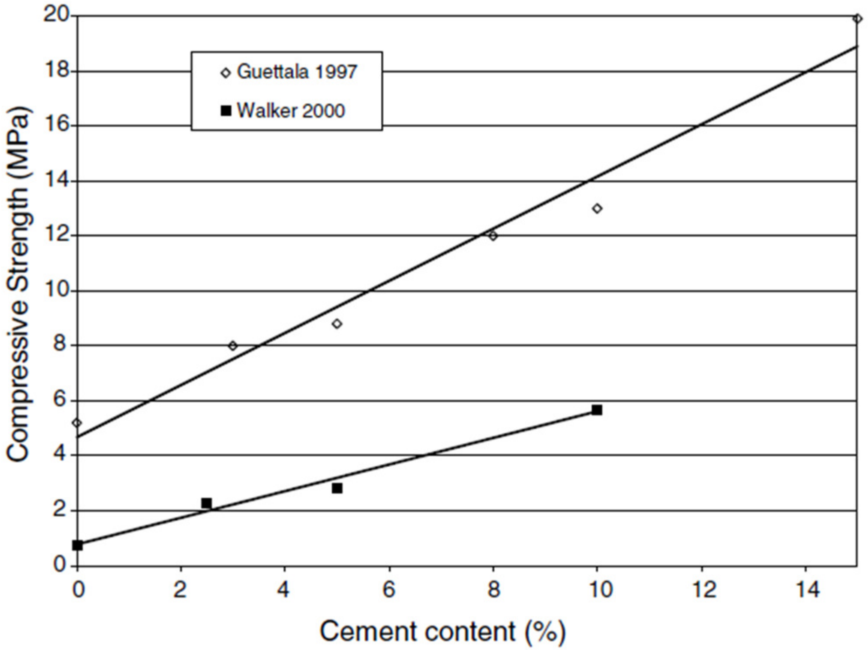
(after Kouakou and Morel, 2009)

Background

Raw earth construction: limitations

Low strength and stiffness	⟶	Cement or lime stabilisation

(Walker, 1995; Jayasinghe and Kamaladasa, 2007; Morel et al., 2007; Ciancio and Gibbings, 2012; Ciancio et al., 2014; Kariyawasam and Jayasinghe, 2016; Arrigoni et al., 2017b)



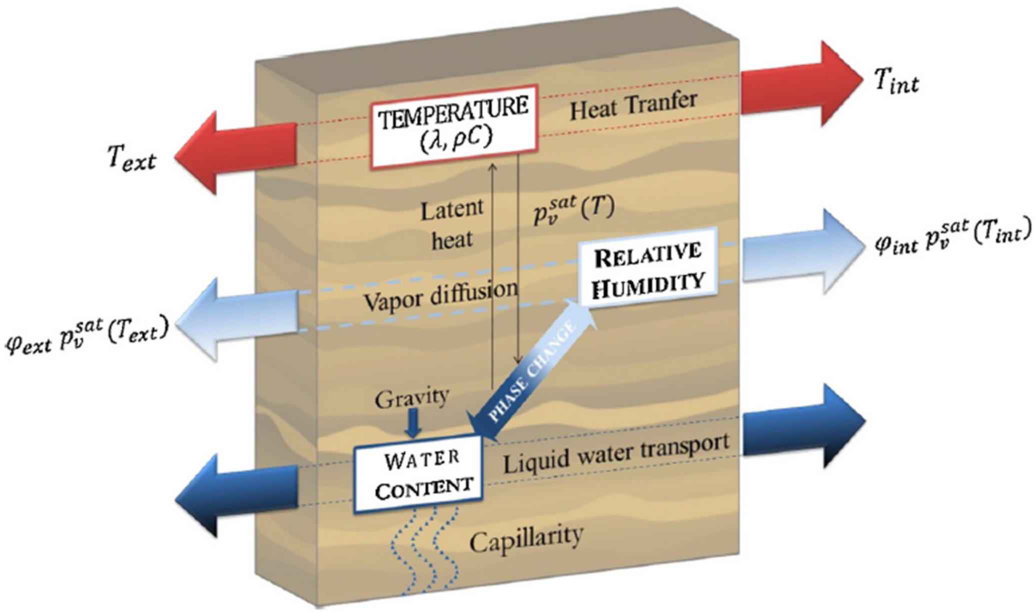
<u>Disadvantages</u>

Cement or lime stabilisation 1) increases the carbon footprint and costs 2) complicates the recycling of demolition waste

Background

Raw earth construction: limitations

Mostly qualitative assessment of hygro – thermal performance



Coupled mechanisms

Water phase changes – heat flux

Numerical and constitutive modelling *(Soudani et al., 2016)* – Laboratory and in-situ measurements *(Allinson and Hall, 2010; Soudani et al., 2017)*

Hygro-mechanical behaviour of hypercompacted earth

Materials and methods

Soil characterisation

Hypercompaction procedure

- Small scale cylindrical samples
- Large scale compressed earth bricks

Mechanical behaviour

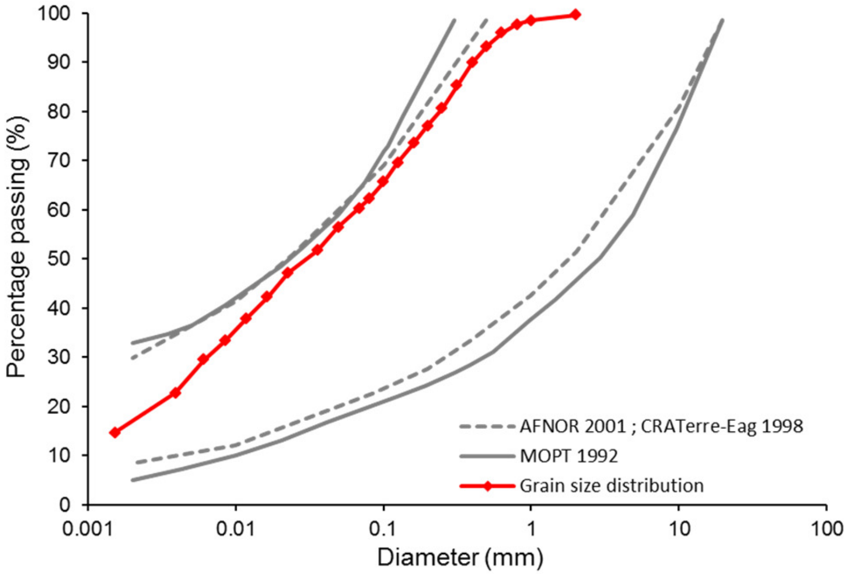
Hygroscopic behaviour

Materials and methods

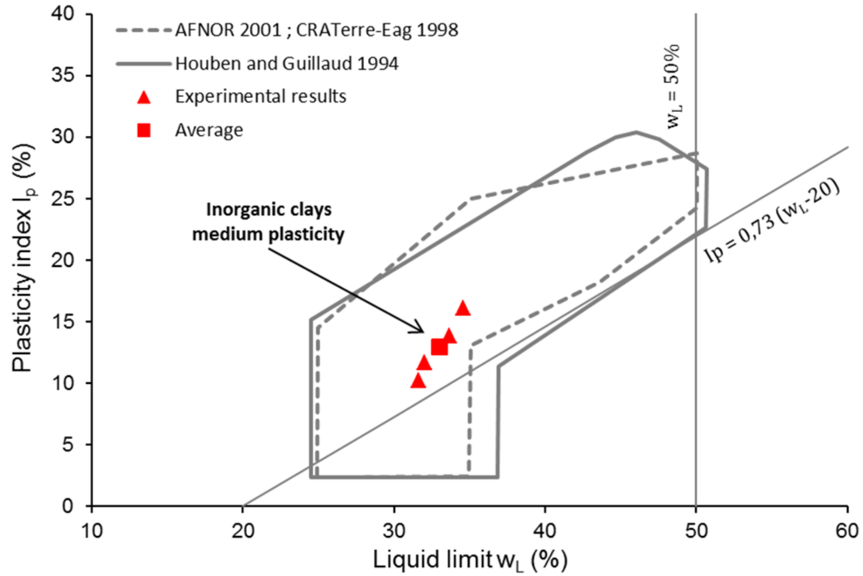
Soil characterisation

- The material used in this work is a sandy silt with illitic clay
- The fine fraction is classified as inorganic clay of medium plasticity

Grain size distribution		
Gravel	> 2 mm	0.4 %
Sand	0.063 – 2 mm	40.4 %
Silt	0.002 – 0.063 mm	42.9 %
Clay	< 0.002 mm	16.3 %
Plasticity properties		
Liquid limit, w_L (%)		33.0 %
Plastic limit, w_P (%)		20.1 %
Plasticity index, I_p (%)		12.9 %
Activity A (-)		0.79
Specific gravity of soil grains		
G_s (-)		2.66



Grain size distribution (wet sieving + sedimentation)

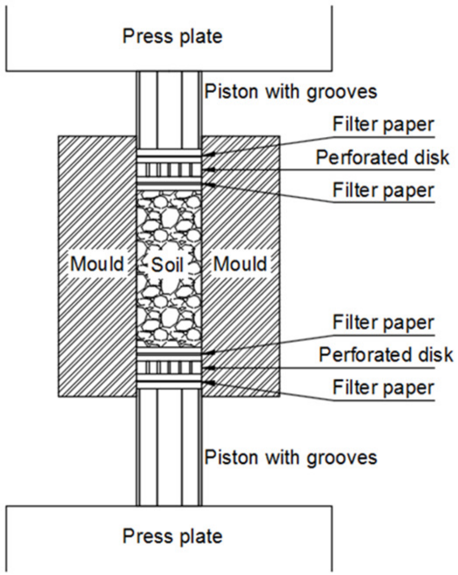


Plasticity chart and recommended region for compressed earth

Materials and methods

Hypercompaction procedure: small scale cylindrical samples

- High pressure – three levels of compaction stress: 25, 50 and 100 MPa
- Double compaction with floating mould
- Drainage paths – dissipation of pore water overpressure (soil consolidation)



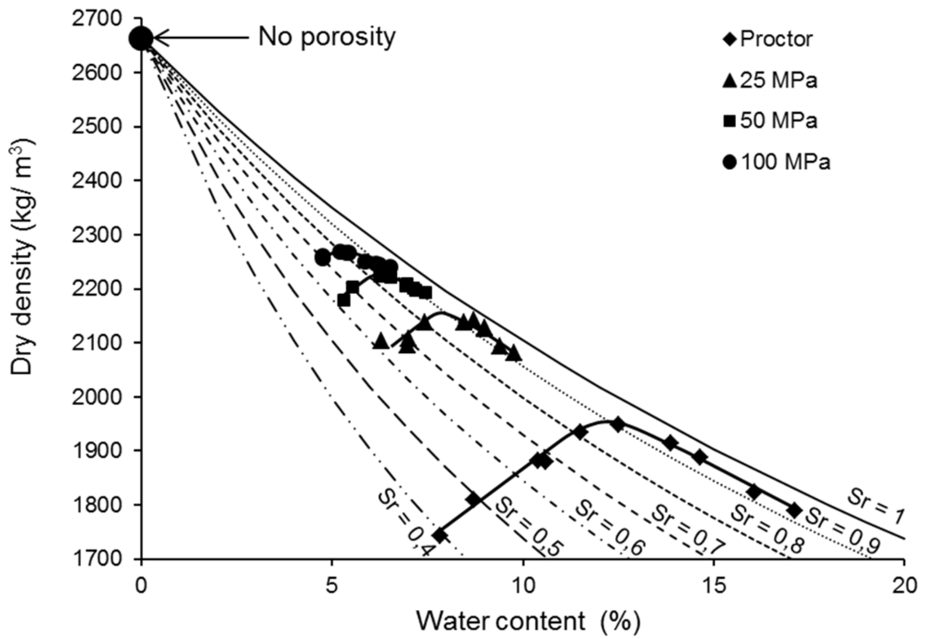
Schematic of the compaction mould

Photograph of compaction mould

Materials and methods

Hypercompaction procedure: small scale cylindrical samples

- For each pressure level, samples compacted at different water contents
- The increase of dry density is less than linear with increasing pressure level
- Water drainage observed only for wetter samples

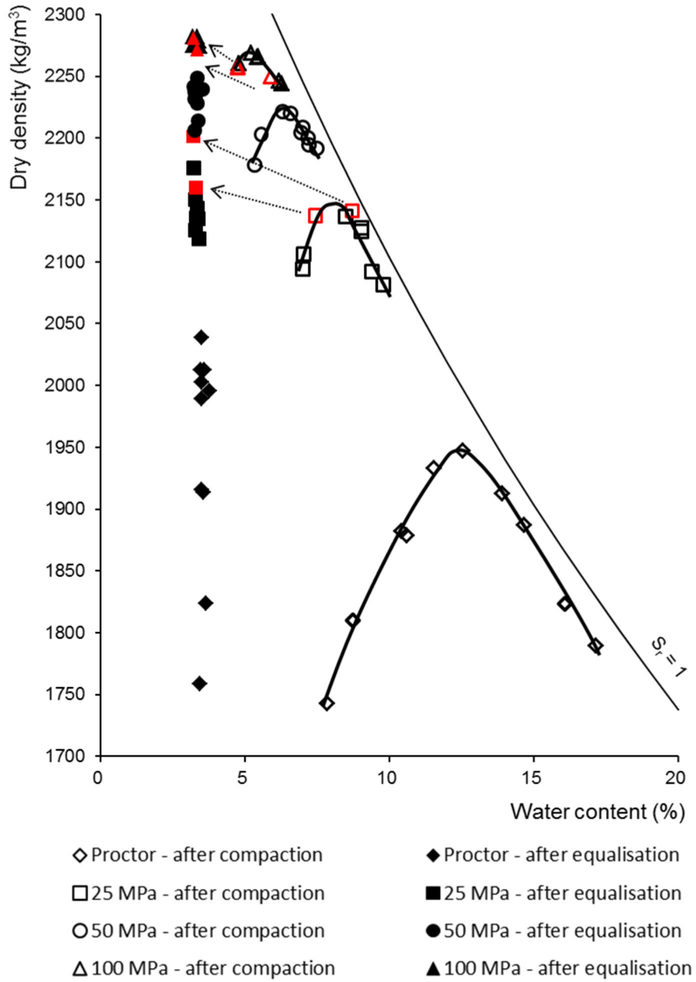


Compaction curves at 25, 50 and 100 MPa together with standard Proctor

Materials and methods

Hypercompaction procedure: small scale cylindrical samples

- Equalisation at T = 25 °C and RH = 62%
- All samples exhibited desaturation and shrinkage
- Water content reduced to 3.5% for all samples
- Dry density increased mainly for wetter samples
- Greater uniformity of samples compacted at 100 MPa

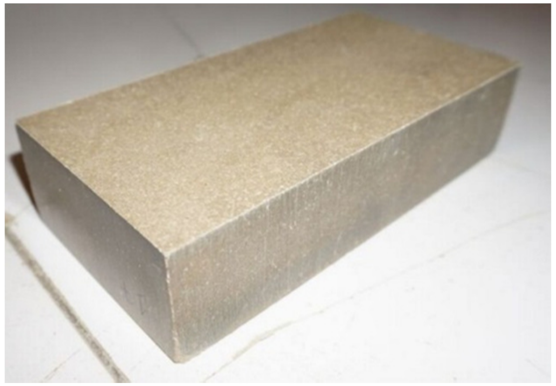


Compaction curves after equalisation

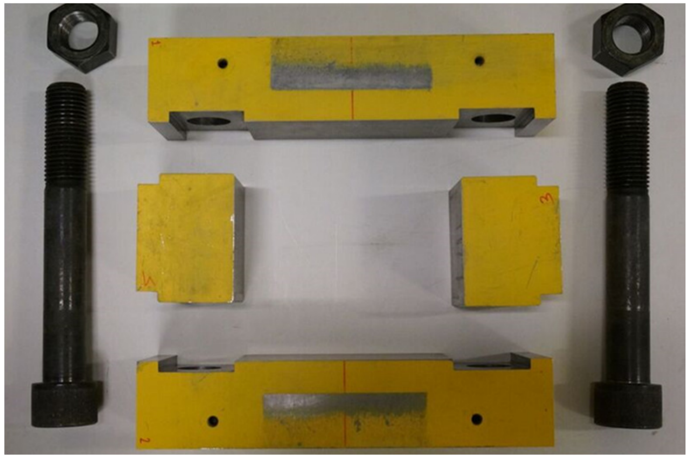
Materials and methods

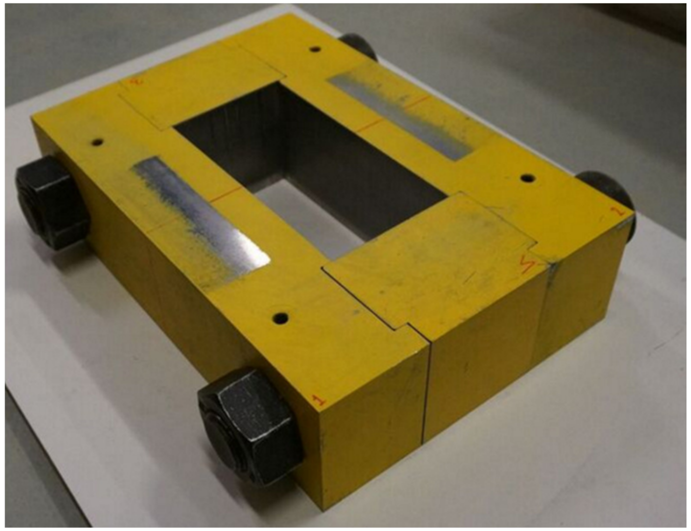
Hypercompaction procedure: large scale compressed earth bricks

- Compressed earth bricks (200 x 100 x 50 mm^3)
- Compacted at 100 MPa and optimum water content of 5.2%
- Compaction mould composed by four separated pieces assembled together by two bolts M42



Compressed earth brick (200 x 100 x 50 mm^3)

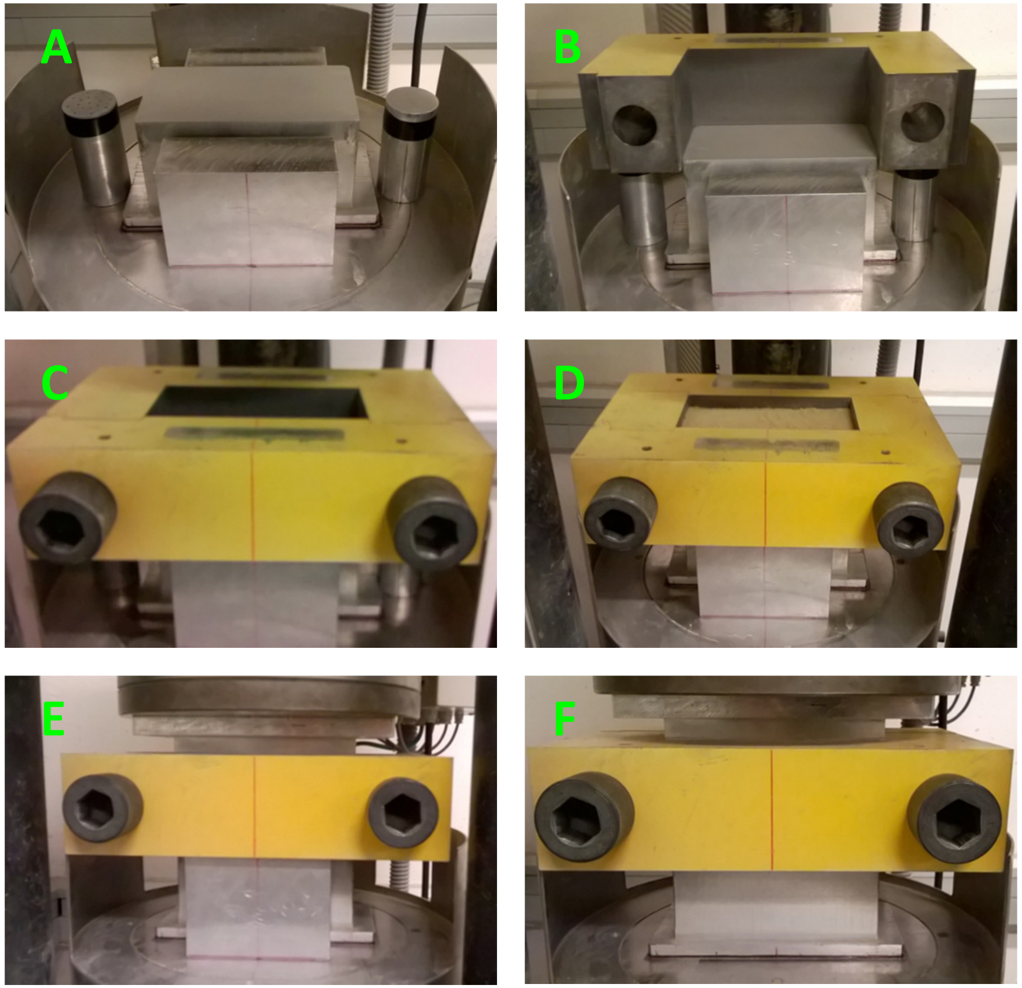




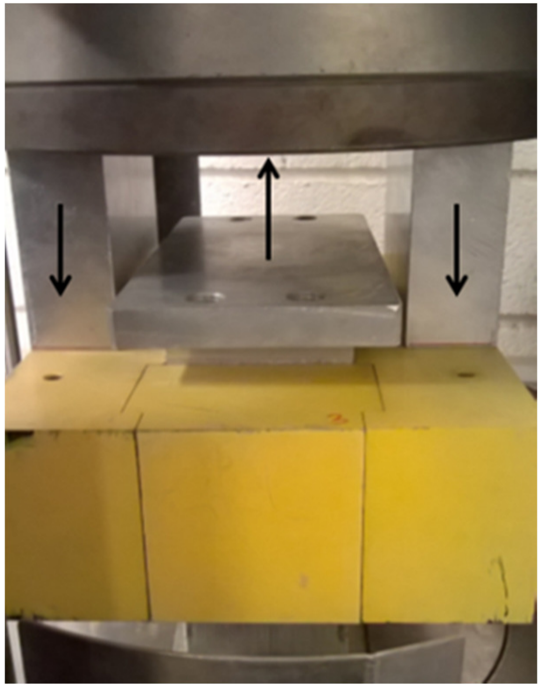
Photographs of compaction mould

Materials and methods

Hypercompaction procedure: large scale compressed earth bricks



Double hypercompaction inside floating mould



Brick demoulding

Materials and methods

Hypercompaction procedure: large scale compressed earth bricks

- Equalisation at T = 25 °C

	w (%)	ρ_b (kg/m^3)	ρ_d (kg/m^3)	n (-)	S_r (%)
Minimum	2.3	2378	2310	0.122	44.4
Maximum	3.2	2399	2339	0.133	58.9
Average	2.8	2390	2325	0.127	51.4
SD	0.2	5.5	6.1	>0.1	3.9
CV (%)	7.1	0.2	0.3	>0.1	7.6

Statistical properties of forty bricks equalised at T=25° C

Hygro-mechanical behaviour of hypercompacted earth

Materials and methods
- Soil characterisation
- Hypercompaction procedure
  - Small scale cylindrical samples
  - Large scale compressed earth bricks

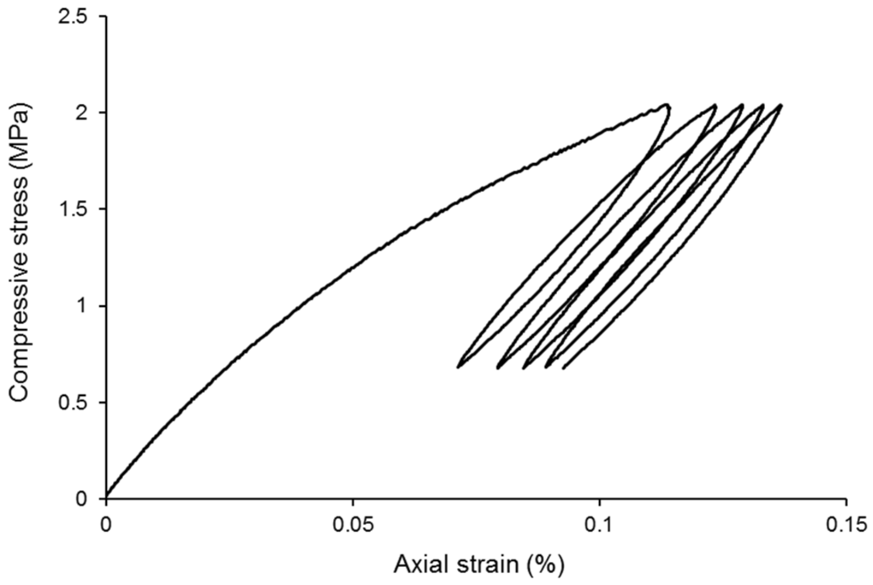
Mechanical behaviour
- Effect of material density
- Effect of relative humidity
- Compressive strength of hypercompacted bricks

Hygroscopic behaviour

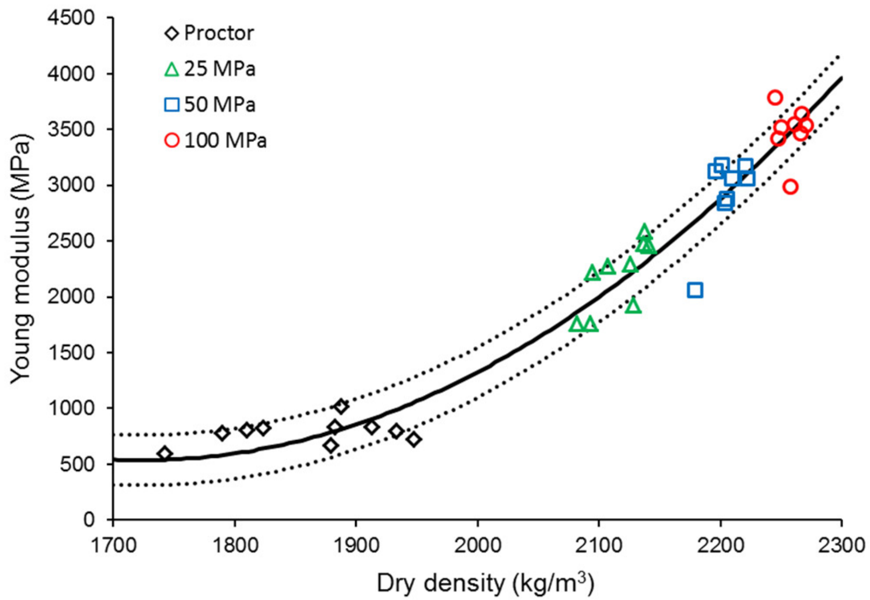
Mechanical behaviour

Effect of material density: Young modulus

- Five loading-unloading cycles to measure the Young modulus
- Hysteretic behaviour during loading-unloading cycles
- Young modulus taken as average slope of fitting lines of unloading branches
- Young modulus increased more than linearly with increasing dry density



Typical stress-strain relationship under loading-unloading cycles

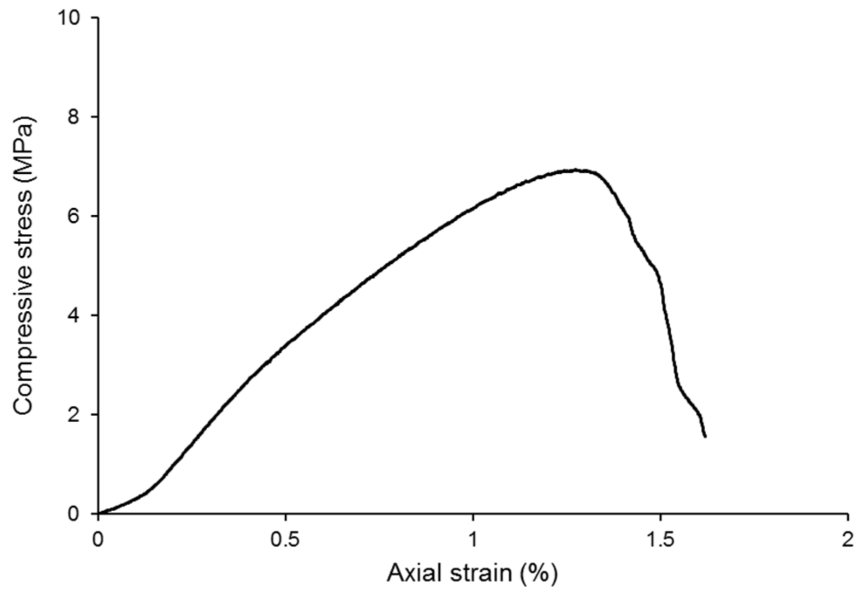


Variation of Young modulus with dry density

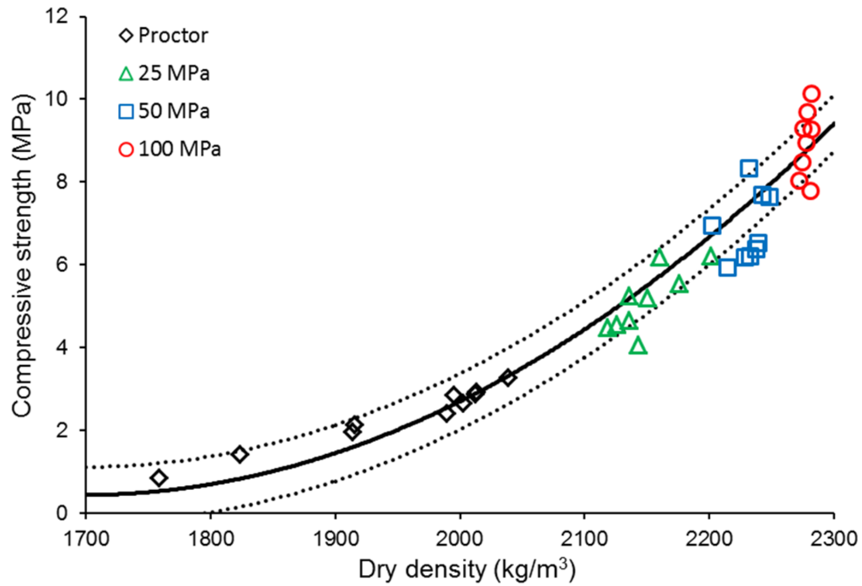
Mechanical behaviour

Effect of material density: compressive strength

- Peak of compressive strength and brittle failure
- Compressive strength grew more than linearly with increasing dry density
- Further marginal increase of dry density would significantly improve mechanical performance



Typical stress-strain relationship under compressive strength test



Variation of compressive strength with dry density

Mechanical behaviour

Effect of relative humidity

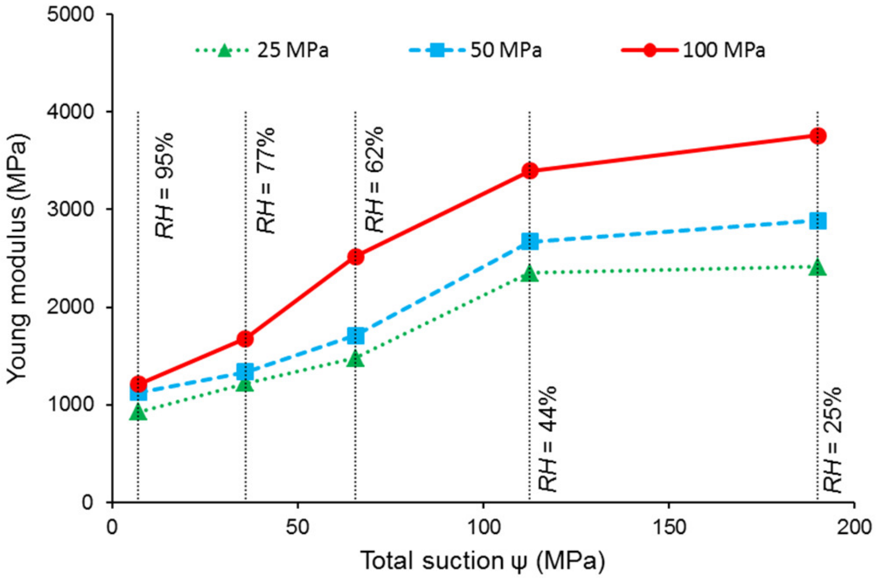
- Cylindrical samples compacted at 25, 50 and 100 MPa and optimum water content
- Equalisation at T = 25°C and RH= 95%, 77%, 62%, 44% and 25%
- Five loading-unloading cycles to measure the Young modulus
- Load increased until sample failure to measure compressive strength
- Temperature T and relative humidity RH converted into total suction ψ by Kelvin equation

$$\psi = -\frac{R\,T}{V_m}\ln(RH)$$

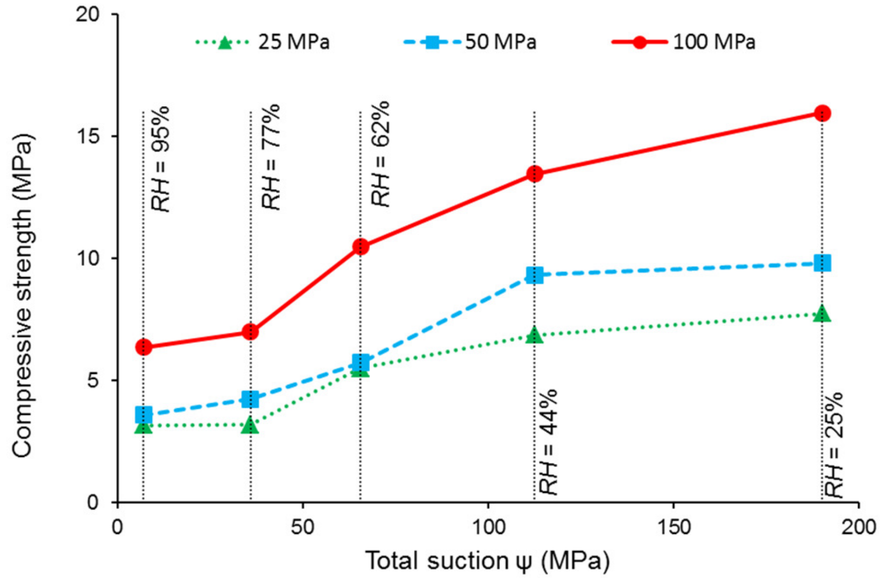
Mechanical behaviour

Effect of relative humidity

- Stiffness and strength grew as suction increased from 7 to 112 MPa but stabilised afterwards
- Result is consistent with *Fischer (1926)*, i.e. stabilising effect of water menisci grows with increasing total suction towards constant asymptote



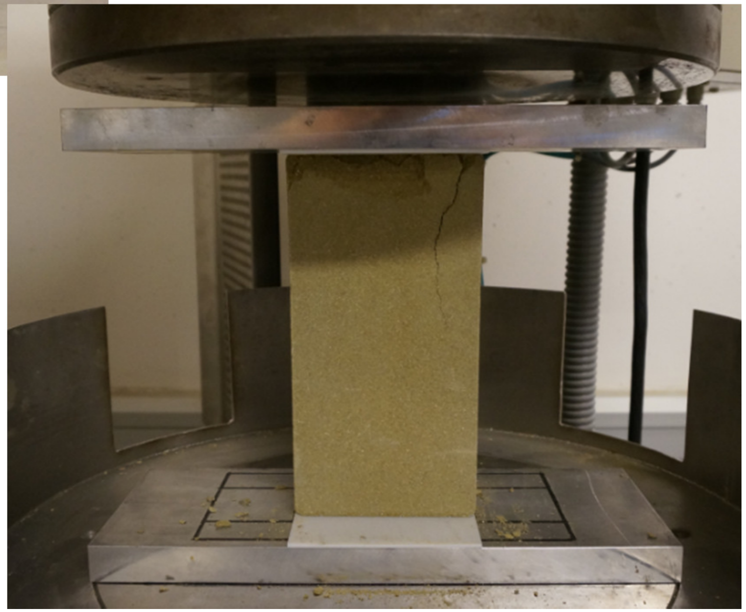
Variation of Young modulus with total suction: unstabilised samples



Variation of compressive strength with total suction: unstabilised samples

Mechanical behaviour

Compressive strength of hypercompacted bricks

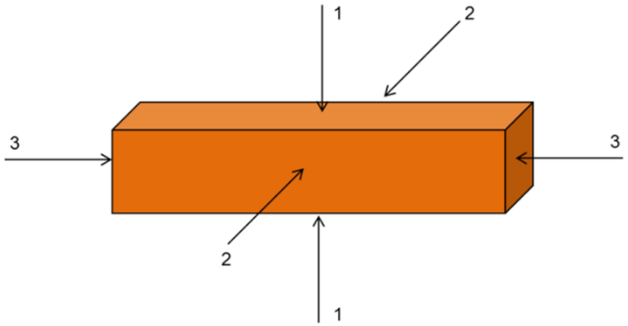


- Effect of aspect ratio
- Effect of end-friction confinement

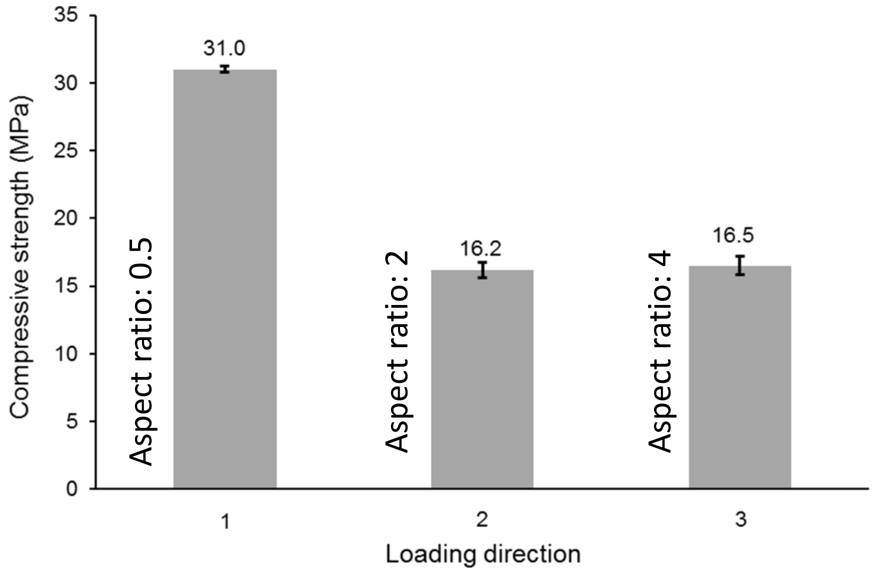
Compressive strength of hypercompacted bricks

Effect of aspect ratio

- Bricks loaded along three perpendicular directions
- The highest compressive strength measured when load is applied on largest surface *(Aubert et al., 2016)*
- Lower and more reliable values of compressive strength obtained along the other two directions



Loading directions



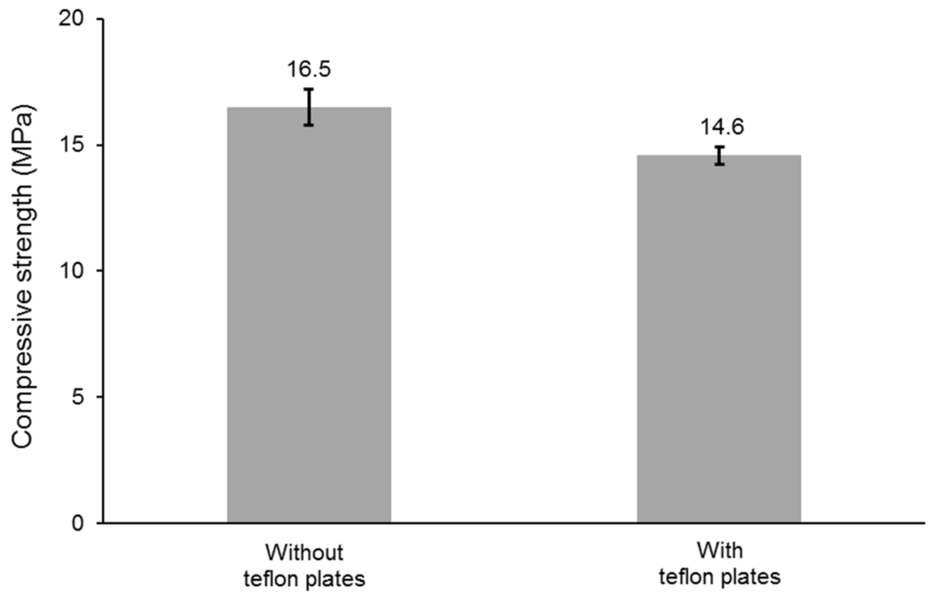
Variation of compressive strength with loading direction

Mechanical behaviour

Compressive strength of hypercompacted bricks

Effect of end-friction confinement

- Bricks loaded on smallest surface with and without Teflon capping
- Teflon capping reduced average compressive strength of 12%
- Most representative value of material strength given by test with Teflon capping



Compressive strength of bricks with or without Teflon capping

Material	Compressive strength (MPa)
Compressed earth bricks (present work)	14.6
Compacted stabilised soil (Guetlala 1997)	From 5.2 to 12.9
Standard masonry bricks (ASTM C270, 2014)	From 6.9 to 27.6

Compressive strengths of raw and fired earth bricks

Hygro-mechanical behaviour of hypercompacted earth

Materials and methods

- Soil characterisation
- Hypercompaction procedure
  - Small scale cylindrical samples
  - Large scale compressed earth bricks

Mechanical behaviour

- Effect of material density
- Effect of relative humidity
- Compressive strength of hypercompacted bricks

Hygroscopic behaviour

- Moisture buffering capacity

Hygroscopic behaviour

Testing procedure

- Tests on samples compacted at 25, 50 and 100 MPa and optimum water content
- Relative humidity cycles of 75% (12h)/ 53% (12h) at 25 °C with regular sample mass measurements *(ISO 24353, 2008)*
- Cycles end when moisture uptake at RH=75% is equal to moisture release RH=53% during last three cycles
- Determination of the **Moisture Buffering Value MBV**

"The MBV indicates the amount of water that is transported in or out of a material per open surface area, during a certain period of time, when it is subjected to variations in relative humidity of the surrounding air". (Rode et al., 2005)

$$\mathbf{MBV} = \frac{\Delta \boldsymbol{m}}{\boldsymbol{S}\ \Delta\%\boldsymbol{RH}}$$

Climatic chamber

Hygroscopic behaviour

Moisture buffering capacity

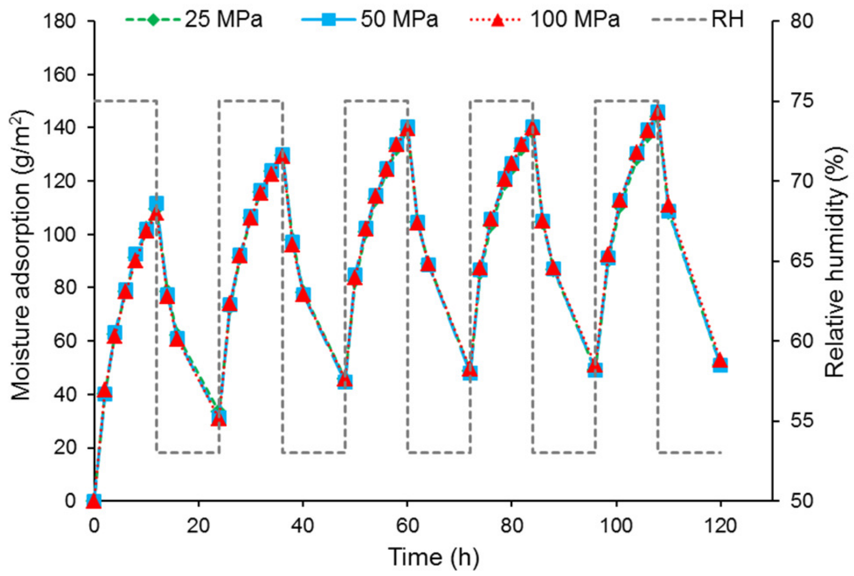
- All samples showed same hygroscopic behaviour regardless of compaction pressure

$$(T = 25°C \,; HR = 53\%) \rightarrow \psi = -\frac{\rho_w RT}{M_w} ln(HR) = 87\ MPa$$

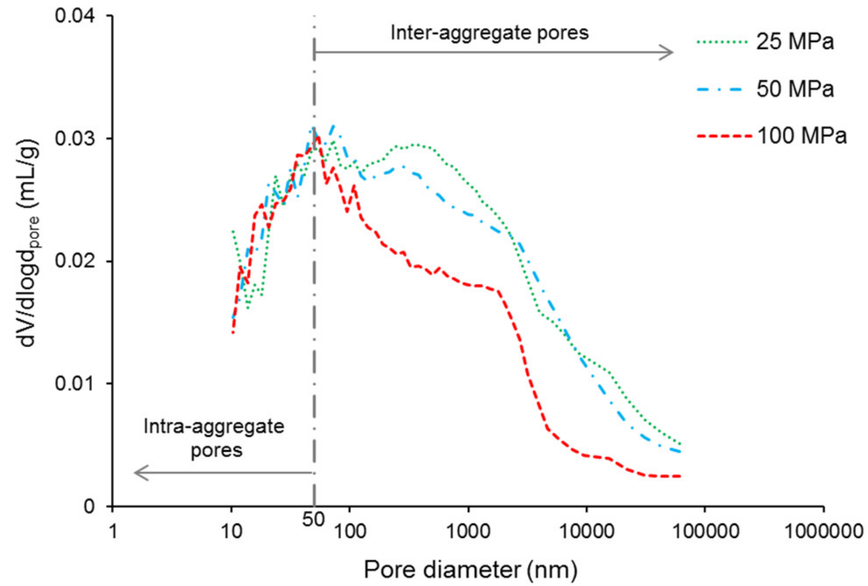
$$(T = 25°C \,; HR = 75\%) \rightarrow \psi = -\frac{\rho_w RT}{M_w} ln(HR) = 39\ MPa$$

$$\psi = 87\ \text{MPa} \rightarrow d = \frac{4\,\psi}{\gamma} = 3\ nm$$

$$\psi = 39\ \text{MPa} \rightarrow d = \frac{4\,\psi}{\gamma} = 7\ nm$$



Moisture adsorption of unstabilised samples compacted at 25, 50 and 100 MPa



Pore size distribution of cylindrical samples compacted at 25, 50 and 100 MPa

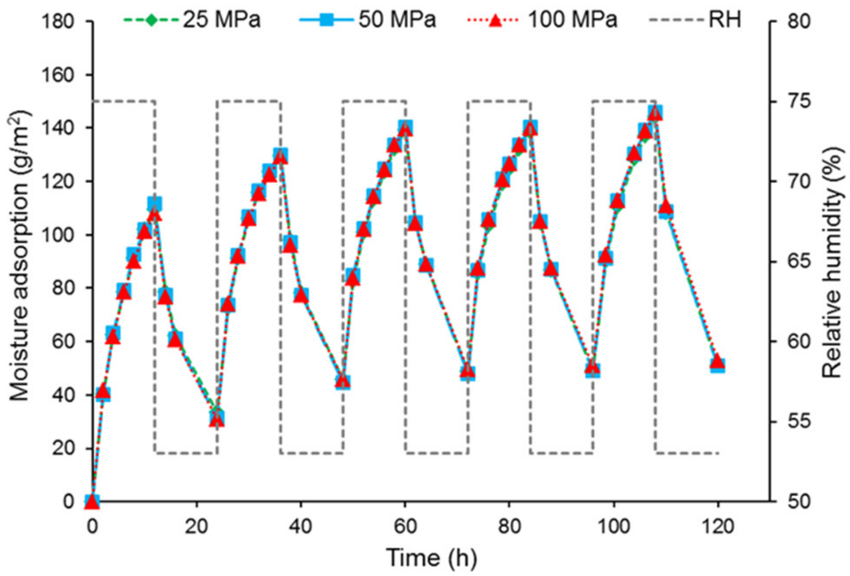
Hygroscopic behaviour

Moisture buffering capacity

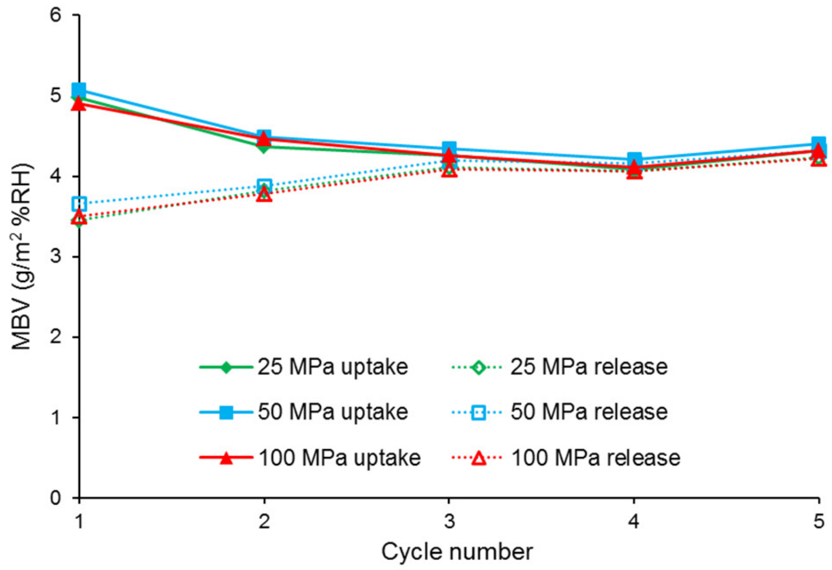
- Hysteresis during the first two cycles but reversible behaviour afterwards
- MBV uptake and MBV release

$$\mathbf{MBV} = \frac{\Delta \boldsymbol{m}}{\boldsymbol{S}\ \Delta\%\boldsymbol{RH}}$$

- Characteristic MBV of the material is equal to 4.2



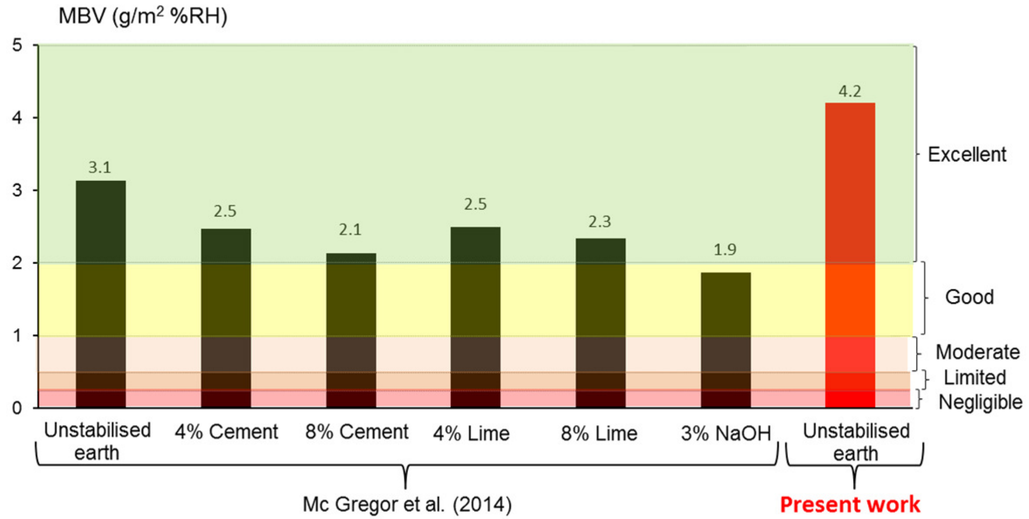
Moisture adsorption of unstabilised samples compacted at 25, 50 and 100 MPa



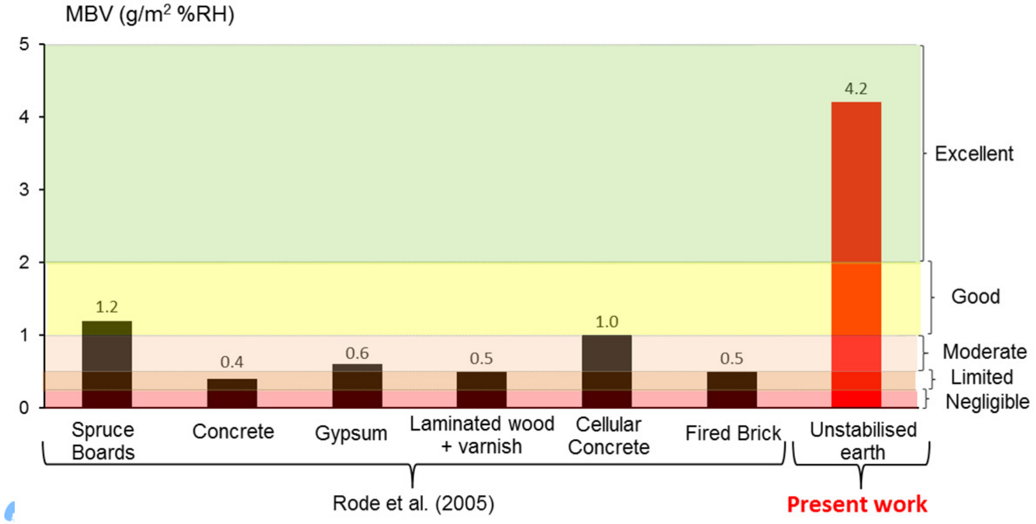
MBV uptake and MBV release of samples compacted at 25, 50 and 100 MPa

Hygroscopic behaviour

Moisture buffering capacity



- Comparison with MBVs obtained by *McGregor et al. (2014).* Same testing conditions [cycle 75% (12h)/ 53% (12h)] *(ISO 24353, 2008)*



- Comparison with MBVs obtained by *Rode et al. (2005).* Different testing conditions [cycle 75% (8h)/ 33% (16h)] *(NORDTEST project)*

Hygro-mechanical behaviour of hypercompacted earth

Conclusions

- Hypercompaction procedure at two scales: cylindrical samples and compressed earth bricks
- Stiffness and strength increase more than linearly with increasing dry density
- Stiffness and strength increase with increasing total suction
- Strength of hypercompacted bricks similar to stabilised earth and standard masonry bricks
- Excellent moisture buffering capacity not affected by compaction pressure

Durability against water erosion

Weak durability against water erosion → Soil stabilisation

Cement or lime stabilisation: addition of cement and lime in percentages ranging from 5% to 15% *(Walker, 1995; Bui et al., 2009; Kariyawasam and Jayasinghe, 2016; Arrigoni et al., 2017)*

Alkaline activation: mixing the soil with solution of $Ca(OH)_2$, KOH and NaOH *(Cheng and Saiyouri, 2015; Elert et al., 2015; Slaty et al., 2015)*

Silicone based admixture: addition of silane-siloxane emulsions or surface treatments *(Kebao and Kagi, 2015)*

Plant aggregates or animal waste: addition of cereal straw, wood aggregates, bast fibres or sheep wool, cow dung *(Galan-Marin et al., 2010; Aymerich et al., 2012; Danso et al., 2015; Laborel-Préneron et al., 2016; Millongo et al., 2016)*

MICP: microbial induced calcite precipitation *(Dejong et al., 2013; Salifu et al., 2016)*

Heat: earth bricks thermally treated at low firing time and temperature *(Mbumbia et al., 2000; Karaman et al., 2006)*

Durability against water erosion

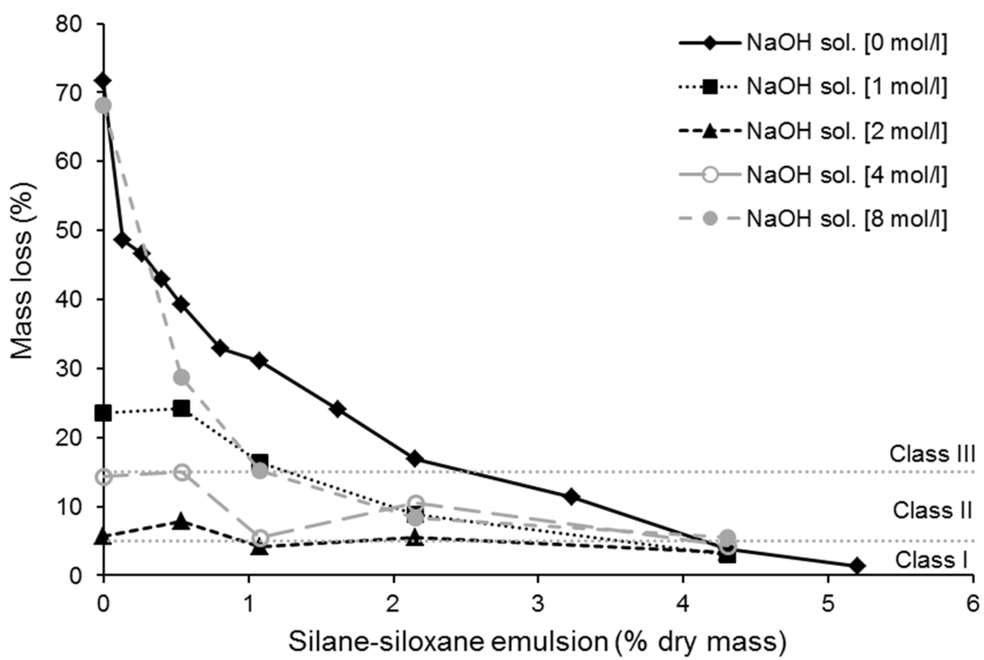
Stabilisation methods

- Preliminary assessment of durability performed by immersion tests *(DIN 18945, 2008)*
- Unstabilised earth exhibited limited durability stabilisation considered indispensable
- Stabilisation achieved by mixing the soil with stabilising liquid additives composed by:
  - Silane-siloxane emulsion
  - Solution of NaOH at molarities 1, 2, 4 and 8 mol/l – pure or blended with Silane-siloxane emulsion

Durability against water erosion

Immersion tests *(DIN 18945, 2013)*

- Samples stabilised with higher concentrations of silane-siloxane showed limited mass loss
- Addition of NaOH improved durability as concentration increased from 1 mol/l to 2 mol/l
- Further increase of NaOH (i.e. 4 mol/l and 8 mol/l) was no longer effective



Results from immersion tests

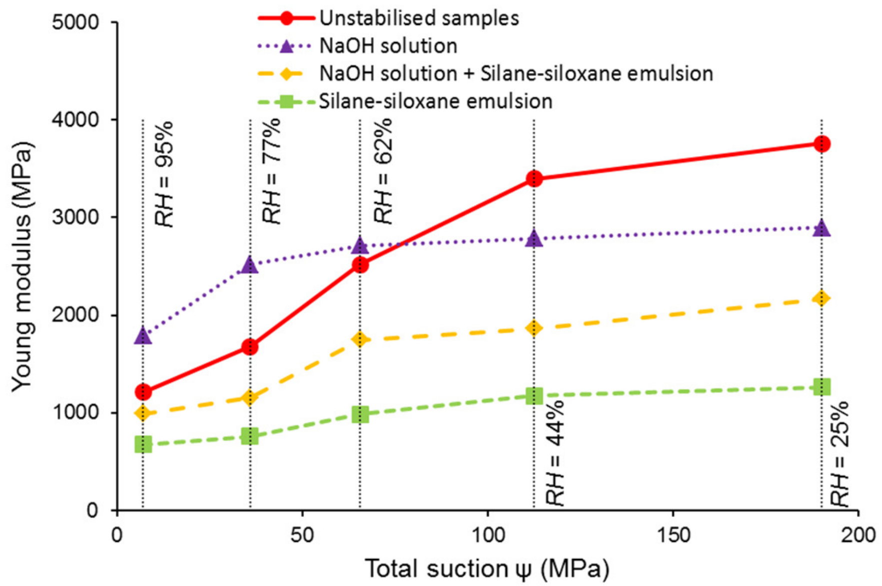
Three compositions were selected for further testing:

- 5.20% silane-siloxane emulsion
- 5.20% NaOH solution at 2 mol/l
- 1.08% silane-siloxane emulsion + 4.12% NaOH solution at 2 mol/l

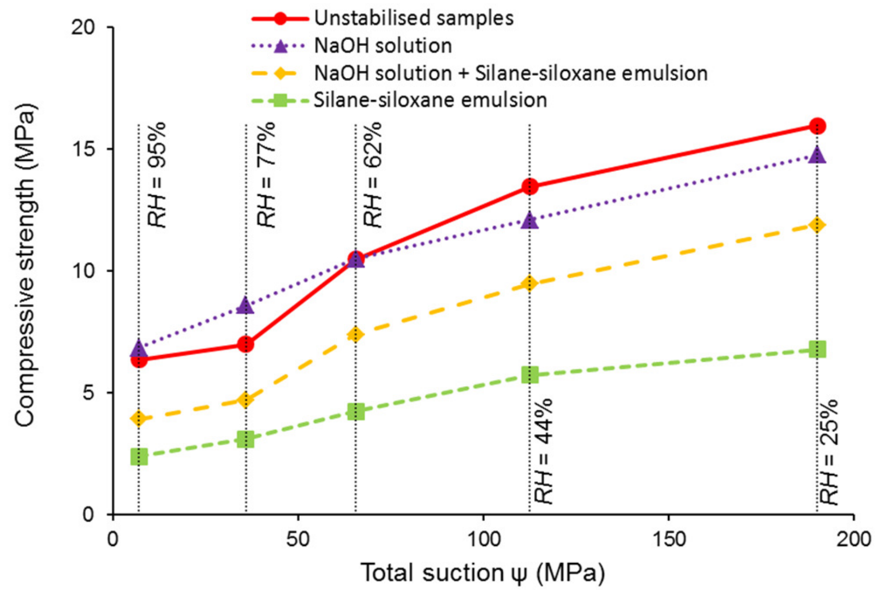
Durability against water erosion

Effect of relative humidity on stiffness and strength

- Stabilised samples are less sensitive to variations of relative humidity
- Stabilised samples show weaker mechanical properties
- Chemical stabilisation inhibited inter-particle bonding produced by capillarity



Variation of Young modulus with total suction: unstabilised and stabilised samples compacted at 100 MPa

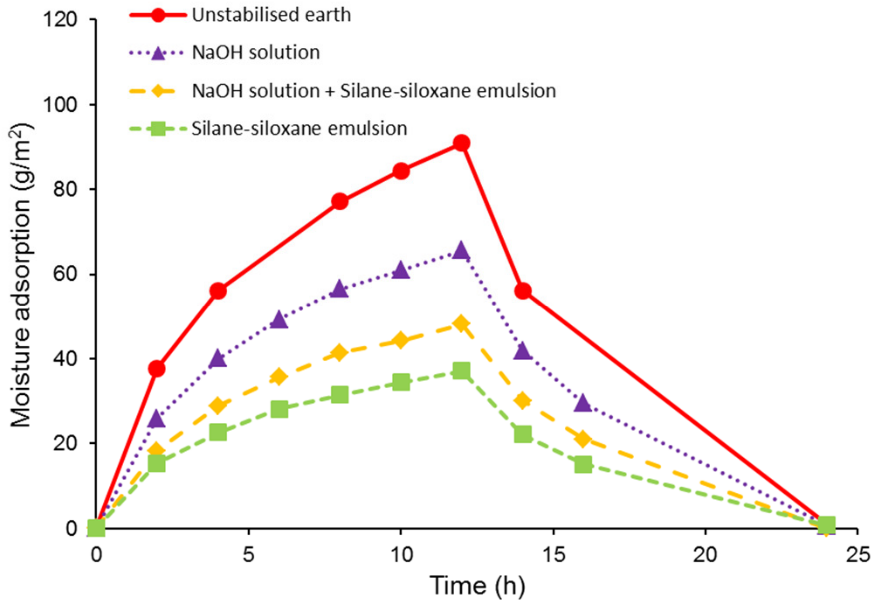


Variation of compressive strength with total suction: unstabilised and stabilised samples compacted at 100 MPa

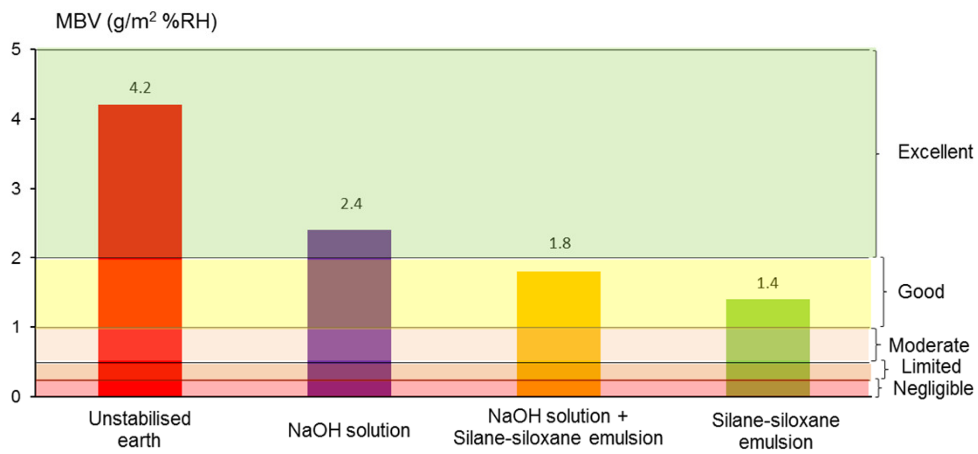
Durability against water erosion

Moisture buffering capacity of unstabilised and stabilised samples

- Stabilisation reduced moisture buffering capacity depending on type of stabiliser
- Hygroscopic performance ranges between excellent (NaOH solution) and good (Silane-siloxane emulsion, mix of NaOH and Silane-siloxane emulsion)



Last stable cycle of unstabilised and stabilised samples



MBVs of unstabilised and stabilised samples

Durability against water erosion

Conclusions

	Unstabilised earth	NaOH solution	NaOH solution + Silane-siloxane emulsion	Silane-siloxane emulsion
Mechanical properties	☺	☺	😐	😐
Moisture buffering capacity	☺	☺	☺	😐
Durability against water erosion	☹	😐	😐	☺

Recommendations for future work

- Further investigation should be conducted to develop **novel stabilisation methods** that protect earthen materials from water erosion while maintaining a high moisture buffering capacity, adequate mechanical performance and low environmental impact

- The influence of compressed earth bricks on the **quality of indoor air** has not been assessed in the present work. Further research in this direction could investigate the potential of earthen materials to improve living condition inside dwellings

- A **life cycle assessment** of earth structures should be performed to quantify the environmental impact of this construction technique. This assessment could also inform the choice of stabilisation method.

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Thank you for your attention

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