Outcome

- Definitions
- Presentation of products, use and factors affecting their performance
- Internal factors affecting GCLs performance
- Quantification of the performance of GCLs towards transfers
- Durability of GCLs
- Hydraulic behaviour of GCLs in composite liners
- Recommendations to ensure the long-term performance of GCLs
Geosynthetic clay liners (GCLs) (IGS recommended terminology)

An assembled structure of geosynthetic materials and low hydraulic conductivity earth material (clay), in the form of a manufactured sheet, used in civil engineering applications.

Clay geosynthetic barrier (GBR-C) (EN ISO 10318)

Factory-assembled structure of geosynthetic materials in the form of a sheet which acts as a barrier

NOTE The barrier function is essentially fulfilled by clay. It is used in contact with soil and/or other materials in geotechnical and civil engineering applications.
Unique function

Lining

GCLs

Differ by
- manufacturing
- bentonite nature
- bentonite granularity
- inclusion of a coating/laminated film or not
  (multicomponent GCLs)
Manufacturing

Needle punched GCL

Stitch bonded GCLs

multicomponent GCLs

Bentonite+glue

geotextile

film, geomembrane or coating
Examples of multicomponent GCLs

Use of GCLs

Landfills: 85%
Use of GCLs

Ponds: 10%

Along roads: 5%

Factors affecting the performance of GCLs

- freeze/thaw
- loading/hydration
- manufacturing bentonite (nature, smectite content, granularity, mass per unit area) coating/laminated film
- puncture protection
- association with a geomembrane
- hydration/desiccation
- cation exchange
- roots

internal
short-term
long-term
Internal factors affecting the performance of GCLs

- Bentonite nature
  - Cations
  - Smectite content
- Bentonite granularity
- Mass per unit area
- Manufacturing
- Inclusion of a coating/laminated film or not

Bentonites

Ability to absorb water between clay platelets → swell, high sensitivity to cations (CEC ≥ 90 meq/100g)

Mineralogic structure of a bentonite
Bentonite types

Results of swell index tests

Principle: swell of 2g of bentonite in 100 ml of liquid during 24h
The swell index is given in en ml / 2g of bentonite

With distilled water

Sodium and Ca act bentonites
29 ml/2g ≤ SI ≤ 36 ml/2g

Calcium bentonites
SI ≤ 10 ml/2g

ASTM D 5890
XP P84-703
Relationship between results of swell index tests and proportion of Na

Guyonnet et al. (2009)

Mineral composition of bentonites (Proportions are given in %)

<table>
<thead>
<tr>
<th>Minerals</th>
<th>LX1</th>
<th>LX2</th>
<th>LX3</th>
<th>LX4</th>
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</table>
Relationship between CEC and Smectite content

Guyonnet et al. (2009)

Typical hydrated smectite microstructures

Guyonnet et al. (2009)

Transmission electron microscope images

Guyonnet et al. (2009)
Effect of the manufacturing on swell

Four different GCLs studied: 2 needle punched and two stitch bonded products containing natural sodium bentonite # 5kg/m²

Hydrated without load in an oedopermeameter cell

0.25 m diameter cell
5 days of hydration in test cell
Hydraulic head # 10⁻² m

Aspect of GCLs after hydration

GCL2
GCL3
GCL4
Water contents of GCLs

Effect of the degree of bentonite hydration on the void ratio

\[ e_b = \frac{H_{GCL} - H_s}{H_s} \]

\[ H_s = \frac{M_{\text{bent}}}{\rho_{\text{bent}} (1 + \omega_0)} + \frac{M_{\text{geo}}}{\rho_{\text{geo}}} \]

Petrov et al. 1997
Quantification of the performance of GCLs towards transfers

adveective flow rate

\[ H_1 \]

\[ H_2 < H_1 \]

diffusive flow rate

\[ C_1 \]

\[ C_2 < C_1 \]

Evaluation of the adveective flow rate

\[ H_1 \]

\[ H_2 < H_1 \]

NF P84-705

ASTM D 5887

Courtesy E. Blond
Diffusion through GCLs

$C_1$ > $C_2$

sorbed molecules or ions

Quantification of adsorption on geotextiles and bentonite

Geotextile + solutions at $C$ (μg/l)  
Bentonite + solutions at $C$ (μg/l)

Solid/liquid ratio

1/40  
1/20
Determination of adsorption isotherms

Factors affecting the hydraulic performance of GCLs

Nature of the bentonite
thickness ⇔ load during hydration
manufacturing
coating/laminated film
Influence of the nature of the bentonite

- Hydraulic conductivity (m/s)
  - Specimens: LX1, LX2, LX3, LX4, LX5, LX6, LX7, LX8
  - Values: $10^{-8}$, $10^{-9}$, $10^{-10}$

Influence of the mass per unit area of bentonite under a 10 kPa load

- Flow rate (m$^3$/m$^2$/s)
  - Mass per unit area of dry bentonite (kg/m$^2$)
  - Data points for GCL 1 0.3m, GCL 1 0.6m, GCL 2 0.3m, GCL 2 0.6m
  - Values range from $10^{-10}$ to $10^{-8}$

under a 10 kPa load
Effect of the thickness on the hydraulic performance of GCLs

\[
e_b = \frac{H_{GCL} - H_s}{H_s}
\]

\[
H_s = \frac{M_{bent}}{\rho_{bent}(1+w_0)} + \frac{M_{geo}}{\rho_{geo}}
\]

Petrov et al. (1997)

Beneficial effect of needle punching

Hydration in tests cell without load

6 hours of rain/day, 5 days
Hydraulic conductivity measurement
According to NF P84-705 (rigid wall permeameter)

20 kPa

GCL

Adaptation of the protocol for GCLs of uneven surface

Use of glass beads
Effect of thermally treated needle punched fibers

(Lake & Rowe 2000)
Sorption isotherms for phenolic compounds on GCLs and evaluation of diffusion

Evaluation of the sorption coefficient

K is then deduced based on a linear model $S = K_d \cdot C_{eq}$ (VOCs)
Freundlich model $S = K_F \cdot C^\alpha$ (phenolic compounds)
Inorganic species

- Diffusion and sorption quantified for NaCl, NH$_4^+$, Al$^{3+}$, several heavy metals
- Significant attenuation at pH>6

Organic species

- Diffusion and sorption of VOCs, sorption of phenolic compounds
- High sorption on geotextiles of VOCs
- Similar sorption on geotextiles and bentonite for phenolic compounds
- Increased mass transport at larger temperatures (between 7 and 22°C)
- Increased sorption on organoclays but also increase in hydraulic conductivity

Durability of GCLs
Durability (EN ISO 10318)

Ability of a product to resist deterioration caused by weathering, mechanical, chemical, biological or other time-dependant effects, and thus to maintain the properties necessary for it to function adequately throughout its working life.

Mechanical effects

- puncture protection
- self-healing
- internal erosion
Evaluation of puncture protection for long-term performance

Impact of various materials for protection

GCL extrusion if a wrinkle is present

Impact of inappropriate protection layer on GCL thinning underneath a geomembrane

Quantification of the ability for self-healing (XP P84-708)
Description of products tested

Two needlepunched GCLs

<table>
<thead>
<tr>
<th>GCL</th>
<th>Bentonite mass per unit area (kg/m²)</th>
<th>Water content (%)</th>
<th>Thickness under 2 kPa</th>
<th>Free swell (ml/2g)</th>
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Flow rate vs hydraulic head for different hole sizes
Critical hydraulic heads

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In the absence of other phenomena (cation exchange)

Internal erosion

- The underlayer shall support uniformly the GCL (Peggs & Olsta 1999)
- The resulting confining stress will then be uniformly distributed (Peggs & Olsta 1999)
- Risk of internal erosion if it is not the case (Peggs & Olsta 1999, Rowe & Orsini 2003)
- GCL fabric very important (reinforcement of carrier geotextile) (Rowe & Orsini 2003)

Peggs & Olsta (1999)
Chemical interactions

- cation exchange
- effect on swell index
- effect on the hydraulic conductivity
- effect of a change in hydraulic conductivity on diffusion

Cation exchange properties

High swelling capacity of sodium bentonites and calcium activated bentonites

But if Na$^+$ is exchanged by other cations...

...the ability to swell is reduced and the microstructure changes
Change in microstructure

Initial saturation with multivalent cations

Initial saturation with water

Pre-hydration with water followed by permeation with multivalent cations

Ashmawy et al. (2002)

Effect of the concentration of CaCl$_2$ on the hydraulic conductivity

Hydraulic conductivity (m/s)

CaCl$_2$ concentration (M)

Vasko et al. (2001)
Jo et al. (2004)
Lee et al. (2005)
General trends observed after contact with leachate

- Influence of the first hydrating medium not as critical as for single-salt species
- Real leachate is generally less aggressive than synthetic leachate
- Recirculation leachate is not more aggressive
- Low calcium carbonate content in the bentonite recommended
- Polymer treatment could improve the bentonite resistance
- For low electrical conductivity solutions, tests with NaCl and CaCl$_2$ give a good estimation of performance

Question remaining regarding equilibrium in most tests

Criteria for termination of tests

- steady hydraulic conductivity
- ratio of outflow to inflow of approximately unity
- minimum of two pore volumes of flow (PVF) passed through the specimen
- ratios of effluent-to-influent electrical conductivity (EC) and pH within 1.0 ±0.1

In addition, some authors recommend comparing the concentration of specific chemical species between the influent and effluent (e.g., ±10%).
Benson et al. (2008): 6 to 8 PVF necessary to reach the Na$^+$ and Al$^{3+}$ equilibrium
Kolstad et al. (2004): tests conducted beyond 15 to 20 PVF until each of the termination criteria previously noted were achieved.
Calcium activated or natural sodium bentonite?

Criteria for use of GCLs in landfills

- Swell index > 24 ml/2g
- CEC > 70 meq/100g
- Calcium carbonate content < 5 % in mass
Adequation between bentonite and leachate

![Graph showing electrical conductivity vs. permittivity](image)

Effect of a change in hydraulic conductivity on diffusion of VOCs

Degradation of a GCL in contact with a synthetic leachate

![Graph showing hydraulic conductivity vs. number of pore volumes](image)

Rosin-Paumier et al. (2011)
Effect of a change in hydraulic conductivity on diffusion

GCL1: dry mass per unit area of powdered natural sodium bentonite = 5.7kg/m². Needlepunched

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<th>GCL1 after cation exchange</th>
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<td>DCA</td>
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<td>TCE</td>
<td>$3.9 \times 10^{-10}$</td>
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</tr>
<tr>
<td>$e_b$</td>
<td>3.7</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Increase in the diffusion coefficient but not proportional to the increase in hydraulic conductivity.
To check with other GCLs and other contaminants

Weathering effects

- freeze-thaw
- hydration-desiccation
- shrinkage
Effect of freeze-thaw

Can be evaluated through CEN TS 14418

Geosynthetic barriers — Test method for the determination of the influence of freezing-thawing cycles on the permeability of clay geosynthetic barriers

The flux through 100 mm diameter clay geosynthetic barrier specimens is determined with a flexible wall permeameter both on a specimen exposed to freezing-thawing cycles (4 cycles) and on unexposed reference specimen. Sample saturated under a pressure of $(4 \pm 0.2)$ kPa for 48 h at constant room temperature. One sample is stored in the freezer at -5°C for 24 h. After the freezing period sample allowed to thaw at room temperature for 24 h. Sample submerged again for 24 h at room temperature.

No effect on the hydraulic conductivity even after 125 freeze-thaw cycles. No data on coupling of freeze-thaw cycles with cation exchange.

Effect of hydration-dessication

Can be evaluated through CEN TS 14417

Geosynthetic barriers - Test method for the determination of the influence of wetting-drying cycles on the permeability of clay geosynthetic barriers

The flux through 100 mm diameter clay geosynthetic barrier specimens is determined with a flexible wall permeameter both on specimens exposed to wetting-drying cycles and on unexposed reference specimens after four cycles

- Sample saturated under a pressure of $(4 \pm 0.2)$ kPa for 48 h at constant room temperature
- Drying in an oven at 110 °C for 24 h
- Sample allowed to cool to room temperature for 24 h
- Samples submerged again for 24 h at room temperature

No effect on the hydraulic conductivity through four wet-dry cycles (Lin & Benson, 2000)
GCL Shrinkage

Mechanisms involved:

- Tension in the GCL
- Hydration-drying cycles
- Shrinkage of geotextiles
- GCL panel lateral gathering
- Bentonite shrinkage due to cation exchange

Aspect ratio = 1.0

Aspect ratio = 3.0

Courtesy R. Koerner
Cyclic hydration and drying

Before testing  
After 20 cycles

Thiel et al. (2006)


- No significant shrinkage of geotextiles
- Amount of shrinkage in the laboratory consistent with field observations
- Less water $\Rightarrow$ less shrinkage
- The presence of a woven fabric reduces the amount of shrinkage
- Increased needle-punching $\Rightarrow$ less shrinkage
- Influence of restained vs unrestrained tests
- Influence of the type of GCL
- Effect of the mass per unit area of bentonite (especially for low masses per unit area)

Recommendations for shrinkage prevention

- Do not leave GM/GCL composite liners exposed (minimum 0.3m of soil)
- Do not use GCLs with needlepunched nonwoven geotextiles on both sides unless one is scrim reinforced
- Increase the GCL overlap
- Protect the exposed composite liner during its exposure (thermal blankets, geofoam)
- Heat tacking of seams

Bostwick et al. (2009)
Combined chemical interaction and hydration dessication

Results from excavations
- in landfill covers
- in hydraulic applications
after some years in service

GCLs performance in dikes

1.75 m < Height < 3 m
150 m < Length < 170 m
GCLs samplings

Cation exchange after 3 and 5-6 years in service

![Sandy clay](image)

![Cation exchange chart](chart)
Flow rate measurement after 3 years in service

- load = 10 kPa
- 1 cm < hydraulic head < 10 cm
- No swell
- no significant water absorption
- flow rate and hydraulic conductivity still acceptable

Flow rate measurement after 5 to 6 years in service

- load = 10 kPa
- 0.5 cm < hydraulic head < 5 cm
- No swell
- large flow rate and hydraulic conductivity
Excavations from landfill covers

France (Touze-Foltz et al., 2010)

Germany (Zanzinger and Touze-Foltz, 2009)

Landfill A

Area repaired in 2006 according to observations performed during excavation

As installed in 2003
<table>
<thead>
<tr>
<th>Hole</th>
<th>Dry mass per unit area of GCL specimen (kg/m²)</th>
<th>Water content (beginning of the test) (%)</th>
<th>Water content (end of the test) (%)</th>
<th>Hydraulic conductivity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4.08</td>
<td>48</td>
<td>100</td>
<td>1.07x10⁻⁶</td>
</tr>
<tr>
<td>3</td>
<td>3.95</td>
<td>63</td>
<td>112</td>
<td>1.71x10⁻⁶</td>
</tr>
<tr>
<td>6</td>
<td>3.50</td>
<td>37</td>
<td>101</td>
<td>6.91x10⁻⁶</td>
</tr>
</tbody>
</table>

landfill B

confining soil 1.2 m thick
Landfill B

GCL

calcium bentonite
mass per unit area : 16 - 19 kg/m²
water content : 70 - 80%
swell index : 7 mL/2g
permittivity under 30 kPa :
5×10⁻⁹ s⁻¹ to 8×10⁻⁹ s⁻¹

No change in the bentonite after 6.5 years
Good lining
Roots in contact with the GCL but no penetration

Landfill C

GCL

sodium bentonite
mass per unit area : 10.3 kg/m²
water content : 85%
swell index : 7 - 8 mL/2g
permittivity under 20 kPa :
1.6×10⁻⁸ s⁻¹ to 1.9×10⁻⁸ s⁻¹

After 10 years
No influence of roots on the permittivity value
Cation exchange has entirely taken place
The GCL fulfills its function
Desiccation cracks in the bentonite

When GCLs suffer cation exchange and cation exchange cracks appear they may not reseal during further hydrations

*Case of a sodium bentonite in a GCL+ solution 0.0125M CaCl₂*
after 4 cycles $K > 4 \times 10^{-11}$ m/s
after 8 cycles $K > 7 \times 10^{-8}$ m/s

*(Bouazza et al. 2006)*
Effect of desiccation cracks on leakage

From Henken-Mellies & Zanzinger 2004

Effect of the fraction of monovalent cations on the hydraulic conductivity

GCLs from single liners

GCLs from composite liners

Meer and Benson (2007)

Benson & Scalia (2010)
Effect of the water content of specimen during sampling

Benson & Scalia (2010)

Effect of RMD

\[ \text{RMD} = \frac{M_m}{M_d^{0.5}} \]

- \( M_m \) total molarity of monovalent cations
- \( M_d \) total molarity of multivalent cations in the solution,
- represents the relative abundance of monovalent and multivalent cations
In contradiction with results from Meer & Benson (2007)
Wisconsin and Georgia

Dikes, canals:
0.8m of protection (sand, gravel) sufficient after 6 years in service
(Fleischer & Heibaum 2008)

Middle European climatic conditions

1m

Müller-Kirchenbauer et al. (2008)
Zanzinger (2008)
Cover composition

GCL
• mass per unit area of dry sodium bentonite \( \geq 4.5 \text{ kg/m}^2 \)
• mass per unit area of dry calcium bentonite \( \geq 9 \text{ kg/m}^2 \)

Protection layer
• Sand has the ability to store water and feed the GCL with this water

Drainage layer
• Maintain a small hydraulic head
• Prevent from suction application on the GCL
Cover composition

Confining layer

German recommendation: 1.5 m thick as a minimum

- in dry climatic conditions (< 800 mm/a): 1.8 to 2 m with a storage function of the confining layer
- “field capacity” as large as possible (ideally 200 mm/m)
- If no care to the vegetation, increase this thickness
- installation without compaction
- If thickness lower than 2m use a dense gravel layer at the base to prevent from root intrusion

Zanzinger & Touze-Foltz (2009)

Hydraulic performance of GCLs in composite liners as a function of the nature of bentonite
Leakage mechanism

Brown et al. (1987)

Leakage
Geomembrane
Interface (transmissivity)
Circular hole

Symmetry axis

Materials tested

Stitch Bonding rows
Woven geotextile
Bentonite

Woven geotextile
Bentonite
Needle-Punched
Non woven geotextile

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>$k_{GCL}$ (m/s)</td>
<td>$3.2 \times 10^{-11}$</td>
<td>$6.9 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-11}$</td>
<td>$5.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>$S_l$ (cm$/2g$)</td>
<td>34</td>
<td>10</td>
<td>33.5</td>
<td>&lt;10</td>
</tr>
</tbody>
</table>
Transmissivity equipment

COMPOSITE LINER:
- Drainage layer
- Geomembrane HDPE 2mm
- GCL
- Defect Ø 4 mm or 10 mm
- Compacted soil - CCL
- $k = 8 \times 10^{-11} \text{ m/s}$

Water supply

Mariotte Bottle

Granular layer

Top cylinder

Compacted clay liner CCL

Bottom cylinder

Bottom plate

Effluent

COMPOSITE LINER:

Mechanical press

Plexiglas cell

Water supply (constant head)

Mariotte Bottle

GCL

Compacted Clay Liner
Results – Flow rate

Diameter hole in the GM = Ø 4 mm

- Significant decrease
- Slow decrease
- Steady state

Hydraulic Head: 0.3m
Confining stress: 50 kPa

Results – Flow rate (2)

Diameter hole in the GM = Ø 10 mm

- Calcium bentonite: larger time to reach steady state
- Similar final flow rates
Impact at field scale

$H_{CCL} = 0.5 \text{ m}$

$H_{AL} = 5 \text{ m}$

$K_{GCL} = 8 \times 10^{-11}$

$10^{-6} \text{ m/s}$

Attenuation layer

$k_{CCL}$ in tests

$k_{CCL}$ recommended (MEEDDAT 2009)

$k_S$
Recommendations for ensuring the long term performance of GCLs

- Mass per unit area of dry bentonite > 5kg/m²
- Swell index > 24 ml/2g
- CEC > 70 meq/100g
- Calcium carbonate content < 5 % in mass
- Adaptation of bentonite to leachate to contain
- Hydration under load with low ionic strength solution
- Provide adequate underlayer
- Provide cover soil thick enough to prevent from desiccation/hydration cycles

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CETCO, Huesker, Naue
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References


CEN/TS 14417. Geosynthetic barriers — Test method for the determination of the influence of wetting-drying cycles on the permeability of clay geosynthetic barriers.

CEN/TS 14418. Geosynthetic barriers — Test method for the determination of the influence of freezing-thawing cycles on the permeability of clay geosynthetic barriers.


