2022:00760- Restricted

Report – part 2

Status of existing information on installation requirements for sealing products (GBR-P, GBR-B and GBR-C) under Nordic conditions

Function: Sealing

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SINTEF Certification
2023-09-26

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KEYWORDS:
Geosynthetics,
Nordic conditions,
installation,
requirements,
sealing
geosynthetic barriers

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VERSION
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CLIENT(S)
Group of participants ROUGH project

CLIENT'S REF.
ROUGH group

PROJECT NO.
10201737

NUMBER OF PAGES/APPENDICES:
43

ABSTRACT

Summary

Within the framework of the project "Recommendations for requirements on characteristics of geosynthetics and geosynthetic-related products relevant to country-specific conditions in Nordic countries", preparatory work was carried out within the ROUGH project to collect information and provide missing data to be able to propose these guidelines.

Considering the difficulties of conducting full-scale experiments for sealing applications, as has been done for the function's reinforcement/stabilisation, filtration, drainage, it has been decided to carry out a literature study to enable a synthesis of the state of the art for this function. This is presented in the present Report-part 2.

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REPORT NO.	ISBN	CLASSIFICATION	CLASSIFICATION THIS PAGE
2022:00760	ISBN	Restricted	Restricted

Group of participants ROUGH project

Finnish Transport Infrastructure Agency
Swedish Transport Administration
Statens vegvesen
BontexGeo
CETCO
DUPONT
Fibertex Nonwovens
HUESKER Synthetic
MACCAFERRI
Naue
Solmax
Tensar International
Thrace Nonwovens and Geosynthetics
ViaCon

Document history

VERSION	DATE
Version No. Final	2023-09-26

09th April 2019 03rd March 2020	Survey Questionary website (Minna Leppänen)
09th April to 18th June 2019	Evaluation and decision for one alternative approach to on-site testing for sealing: → collect information, literature, experiences. → synthesis (Eric Blond & Minna Leppänen)
05th October 2019 - 30th June 2020	Work on collect information, literature, experiences & synthesis (Eric Blond & Minna Leppänen)
6th November 2020	**Draft 00 of "ROUGH report part 2**" (internal)
→ 20th September 2021	Document organisation, drafts & reviews by small writing committee
4th January 2022	**Draft 01 of "ROUGH report part 2" for comments by the partners**
21st – 31st January 2022	**Presentations of Draft 01 to each producer**, discussion and feedback.
7th February 2022	**Presentation of Draft 01 to the authorities** discussion and feedback
24th March 2022	**Draft 02 of "ROUGH report part 2**" sent to all "Rough participants" (internal)
4th April 2022	**Restitution meeting with all partners**
6th April 2022	**Draft 03 of "ROUGH report part 2**" revised version after 4th April meeting sent to all "Rough participants" (internal)
9th May 2022	Deadline for comments by Bodies / Companies on Draft 03
31st May 2022	Revision of the text by native English-speaking expert.
27th June 2022	**Finalisation of "ROUGH report part 2**" (Eric Blond & writing committee).
2nd August 2022	Final version 01 of **"ROUGH report part 2**"
15th September 2022	Signature by Eric Blond of **"ROUGH report part 2**"
15th September 2022 to 1st September 2023	*Revision of the chapter 3 (sealing) of Guidelines for the Use of Geosynthetics in Nordic conditions identical of ROUGH Report part 2*
1st September 2023	Last revision by Eric Blond of the *chapter 3* (sealing) of **Guidelines**
26th September 2023	Final version of **ROUGH Report part 2** *(identical to chapter 3 (sealing) of Guidelines for the Use of Geosynthetics in Nordic conditions)*

Note: the period was disturbed by several confinement periods in the European countries, which have complicated the realisation of the tests, the communication, and the exchanges between the participants.

Table of contents

1 GENERAL REQUIREMENTS FOR PRODUCTS USED IN SEALING APPLICATIONS UNDER NORDIC CONDITIONS

1.1 Impact of the environmental conditions on design choices

Guidance on the design of geosynthetic barrier (GBR) and geosynthetic lining systems is outside the scope of this document, which focuses solely on the selection of the GBR material itself. ISO 18228-9 provides general concepts which can be used to design a lining system and select an adequate GBR. Many recommendations proposed in ISO 18228-9 address chemical compatibility and other aspects which do not depend on weather or installation conditions. However, winter installation with low temperature, presence of ice and snow and freeze / thaw cycles may influence the selection of the sealing product (polymer / type, thickness, finish), and can also affect:

- The choice of products used to complement the sealing layer – and in particular the cushioning layers used for puncture protection, especially considering the type of subsoil and fill material typical to a northern environment.
- The thickness of overburden layers.
- Some details of the design itself, such as the characteristics of the slopes (angle and length, presence of berms), which may be affected by a change in interface friction properties.
- The installation process (e.g., scheduling, welding strategy).
- The quality assurance programme (type of control, approval process, use of electrical leak location).
- In some cases, operations may also be influenced by environmental conditions.

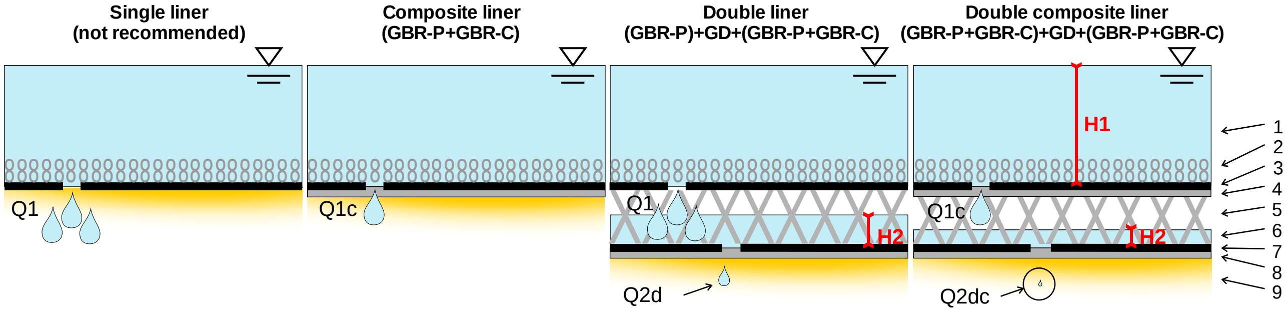
Overall, selection of the sealing material is only one of the many issues which must be addressed to ensure adequate performance of a sealing structure. The design of such a structure includes several other steps which may have significant impacts on the cost and feasibility of the project, beyond the availability of an adequate GBR.

The performance of a sealing layer is defined by the flow of liquid and/or gases passing through the sealing layer. The smaller the leakage rate, the better, which is a reason why geosynthetic barriers are used. However, these products may be damaged during installation or in service, due to their interaction with soil or external loading. The number of leaks per hectare of GBR-P or GBR-B reported in the literature ranges between 0.25 (Gilson-Beck, 2019) and 7 (Nosko, 2015) for projects where Electrical Leak Location Surveys were specified and conducted. This number may be even higher where no or insufficient quality control is conducted, as reported by Forget (2005).

To mitigate the risk of leakage, while acknowledging that the GBR is more likely to be damaged if installed during winter, engineered, multi-layered lining systems should be preferred to single liners. These engineered lining systems typically include:

- A geotextile protection layer, or cushion, installed above the polymeric or bituminous geosynthetic barrier (GBR-P or GBR-B), to protect it from static or dynamic aggregate puncture during backfilling or in service.
- A compacted clay liner (CCL) or a clay geosynthetic barrier (GBR-C), installed below the GBR-P. This material offers a low-permeability substrate to reduce the flow of liquid passing through a potential leak in the GBR-P. Such a structure is called a 'composite lining system'.
- Addition of a second barrier as well as a geocomposite drain between the primary (upper) and the secondary (lower) barrier. The aim of this design is to reduce the head of liquid prevailing on the secondary barrier. As the flow is proportional to the water head, doing so reduces the flow of liquid released into the environment. Such a structure is called a 'double lining system'.

Typical structures of composite, double, and double-composite lining systems are depicted in Figure 1.1. A more detailed discussion on the benefits and limitations of multi-layered geosynthetic barrier systems can be found in Rowe (2005).



Flow Q1 controlled by: - head on primary barrier H1 - size of the hole	Flow Q1c controlled by: - head on primary barrier H1 - size of the hole - permeability of clay barrier	Flow Q1 controlled by: - head on primary barrier H1 - size of the hole	Flow Q1c controlled by: - head on primary barrier H1 - size of the hole - permeability of the primary clay barrier
		Flow Q2d controlled by: - head on secondary barrier H2 (i.e., drainage efficiency) - size of the hole on the secondary barrier - permeability of the secondary clay barrier	Flow Q2dc controlled by: - head on secondary barrier H2 (i.e., drainage efficiency) - size of the hole on the secondary barrier - permeability of the secondary clay barrier

1: Confined fluid above the primary barrier	4: Clay barrier to create composite liner	7: Secondary (polymeric) barrier
2: Primary drainage layer (where applicable)	5: Secondary Drainage	8: Clay barrier to create composite liner
3: Primary (polymeric) barrier	6: Leaking fluid in the drainage layer	9: Permeable subgrade

Figure 1.1: Typical structures of composite and double lining systems

It is important to highlight that the use of double and composite lining systems improves the performance of the lining system and significantly reduces the risk of leakage. However, installation of a geosynthetic lining system and backfilling of soil on top of it in winter remains significantly more challenging than if these actions are taken while the environmental and soil conditions are much easier to handle, during the summertime. Consequently, as far as possible, delaying the project until the temperature is permanently above 0 degrees (e.g., summertime) remains the best solution to minimize leakage.

1.2 Aspects related to the raw material/structure of the products.

The ease of installation and the long-term performance of geosynthetics are partially defined by how much the products will be exposed to cold weather, and at what time of their life – including transportation, storage, installation and during their service life. If the product is highly temperature-sensitive but is intended to be covered by a thick layer of soil that will protect it from cold temperatures just after installation, it is theoretically possible to store it at a warm temperature and wait until the weather conditions permit its installation and installation of the soil cover. The actual possibility to use a particular product is not defined by strict boundaries and should be assessed on a case-by-case basis considering the flexibility of construction schedule and likelihood of extreme environmental events during the projected construction period. However, the less sensitive the product is to the anticipated environmental conditions, the less complex will be its installation and therefore the more manageable the construction schedule.

Figure 1.2 summarizes the various issues that must be considered for any given project. The section following discusses these issues.

The GBR must preserve its integrity during transportation and storage

⇩

It must be possible to unroll the GBR in place under freezing temperatures, on a frozen soil subgrade, without damaging it

⇩

Worker safety must not be affected by a behaviour of the GBR

⇩

Welding of GBR-P or GBR-B to assemble panels or to repair a tear must be possible under the anticipated environmental conditions.

⇩

The GBR must not be affected by the installation of the next layer, such as the soil cover (when applicable)

⇩

The long-term performance of the GBR must not be affected by the installation process

⇩

The (installed) GBR must exhibit adequate long-term properties when exposed to cold temperatures during service

Figure 1.2: Issues to consider when selecting a geosynthetic barriers to be installed under freezing temperatures.

To define performance criteria, it is also important to assess the service conditions that will be experienced by the product. For the most common applications, the following classes of service were defined. Each of them reflects a type of stress that may affect the selection of the geosynthetic barrier, and/or that may be mitigated by implementing particular measures during storage, installation, and backfilling.

Class 1 – Exposed applications

where the geosynthetic barrier system is intended to be left exposed in a Nordic region, therefore experiencing extreme temperatures, temperature cycles, ice and snow but may NOT covered and therefore confined when in service. Examples of such applications include liquid containment or secondary containment structures where the geosynthetic barrier is left exposed, or canals with an exposed geomembrane liner.

Class 2 – Shallow cover

where the geosynthetic barrier while in service is intended to be permanently covered by a shallow layer of soil that will provide a uniformly distributed confining stress on the geosynthetic barrier or lining system. For these applications, the geosynthetic barrier will experience almost similar freeze / thaw conditions as for Class 1, but the confining stress will prevent temperature-induced contraction/expansion, offer a protection layer against impact, prevent wind uplift, etc. Examples of such applications include road ditches and ponds where the geosynthetic barrier could be covered by 300 to 500 mm of soil.

Class 3 – Fully covered applications

where the geosynthetic barrier is intended to be covered by a thick layer of soil and never exposed to extreme environmental conditions once the project is completed. In these applications, exposure of the geosynthetic barrier to freezing temperatures is limited to the construction phase, and the liner will be confined under a sufficiently thick layer of soil to prevent any temperature-induced contraction during its service life. Examples of applications include landfills and other waste containment structures where a sufficient thickness of material is installed rapidly, or heap leach pads using a granular drainage layer. Depending on the service and operating conditions of the structure, class 3 may initially have to be considered as class 2 for a certain duration.

1.3 Performance requirements for the geosynthetic barrier

In further sections, the performance requirements for the geosynthetic barrier are proposed and modulated considering the above-defined classes of service. When applicable, proposals pertaining to the design of secondary layers (e.g., cushions) or installation conditions are considered. All the requirements are summarized in Appendix A.

1.3.1 Preservation of GBR's integrity during transportation and storage

This aspect of geosynthetics installation does not involve the properties of the product itself but the packaging. Care should be taken that water-sensitive products, such as GBR-C, are wrapped to avoid any accidental exposure to water, dirt and UV during transportation and storage. To protect all the surfaces likely to be exposed to water, it is recommended to use:

- Packaging that maintains the integrity of GBR-C during shipping, unloading and storage, tied at both ends of the roll.
- Plastic cores, or cardboard cores treated to be water repellent to avoid degradation.

Cling-wrap is sometimes used for packaging geosynthetics as it also helps to tighten the rolls. However, cling wrap is not a waterproof barrier, and it exhibits a much lower mechanical resistance than adequate polyethylene film. Should water enter a GBR-C roll anyway, on an edge, between laps, or through a damage, the roll could be hard or impossible to unroll. Should GBR-C rolls be wrapped with cling-wrap, additional measures must be taken to protect them from accidental exposure to water, i.e., they must be transported in closed trailers (instead of flatbeds), and enhanced measures must be taken to protect them while in storage on site.

For GBR-C, the duration of onsite storage should be minimized, to reduce the risks of accidental exposure to water. The rolls should be moved as late as possible from the well-organized site storage to their final location – where good storage conditions are sometimes difficult or impossible to achieve. Ideally, the rolls should only be moved to their final location on the day they are deployed.

Other geosynthetic barriers, e.g., polymeric, are not sensitive to water and are therefore more tolerant to exposure to water and ice during transportation and handling. No specific packaging is needed beyond usual recommendations.

These requirements are summarized in Table 1.1.

Table 1.1: Summary of recommendations applicable to criteria 'a' – integrity of the GBR during transportation and storage

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Packaging	Water-sensitive GBR must be wrapped in adequate watertight wrapping	Preferred (GBR-C only) (1)		
Cores	The cores must be insensitive to water	Mandatory		

(1) Use of other wrapping materials, such as cling wrap, may be considered if transportation and storage are adapted, e.g., transportation in closed trailers, on-site storage avoiding contact with snow or rain, and delaying distribution to the final location as much as possible.

1.3.2 Possibility of unrolling the GBR in place under freezing temperatures, on a frozen soil subgrade, without damaging them.

There are three material-related issues to address to make installation possible:

- Low temperature increases both tensile and flexural modulus by changing the properties of polymeric and bituminous geosynthetic barriers (GBR-P and GBR-B), and by freezing water for GBR-C.
- Macro-discontinuities – e.g., edge between two passes of a compaction roller – may abrade, tear, or cause plastic deformations to the product when the soil is frozen.
- Installation under freezing temperatures often leads to the use of greater force by workers, while the product has become stiffer because of the increase of flexural modulus.

Installation must be planned considering that the product may adhere to a frozen subgrade due to frost action.

Clay Geosynthetic Barriers

A high water-content, frozen GBR-C can hardly be unrolled if frozen. This may happen when GBR-C are manufactured with damp bentonite, e.g., moisture content in excess of 50%, or when the packaging of a GBR-C is damaged and lets water make contact with the bentonite. Such high water-content GBR-C must be stored at a temperature above freezing point to minimize exposure of the wet clay to low temperature. Their deployment should also be planned at a time when all the layers can be laid, and the soil backfilled while the temperature remains above freezing point.

It is very difficult to achieve proper subgrade preparation and compaction in winter, and to completely remove snow and ice in cases where there is a snow event between subgrade preparation and deployment of the GBR-C. This leads to a higher risk of exposure of the GBR-C to moisture uptake from a thawing subgrade (thawing being a consequence of the installation of the geosynthetics). This scenario can be prevented with the use of laminated or coated clay geosynthetic liners, with the laminated film layer or coating installed downward. Selection of a laminated or coated GCL may require further confirmation of the structural stability of the veneer, should it lead to the entrapment of liquid water between the laminated/coated GBR-C and a frozen subgrade. Subgrade conditions shall follow manufacturers' installation guidelines or requirements in the specification.

A GBR-C with enhanced tensile properties is also recommended because installation under freezing temperatures often requires using greater force for deployment. Products with sufficient stiffness to preserve dimensional stability, a higher tensile strength, and better cushioning properties should therefore be preferred.

Nevertheless, considering that no corresponding specifications on mechanical properties exist yet, mass per unit area is generally used to ensure this requirement (See Finnish guidelines InfraRYL Appendix 8, Table 8: T11).

In this respect, it is recommended that GBR-C manufactured with a nonwoven geotextile of at least 200 g/m² and a 100 g/m² woven fabric should be used. Should the subgrade conditions be exceptionally harsh, further investigation should be conducted to assess adequate puncture protection of the GBR-C.

To meet these requirements, the properties of the GBR-C can be defined as follows:

- The minimum weight of the geotextile components is recommended to be 300 g/m²: 200 g/m² nonwoven + 100 g/m² woven.
- Presence of a stiff component can be confirmed by a first peak strength measured at an elongation of 30% or less acc. EN ISO 10319. The product should exhibit a minimum strength at the first peak of at least 10 kN/m, (value taken from the Finnish guidelines InfraRYL Appendix 8, Table 8: T11)

These requirements are summarized in Table 1.2.

Table 1.2: Summary of recommendations applicable to criteria ‘b’ – unrolling and placement, for GBR-C

Preferred characteristics	Criterion (GBR-C)	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Lay-flat properties	W < 35% (1)	N/A (2)	Preferred, or (3)	Preferred, or (3)
Resist excessive moisture uptake during installation on icy, snowy, or damp soils	Use of laminated/coated GBR-C (4)	N/A (2)	Recommended (5)	Recommended (5)
Improve cushioning properties	minimum weight of the geotextile components: 200 g/m² non-woven + 100 g/m² woven	N/A (2)	Recommended (6)	Recommended (6)
Resist mechanical stress	Strength at break: 10 kN/m	N/A (2)	Recommended (6)	Recommended (6)
Preserve dimensional stability during installation	Elongation at first peak (%): < 30%	N/A (2)	Recommended (6)	Recommended (6)

(1) note: in case of very exposed critical conditions (e.g., truck-bed without protection) certain installers recommend a lower value of the water content (e.g., ÖNORM S 2081).

(2): exposed applications are not recommended for GBR-C

(3): store the product at a temperature greater than 0°C, install and cover when no frost is expected until all layers and the soil backfill are completed.

(4): laminated/coated GBR-C includes a film of polymer on one side of the product.

(5): this recommendation applies essentially to subgrades which are difficult to compact and exhibit a high content of frozen water. It may be avoided if no excessive moisture is anticipated in the subgrade or when a soil cover is to be installed within hours after laying the GBR-C.

(6): may be avoided if mild installation conditions are anticipated.

Polymeric- and Bituminous-Geosynthetic Barriers

For GBR-P, the intrinsic property of the material must permit its deployment without endangering its integrity. This requirement can be expressed in terms of engineering properties considering the bending stiffness, or flexural modulus, which affects the lay-flat properties of the product.

Most geosynthetic barriers exhibit relatively low flexural modulus at room temperature, therefore good lay-flat properties. However, the flexural modulus increases as the temperature decreases, which may eventually endanger the ease of installation. Such an increase of flexural modulus may be overcome using different construction practices. However, sudden changes of flexural modulus with small changes in temperature (leading to a significantly worse lay-flat) may eventually become problematic. For example, it may require significantly more effort to position the panels, rolls may tend to rewind back, folds may be hard to flatten, etc. To minimize these problems, it is recommended to limit changes in flexural modulus to a factor of ~2 compared to the properties measured at 23°C.

Note: This factor reflects the change of properties of HDPE, for which installation at low temperature is known to be feasible. HDPE was used as a reference and the authors suggest extending this criterion to other polymers in the absence of other evidence.

This criterion is expressed in Equation 1:

$$\frac{E_T}{E_{23°C}} \leq \sim 2 \qquad (1)$$

Where:

- E_T: Flexural modulus at the anticipated temperature of installation
- $E_{23°C}$: Flexural modulus at 23°C

The flexural modulus can be measured using ISO 178.

Certain types of GBR-P can be prefabricated and delivered to the site in very large panels, such as PVC-P, EPDM and LLDPE. In this case, an increased stiffness / flexural modulus may lead to the development of tears at the time the folded GBR panels would be deployed on site. This phenomenon has been observed with standard grades of PVC GBR (e.g., complying to ASTM D7176, FGI 1120 or similar), and more research is needed to assess the performance of advanced grades of PVC-P, EPDM and LLDPE prefabricated panels at the time they are deployed under extremely cold environments.

Note: using heated tents to control storage conditions and to maintain the geosynthetic barrier at a temperature higher than the outdoor temperature is possible. This strategy may facilitate its installation by controlling its lay-flat properties at the time the product is unrolled. This strategy presents two limitations: firstly, it requires extremely fast operations, which are often not compatible with extreme field conditions; secondly, once unrolled, the temperature of the geosynthetic will quickly be controlled by the subgrade, the air, and solar exposure, leading to thermal contraction, and to stiffening of the product within hours. Its use should therefore be considered with caution.

Products with higher robustness against mechanical damage are also recommended because installation at freezing temperatures often leads to the use of greater force for deployment, and/or abrasion from the subgrade if no cushioning material is installed underneath.

For GBR-P made from HDPE or LLDPE, this typically leads to the use of products with a thickness of at least 1.5 mm. Other design considerations may lead to the selection of thicker products.

Note: the 1.5 mm requirement is based on field experience gathered with HDPE or LLDPE GBR-P. Although thickness does not qualify mechanical properties, it is suggested as a criterion in the absence of detailed information.

These requirements are summarized in Table 1.3.

Table 1.3: Summary of recommendations applicable to criteria 'b' – unrolling and placement, for GBR-P and GBR-B

Preferred characteristics	Criterion (GBR-P and GBR-B)	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Lay-flat properties	$\frac{E_T}{E_{23°C}} \leq \sim 2$	Recommended (1) (2)	Recommended (2)	Recommended (2)
Offer mechanical resistance	GBR-P: Thickness > 1.5 mm GBR-B: Thickness > 4.0 mm	Recommended (3)	Recommended (3)	Recommended (3)

(1): proposal made in absence of supporting literature.

(2): store the product at a sufficiently high temperature, install and cover the GBR when environmental conditions are favourable. The anticipated temperature of the liner once covered should not be lower than the low-temperature flexibility.

(3): may be avoided with an extremely cautious installation.

1.3.3 Worker safety during installation of the sealing layer.

Smooth GBR-P become extremely slippery under freezing temperatures, even at low humidity levels. As soon as there is any dampness or snowflakes on their surface, it may become virtually impossible to walk, affecting worker safety and productivity. Using materials with sufficient grip to workers' boots while covered by a thin layer of snow is recommended for GBR intended to be covered and should be considered mandatory for GBR intended to be left exposed (Table 1.4).

Table 1.4: Summary of recommendations applicable to criteria 'c' – properties influencing worker safety.

	Criterion (GBR-P and GBR-B)	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Preferred material features	Sufficient friction surface / textured / non-slip surface facing up	Mandatory	(1)	

(1): using a textured / non-slippery material may be considered to improve worker safety if no other measure is taken; nevertheless, it may have an impact on the ease of welding on textured regions of the GBR and it should be considered a compromise.

1.3.4 Welding of the GBR to assemble or to repair.

Weldability of geosynthetic barriers should be considered with respect to two aspects:

- It must be possible to weld the panels together, i.e., to prepare the surfaces and adjust the welding equipment to create a seam that will offer the required performance, i.e., mechanical properties (peel and shear strength) and adhesion.
- The micro-structure of the polymer and the macrostructure of the area should not be overly affected by the seaming, to the point where welding could affect the long-term performance of the sealing layer. For GBR-P, welding parameters must be selected to ensure effective welding,

while avoiding over-heating of the seam. For GBR-B, the quantity of heat must be just enough to melt the bitumen and permit welding, without 'emptying' the nonwoven by excessive heating.

There is evidence of well-performing welds of HDPE or LLDPE GBR-P made under extremely cold environments. Assembling geosynthetics by means of thermal welding is possible, although very challenging in the field, requiring more preparation and caution than under warmer environments. Practically, it is possible to control the environmental conditions locally to assemble two panels, or to repair a leak (see section 2.5.2 figure 8). It requires well-qualified workmanship and good practices which are described later in the document.

However, other methods such as chemical fusion (for PVC) or vulcanization (for EPDM) may be more challenging for a variety of reasons. The use of thermal welds with adapted procedures should be considered the only acceptable method, when performed as described in Section 3.2.5.

Torch-welding of GBR-B is more challenging at low temperature than it is at high temperature. The lower the temperature of the GBR-B, the higher the temperature difference between the membrane and the welded area, where the bitumen must melt enough to facilitate assembly of the rolls, but not too much to avoid loss of bitumen from the nonwoven. In the absence of mechanized welding equipment for GBR-B, excellence of the workmanship is critical to the quality of welding.

Weldability of a GBR-P may also be affected by the following properties of the product:

- The surface texture, or, more precisely, the possibility of cleaning the surface of the GBR-P to prepare for welding. Textured HDPE and LLDPE GBR-P are often supplied with smooth edges, which facilitates welding. When welding is necessary in the textured area, thorough cleaning – and drying, e.g., with a heat gun – of the surface is essential.
- The thickness: managing high temperature gradients between the membrane and the temperature of welding increases the risk of faulty welds, 'burnings', and holes. Based on hands-on experience, GBR-P with a thickness of 1.5 mm or more can be welded under cold environments – i.e., using a wedge-welder or extrusion welder. In a similar fashion, the thicker a GBR-B, the easier the control of temperature between the sheets, therefore the less risk of excessive melting of bitumen. A 'soft' criterion of 4.0 mm is proposed for installation at low temperature, bearing in mind that the use of a thinner material is possible but makes the welding more challenging.
- Crystallinity, for polyethylene GBR-P: the higher the crystallinity, the stiffer and more sensitive to cracking the sheet, especially in the area of the seams. When acceptable for the anticipated chemical environment, GBR-P made of LLDPE resin should be preferred over HDPE resin to reduce (but not suppress) the risks of cracking and facilitate welding.

These requirements are summarized in Table 1.5.

Table 1.5: Summary of recommendations applicable to criteria 'd' – assembly and repair of geosynthetic barriers (GBR-P and GBR-B)

	Criterion (GBR-P and GBR-B)	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Preferred material features	Smooth edges Lower crystallinity of GBR-P resin (for PE: LLDPE preferred to HDPE)	Recommended Recommended Recommended		
Thickness	GBR-P: Thickness > 1.5 mm GBR-B: Thickness > prefer thicker grades	Recommended (1)		

(1): using thinner products is possible but increases the risk of problems during welding or at a later date.

1.3.5 Installation of the soil cover on the GBR (when applicable)

Aggregate puncture resistance (Figure 3) may be mobilized at the time of installation when vehicles will be circulating over the lining system. A stress may then be applied whose magnitude will be related to the ground pressure of the vehicle (i.e., from tyres or tracks), as well as to the thickness and properties of the fill. The performance of the geosynthetic barrier (or lining system) can be assessed using a performance test involving project-specific aggregate and the candidate geosynthetic materials, including geotextile cushions and GBR-C when applicable. Such tests are performed at room temperature.

Appendix B proposes the concept of a procedure for conducting such tests and making them applicable to low-temperature service conditions. A more detailed recommendation has to be developed concerning the requirement on the protective cushion and the geotextile characteristics. Based on hands-on observations, the mass per unit area of protective cushions must be higher for winter installations than those defined by standard design.

Should a GBR-C be installed as single plane of sealing, cover soils with a well graded particle size distribution should be preferred, unless the intended function of the cover soil prohibits this. The maximum particle size in contact with the product should not exceed 31.5 mm for natural soils exhibiting rounded or sub-rounded particles, or 16 mm with crushed rock for angular or sub-angular particles to minimize the risk of mechanical damage, based on Finnish experience (InfraRYL 14231.3.2 Bentoniittimaton asentaminen (Installation of GCL)" Bentoniittimattoa vasten tulevan materiaalin enimmäisraekoko on kalliomurskeella 16 mm ja luonnonkiviaineksella 31,5 mm.

Tables 1.6 & 1.7 present the summary of recommendations applicable to criteria 'e' – installation of soil cover (GBR-P and GBR-B & GBR-C)

Table 1.6: Summary of recommendations applicable to criteria 'e' – installation of soil cover (GBR-P and GBR-B)

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Aggregate puncture during installation	Increase the mass per unit area of the geotextile cushion by 1.5x to 2x the calculated value, and to at least 500 g/m²	Not applicable	Recommended	

Table 1.7: Summary of recommendations applicable to criteria 'e' – installation of soil cover (GBR-C)

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Gravel puncture during installation	1 - well graded particle size distribution 2 - d_{100} of the soil in contact with the GBR-C: Angular or sub-angular particles: $d_{100} \leq 16$ mm - Rounded or sub-rounded particles: $d_{100} \leq 31.5$ mm	Not applicable	Recommended	

1.3.6 **Influence of installation process on the long-term performance of the sealing layer**

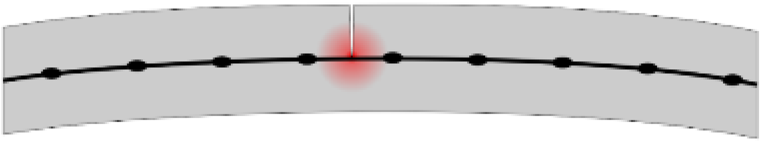
The long-term performance of geosynthetic barriers is beyond the scope of this document. Long-term performance depends on the service conditions, overall design of the project, failure criteria considered, in addition to the properties of the product and quality of installation. The long-term performance of GBRs is discussed in more detail in ISO-18228-9.

The scope of this section is limited to the effect of installation, which must not affect the properties of the geosynthetic barrier to the point at which these will affect its long-term performance.

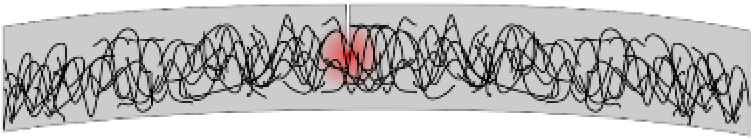
Geosynthetic barriers manufactured with components sensitive to cracking at low temperature such as GBR-B manufactured with an insufficient amount of SBS (Styrene-butadiene-styrene) additive, as well as some GBR-P (e.g., fPP and some formulations of PVC) may exhibit brittle behaviour during installation, and microcracks may appear. A phenomenon such as micro-cracking must be avoided even if there is no loss of continuity of the sealing layer, for two reasons:

- It locally reduces the thickness of material not in contact with the environment, which may affect its durability in the region of the crack by providing an easier access to oxygen or chemicals.
- It creates a stress concentration, therefore a region which is more likely to crack should the material be exposed to stress, e.g., because of further thermal contraction.

For some reinforced geosynthetic barriers such as bituminous GBR-B, reinforced flexible polypropylene (fPP-R), PVC (PVC-R) or EPDM (EPDM-R), the matrix may be more sensitive to cracking at low temperature than the reinforcement. The reinforcement may therefore preserve the overall integrity of the barrier and its apparent integrity. However, microcracks expose the reinforcement to oxygen and/or chemicals, and thus accelerate its degradation, which may eventually endanger the structural integrity of the geosynthetic barrier (Figure 1.3).



(a): woven tapes or scrim-reinforced GBR with a cracked matrix



(b): nonwoven – reinforced GBR with a cracked matrix

Figure 1.3: Exposition of the reinforcement of a reinforced geosynthetic barrier, polymeric or bituminous

Microcracks in GBR-B may sometimes heal themselves if the bitumen is exposed to a temperature greater than its softening temperature. However, healing may only take place if the bitumen reaches a temperature high enough to soften before it is contaminated by dust or exposition to chemicals. Reaching a sufficiently high temperature is unlikely during the winter season, i.e., when these microcracks are most likely to develop.

The ability of the product to resist cracking when bent can be assessed using a low-temperature flexibility test. When bent over a mandrel at a temperature similar to the temperature experienced onsite, the geosynthetic barrier should not exhibit cracking based on visual observation. The test should be conducted on both faces of the geosynthetic barrier. The diameter of the mandrel should be between 3 and 25 mm. The smaller the mandrel, the less sensitive the material is to low temperature. For some products, the performance depends on the type and quantity of additive added to the main polymer (e.g. SBS for bitumen, plasticizer for PVC) while it depends on the grade of polymer for others (e.g., polyethylene). Accepting products offering a mediocre performance (i.e., passing the low-temperature flexibility test on a 25 mm diameter but not on a smaller mandrel) for a given application temperature may be considered when associated with a more stringent quality assurance programme and the use of heated storage until installation.

This criterion is expressed in Equation 2:

$$T_{Flex} \leq T_{installation} \qquad (2)$$

Where:

- T_{Flex}: Low temperature flexibility
- $T_{installation}$: Lowest expected installation temperature

The low-temperature flexibility can be measured by bending the GBR 180°±5° around the selected mandrel after conditioning at the desired temperature for 2 ± 1 seconds.

Note: As for criterion b, using heated tents to control storage conditions and to maintain the geosynthetic barrier at a temperature higher than the outdoor temperature is possible. This strategy may facilitate its installation by controlling the risk of cracking at the time the product is unrolled. This strategy presents two limitations: firstly, it requires extremely fast operations, which are often not *compatible with extreme field conditions; secondly, once unrolled, the temperature of the geosynthetic will quickly be controlled by the subgrade, the air, and solar exposure, leading to thermal contraction and stiffening of the product within hours. Its use should therefore be considered with caution.*

These requirements are summarized in Table 1.8.

Table 1.8: Summary of recommendations applicable to criterion 'f' – effect of installation on long-term properties

	Criterion (GBR-P and GBR-B)	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Low temperature flexibility	$T_{Flex} \leq T_{installation}$(1)	Recommended		

(1): The criterion is applicable to GBR-P, GBR-B and to the lamination/coating of GBR-C

1.3.7 **Long-term properties of the GBR when exposed to low temperature.**

Note: the new reference document ISO guide ISO/TR 18228-9 "Design using geosynthetics - Part 9: Barriers" (publication 04 2022) may help to establish a basis for defining the specific requirements linked to cold temperatures.

Polymeric and bituminous geosynthetic barriers

The rate of degradation of geosynthetic barriers is influenced by the temperature, as the temperature influences the kinetic of chemical reactions controlling the degradation. A common rule of thumb is to consider that an increase of 10°C leads to a kinetic of degradation 2x faster. Therefore, exposure to low temperature will typically reduce the rate of degradation of geosynthetics. Material selection for chemical compatibility and long-term durability can therefore focus only on the temperature and chemical exposure defined by the application.

Consequently, the long-term performance of geosynthetic barriers systems used in northern climates is typically controlled by mechanisms affecting their physical integrity.

Most failure mechanisms can be avoided by following good construction practices and by covering the lining system with soil. The cover soil limits the exposure of the material to extreme environmental conditions and to accidental stresses during its service life.

For materials fully exposed, performance will be controlled by their ability to resist the following stresses at the temperature to which they are exposed: wind uplift and wind-induced vibrations. The wind speed is higher in winter due to the lack of vegetation, and this must be considered when selecting the mechanical properties of a GBR to resist impact from gravel, ice, floating equipment or other sources, including impact by floating ice for ponds.

These requirements are summarized in Table 1.9. They are limited to the behaviour of the GBR-P or GBR-B itself and do not cover the effect of a freezing temperature on the surrounding soils.

Table 1.9: Summary of recommendations applicable to criteria 'g' – long-term exposure to cold temperature of GBR-P and GBR-B

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Low temperature flexibility	$T_{Flex} \leq T_{service}$ (1)	Mandatory	Recommended	
Preferred material feature	Surface with sufficient friction / textured / non-slip surface facing up	Recommended	Preferred	
Minimize sensitivity to slow crack growth and rapid crack propagation	For GBR-P: prefer LLDPE to HDPE resins	Recommended (2)	Recommended (2)	N/A (3)
General design consideration, e.g.: wind uplift, impact resistance, etc.	Include effects of a stiffened material in the design methods	Recommended	Recommended	

(1): The criterion is applicable to GBR-P, GBR-B and to the lamination/coating of GBR-C

(2): The risk of cracking is a combination of factors, which includes the material sensitivity to cracking as well as aspects related to the design and quality of installation.

(3): Class 3 is not exposed to low temperature after installation.

Clay geosynthetic barriers

The long-term behaviour of GBR-C exposed to freeze / thaw cycles has been evaluated by several authors. No significant changes of index flux were observed after 150 cycles, i.e., sodium bentonite does not appear to be significantly affected by freezing temperatures. However, the following aspects should be considered at the time of material selection:

- The absence of confining stress may affect the structure of a GBR-C exposed to hydration: swelling of the clay may lead to the separation of the layers This mechanism may result in a reduced internal shear strength of the GBR-C, which could affect the stability of the structure. Therefore, only as much GBR-C shall be deployed as can be covered at the end of the working day with soil, geomembrane, or a temporary waterproof tarpaulin. The GBR-C shall not be left uncovered overnight. As freezing environment may affect construction schedule and delay the installation of the soil cover, the risk is higher than in summer. It is therefore preferable to use products with higher peel strength to exhibit a resistance to delamination (bonding peel strength). Note that GRI GCL 3 requires at least 360 N/m according to ASTM D6496.
- There is no information available regarding the effect of freezing temperature or freeze-thaw cycles on the performance of polymers used in polymer-enhanced GBR-C. As there are numerous types of polymers used, it is recommended to confirm on a case-by-case basis the freeze-thaw resistance of a candidate polymer-amended GBR-C.

The risk of dehydration of GBR-C exposed to freezing temperatures for extended lengths of time has been highlighted by recent research. Their use as single barriers in environments where they may be continuously exposed to freezing temperatures over extended periods should therefore be thoroughly analysed. A cautious approach would be to prefer using GBR-C in combination with a GBR-P.

These requirements are summarized in Table 1.10. They are limited to the behaviour of the GBR-C itself and do not cover the effect of a freezing temperature on the surrounding soils.

Table 1.10: Summary of recommendations applicable to criterion 'g' – long-term exposure to cold temperature of GBR-C

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
Prevent accidental swelling	Never leave the GBR-C exposed overnight	N/A (1)	Mandatory	Mandatory
Prevent dehydration if continuously exposed to freezing temperatures	Install a GBR-P above the GBR-C	N/A (1)	Recommended (2)	Recommended (2)

(1): GBR-C cannot be left exposed.

(2): GBR-C – GBR-P composites or laminated/coated GBR-C with the lamination/coating side up may be considered. In that case, the film or coating of laminated / coated GBR-C must meet the requirements specified for GBR-P, summarized in Table 9 and also the CE requirements.

2 SPECIFIC INSTALLATION REQUIREMENTS (ASPECTS RELATED TO SEALING APPLICATIONS)

2.1 Project management

Contracting and planning the installation of geosynthetics in winter should be done considering the high sensitivity to weather.

Other aspects to consider include:

- Installers with demonstrated experience of the installation of geosynthetics in similar conditions should be required.
- Prefer design-build projects when applicable.
- Ensure fluent communication between parties with sufficient coordination activities.
- Ensure project planning and limitations associated with the installation of geosynthetics are well understood by the general contractor, who should include a provision in his master schedule to account for potential weather-related delays.
- Ensure that avoidable delays are avoided, e.g., administrative, QA approval, etc.

Based on historical data from experienced contractors, productivity in winter may be at best 65% of the productivity in summer, because of the slower welding rate, workers needing to rest, etc. In addition, workable hours per day are reduced, and bad weather may completely stop the progress of the project. An allowance for delays in the range of weeks or months should be considered.

2.2 Packaging, storage, and handling

Respecting the usual storage and handling recommendations is of paramount importance when the products are to be stored and installed under freezing temperatures. Most importantly, the products must be protected from exposure to water. This water concern applies to the entire process, i.e., transportation from the plant, on-site storage, and final storage before unrolling, especially for porous products such as GBR-C. Rolls or porous materials hauled on a truck-bed without protection may capture water and become difficult or impossible to unroll (Figure 2.1).

Figure 2.1: Packaging of a drainage geocomposite damaged before arrival onsite, making the product impossible to install (photo courtesy Scorpion Containment).

The following aspects must be considered for GBR-C:

- Individual roll packaging is mandatory, using a UV-resistant packaging. Should a packaging be torn, it must be repaired immediately. The use of sleeve polyethylene packaging tied on each side of the roll should be preferred. The polyethylene film is more resistant to damage and offers a better protection to water exposure. If a watertight shrink/cling wrapping is preferred, additional measures must be taken to protect the rolls from accidental exposure to water, i.e., transportation in closed trailers (instead of flatbeds), enhanced measures to protect them while in storage, and delayed distribution to the final location as much as possible.
- GBR-C with moist bentonite over 35% (*) should be stored at a temperature above freezing temperature as long as possible to minimize exposure of the wet clay to low temperature. GBR-C with bentonite moisture contents of < 35% (*) can be stored and installed under freezing temperatures.

(*) *note: in case of very exposed critical conditions (e.g. truck-bed without protection) certain installers recommend a lower value of the water content (e.g., ÖNORM S 2081).*

- On-site storage time must be minimized considering that the water content of the GBR-C may increase over time even when adequately wrapped.
- Every stack of rolls must be covered by an additional tarpaulin to protect them from rain and snow, which could develop into ice between the rolls and make their manipulation more complex (Figure 2.2). This requirement applies until the rolls are distributed close to their final storage location on the site.

Figure 2.2: Tarpaulin installed on top of a pile of GBR-C for site storage (photo courtesy Terrafix Geosynthetics)

For all geosynthetic barriers: GBR-C, GBR-P and GBR-B

- Rolls must be stored on platforms elevated from the ground, and necessary precautions must be taken to avoid direct exposure to the soil and to runoff water.
- Rolls must be handled with a stinger bar inserted into the core, a spreader bar, or slings. No other technique is acceptable.
- Cores must have a sufficient crush strength. Use of caps on the end of the cores is recommended to avoid infiltration of water into the product through the core.
- Labels should be water-resistant and of sufficient quality.
- The use of open flames or heaters to remove ice from a roll accidentally frozen is not acceptable. Rolls accidentally exposed to water and frozen cannot be used until the ice has melted naturally following storage in a warmer environment, and after an inspection to check if any damage has occurred.

In all cases, minimizing the storage time onsite should be preferred to minimize storage problems, whenever possible.

The use of temporary structures (e.g., textile buildings) may be considered for temporary storage to completely avoid exposure of the rolls to snow or water (Figure 2.3). However, the related cost makes this solution applicable to large and/or critical projects only.

Figure 2.3: Use of an air-supported textile structure to control environmental conditions on a critical project (photo courtesy Scorpion Containment)

2.3 Subgrade preparation

The rules prevailing for construction in normal conditions apply to frozen subgrades: they must be compacted and smoothed to the project specification. If the work is executed in unfavourable conditions such as cold weather, it is strongly recommended that a project-specific quality management and installation plan is prepared by the GBR installer with the general contractor and approved by all the parties involved. This plan should consider the risk of extended and unpredictable delays caused by environmental conditions prevailing during the various steps of the project.

The installation of the geosynthetics must start with the inspection and approval of the subgrade. The surface must be as smooth as possible with no loose grains, and no visible edges (compactor, tire, etc.) on the finished surface. The presence of snow and ice should be avoided in both the subgrade and the fill material, so they can be manipulated and compacted. Melting of ice blocks or snow located under the GCR may result in the creation of cavities which could generate strain in the geosynthetics.

The choice of construction equipment – notably its ground pressure and total weight – must be selected considering the higher risk of damaging the layers.

Specific subgrade acceptance requirements may vary with the type and properties of the GBR selected for a given project, as well as with the type of protection layer used, if any. Hence, installation guidelines provided by the selected GBR manufacturer must be consulted when developing acceptance criteria for the subgrade.

If it is not possible to prepare the subgrade to the specifications, the GBR cannot be installed without adjustment to either the subgrade, or the design of the project. Examples of possible measures include:

- For large discontinuities (e.g., roller edges, ruts, etc): addition of a thin layer of dry, fine-grained soil.
- For minor discontinuities, increase of the efficiency of the protection layer, for example by adding a GBR-C under the GBR-P, or a geotextile under the GBR-C.

Should additional protection layers be considered, their impact on the structure must be assessed, e.g., on slope stability / global safety. As example, for systems designed as composite lining systems where the GBR-P or GBR-B must be installed in direct contact with a low permeability subgrade

(GBR-C or compacted clay liner), the high in-plane flow capacity of a thick geotextile makes it not suitable for installation between the GBR and the substrate. For these designs, only GBR-C can be used as protection layers.

Construction and quality assurance activities should be planned to ensure that a prepared surface can be covered the same day with the next layer, to minimize the risk of accumulation of snow in a region which is still to be covered. This recommendation applies to all layers: subgrade, GBRs (after welding) and any other layer, until the last layer is installed (mineral backfill or GBR for exposed applications).

If it is not possible to finish the installation of every layer in a region, this region should be protected from snow and rain. If snow or ice accumulate on a prepared surface before installation of the GBR, their removal is determined on a project-by-project basis.

Removing snow may accidentally create substantial damage to a substrate. The decision to remove a small thickness of freshly fallen snow from a previously approved substrate should therefore be carefully considered. This decision should be taken by the QA Engineer in consultation with the designer, considering the thickness and quantity of snow, complexity of removal, weather forecast, type of subgrade, potential effects of snow confined under the GBR and other project-specific considerations.

2.4 Deployment

Given the additional stiffness caused by the lower temperature, geosynthetics may require more effort to unroll. Their lay-flat ability may also not be as good as under milder environmental conditions. They may therefore be more susceptible to wind uplift, offering more air access to the underside of the membrane. Ballasting strategy should therefore be adapted, i.e., more bags should be considered to ensure the materials are adequately laid.

The temperature of GBR-P and GBR-B still in a roll does not follow the air temperature beyond the first few wraps, given their thermal inertia and relatively low thermal conductivity. Significant thermal contraction of GBR-P may take place immediately after the material is laid. Some time should therefore be given to allow the GBR to reach temperature equilibrium before welding, usually one to a few hours depending on the material.

Removal of snow from a large surface of GBR is virtually impossible without damaging the product. The construction schedule should therefore favour installation of all superposed layers, instead of finalizing the installation of one layer before installing the next one. This aspect may affect the quality management strategy, as discussed in a later section.

Before starting to deploy the GBR, agreement must be reached with the contractor in charge of backfilling regarding the management of granular materials, considering the necessity to cover the geosynthetic materials rapidly after installation of the last geosynthetic layer. Thick layers of soil (500 mm to 1000 mm, see 3.1.2.e) must be planned for circulation of vehicles, and materials must be stockpiled at close distance to facilitate quick backfilling.

2.5 Assembly

2.5.1 Overlap between rolls (GBR-C)

GBR-C are overlapped, not welded, and there are no specific requirements applicable to winter installation. Bentonite is poured between the two overlapping rolls to ensure the continuity of the sealing from one roll to the next. The minimum overlap is 300 mm. The quantity of bentonite applied is typically 0.4 kg per linear meter.

2.5.2 General considerations

A good seam will offer a long-lasting continuity between the panels, capable of withstanding the same service conditions as the sheet itself and of ensuring a sealing function similar to, or better than the sheet itself.

The quality of thermal welds is determined by the amount of energy received by the sheet during the welding operation. It is affected by the exterior temperature and by the specific properties of the material being welded, in particular the type and grade of polymer, type and quantity of additives, as well as the thickness and finish of the sheet (texture, colour, electrical conductivity skin). The welding parameters used, i.e., temperature, speed, and pressure, must therefore be adjusted to deliver the exact amount of energy that will ensure the melting of a thin layer of the surface of the interfacing geomembranes. These two melted surfaces are then pressed together to permit the interpenetration of the polyethylene molecules from both sheets and to allow them to recrystallize to form a continuous structure.

The quality of the seam greatly depends on the selection of the three welding parameters. It is common to describe this by referring to the 'welding bubble' illustrated in Figure 2.4: a good seam will be created only when the coordinates of the welding parameters (temperature, speed, pressure) are within the boundaries of this bubble.

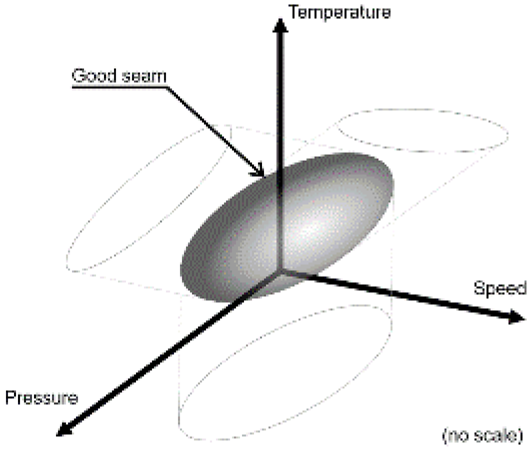


Figure 2.4: three-dimensional welding parameters bubble leading to good seams

Selection of welding parameters within this 'bubble' should also be made considering the risk of change of environmental conditions during the forthcoming shift. For example, if the air temperature is expected to decrease, or clouds to appear, the speed should be set at the lower end of the bubble, so that the energy supplied to the welded region remains sufficient despite a cooling down of the sheet.

When welding below the freezing point, it is commonly accepted that best results are achieved by maintaining a similar welding temperature and roller pressure to that which would be used in milder conditions but using a reduced welding speed. Increasing temperature may overheat the polymer, induce oxidation or even molecular chain scission, and could favour the development of cracking.

Ambient humidity may also affect the quality of the weld, when condensation or frost deposition takes place in the region to be welded. To avoid such risk, welding GBR-P or GBR-B should only be conducted when the temperature of the sheet is less than 3°C higher than the dew point (above 0°C), or frost point (below 0°C).

Remark: Some regions have adopted more stringent requirements, limiting welding to temperatures above 8°C and 3°C above the dew point under DVS 2225-1 to -6 and DVS 2227-1.

2.5.3 Thermal welding (GBR-P)

Adequate welding of GBR-P requires the following preparation:

- The surfaces to be welded must be dry and free of dirt or any contamination.
- The lower surface of the bottom layer must be free of ice, to avoid slipping of the drive wheels of the welder.

Various strategies can be considered to control the condition of the surface to be welded and the environmental conditions, including the application of moderate heat followed by wiping-off of the surface (Figure 2.5). The use of movable tents can be considered in order to reduce the influence of wind and stabilize the temperature in the region of interest (Figure 2.6).

Figure 2.5: Controlling cleanliness of both sides of the geomembrane being welded together (photo courtesy of A&A Technical Services)

Figure 2.6: Use of tents to control environmental conditions and reduce humidity around a seam (photo courtesy of A&A Technical Services)

GRI Test Method GM9 provides guidance on the seaming of GBR-P. As a general rule, welding in a cold environment will use temperature settings similar to welding at higher ambient conditions but the use of a reduced speed.

> The following paragraphs correspond to the reproduction with permission of the guidance on seaming of GBR-P of GM9.

1. Preparation of the geomembrane surfaces to be seamed:

a) Seaming is not to take place when it is snowing, sleeting or hailing on the geomembrane in the area to be seamed.

b) In the area to be seamed, all frost must be removed from the opposing surfaces of the geomembrane sheets in the regions where the actual seaming is to be performed.

c) The residual moisture left after removing frost must be wiped dry.

Note 1: Perhaps the most difficult surfaces to prepare in this regard are textured geomembranes where the texturing extends to the roll edges or roll ends.

d) The application of heat to remove moisture using a handheld hot air device can be used providing care against excessive heat application is taken. An assessment using trial seams is recommended.

e) The specific area to be seamed must be free of soil particles and other foreign matter.

f) For thermal fusion welding, such as the hot wedge method, the underside of the lower sheet should be free of frost so that the lower drive wheels of the device can move evenly and do not slip.

Note 2: It may be necessary to use a rub sheet beneath the area being seamed to separate the geomembrane from frozen soil subgrade. Various materials have been used for rub sheets including smooth membranes, smooth films and even certain types of geotextiles.

g) For fillet extrusion welding the thermal tacking of the sheets together should proceed as with similar welding at temperatures above freezing.

h) Preheating of the geomembrane area to be seamed is common but the amount of preheat and its timing preceding the actual production seaming is at the option of the installer based upon past practice and experience. An assessment using trial seams is recommended.

2. Thermal fusion seaming (e.g., using a hot wedge welding device):

a) In general, the rate of seaming, i.e., the speed of the hot wedge device, is usually slower than when seaming at temperatures above 0°C. Furthermore, the rate should decrease with decreasing sheet temperature.

b) Cold temperature seaming requires more frequent trial seams than when welding at temperatures above freezing. For example, if the CQA plan calls for two trial seams a day at temperatures above freezing, the number should be increased by one per day for each 7.5°C less than freezing. Trial seams should be made at the discretion of the CQA Engineer.

c) *Cold temperature seaming may also require more destructive tests on production seams than when welding above freezing. For example, in addition to the CQA plan written around above freezing temperatures, additional destructive seam samples may be taken at the end(s) of each continuous production seams.*

Note 3: The actual schedule for destructive test samples is at the discretion of the CQA Engineer.

d) *Movable enclosures (i.e., tents) traveling along with the welding device and personnel are particularly effective at sites with high wind. Cold temperature, per se, will not demand the use of protective tents. The decision to use tents is that of the installer and CQC personnel.*

3. Extrusion fillet seaming:

a) *The necessary grinding of the geomembrane surfaces in preparation of placing extrudate should be no further ahead of the extrusion gun than 10 m (30 ft.), or as stated in the CQA plan.*

b) *At the discretion of the parties involved, the profile of the base of the extrusion gun barrel is often shaped more rectangularly than when seaming at temperatures above freezing. The reason for this is to minimize the cooling rate in the thinner extrudate regions, see Figure 9.*

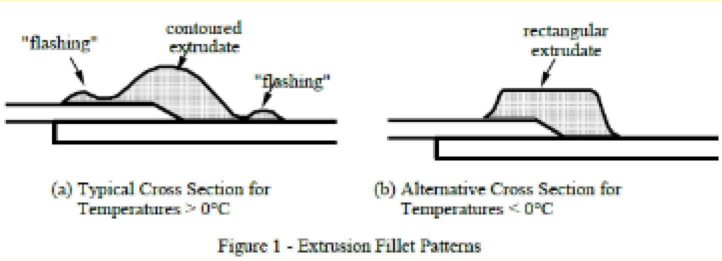


Figure 4: Extrusion Fillet Patterns

c) *In general, the rate of seaming, i.e., the speed of travel, is slower than when seaming at temperatures above 0°. Furthermore, the rate should decrease with decreasing sheet temperatures.*

d) *Cold temperature seaming requires more frequent trial seams than when welding at temperatures above freezing. For example, if the CQA plan calls for two trial seams a day at temperatures above freezing, the number should be increased by one per day for each 7.5°C less than freezing. Trial seams should be made at the discretion of the CQA Engineer.*

e) *Cold temperature seaming may also require more destructive tests on production seams than when welding above freezing. For example, in addition to the CQA plan written around above freezing temperatures, additional destructive seam samples may be taken at the end(s) of each continuous production seam.*

Note 4: The actual schedule for destructive test samples is at the discretion of the CQA Engineer.

f) Movable enclosures (i.e., tents) traveling along with the welding device and personnel are particularly effective at sites with high wind. Cold temperature, per se, will not demand the use of protective tents. The decision to use tents is that of the installer and CQC personnel.

2.5.4 Thermal welding (GBR-B)

In general, the concept of a 'welding bubble' introduced in 2.5.2 applies to GBR-B as well as to GBR-P. GBR-B are typically welded using a torch, and sometimes hot air. When using a torch, the welding parameters are poorly controlled due to an entirely manual operation, while the use of hot-air welders gives a better control of the welding parameters. Welding of a GBR-B essentially consists of melting the bitumen of the two surfaces which are to be assembled over a width of 200 millimetres and pressing them together using a metal roller. A good weld should be continuous across the entire 200 mm width and should exhibit a small bead of bitumen, up to a maximum of 30 mm, which has flowed out of the edge of the roll. When the welding process of GBR-B is not mechanized, the quality of the seam heavily depends on the experience of the welding technician.

Two winter-specific factors can affect the quality of the seams between panels of bituminous geomembrane:

- Bituminous geomembranes require a flat subgrade to permit application of a pressure using a metal roller (the pressure being one of the three welding parameters that must be controlled). The quality of preparation of the subgrade in a cold environment can therefore affect the quality of the seams.
- When torch welding is used, the quality of the seam depends entirely on the skills of the welding technician, who must manually control the amount of heat generated by the torch blower and the speed at which the weld is performed. When the temperature of the sheet decreases, welding requires much more heat, which increases the risk of overheating the bitumen, and hence its liquefaction and flowing away from the membrane, which could affect the sealing properties of the geomembrane. An excessive loss of bitumen (in excess of 30 mm) can be visually observed on the upper side of the welded geomembrane, but not on the lower side.

Hence, welding of GBR-B should only be performed by technicians designated and trained by the manufacturer according to predefined methods (e.g., ultrasonic testing acc. ASTM D7006).

2.5.5 Backfilling

Backfilling is not part of the scope of work of the GBR installer, but it represents a highly critical task with respect to the integrity of the lining system. Only aggregates with a very small amount of fines (ideally with no particles less than 75 µm) should be used as backfill, to ensure that entrapped water cannot freeze and generate an apparent cohesion in the soil or create large blocks highly likely to damage the geosynthetic during backfilling. When a small percentage of fines is present in the backfilled material, a cushioning layer must be selected to resist impact and improve hydrostatic puncture resistance arising from the contact with this coarse aggregate. The maximum particle size of the backfill must be defined according to section 1.2..

Before backfilling, the geomembrane must be secured against wind uplift, and this is typically achieved using sandbags or other moveable weights not liable to damage the GBR – e.g., the rolls of geosynthetics themselves. However fine sand must be replaced by pea gravel to avoid creation of hard blocks of frozen sand under freezing temperatures.

3 Quality control (aspects related to sealing applications)

3.1 Quality assurance strategy

The risk of a leaking GBR is much higher during winter because of a combination of harsher environmental conditions, stiffer materials, and human factors. Consequently, stringent quality control and quality assurance programs must be followed. On the other hand, implementation of these controls should not affect the schedule of work, e.g., certification of the subgrades or of each individual layer (for multi-layered systems) must be done immediately after their installation to avoid delays and the likelihood that the site will be covered by snow before completion of a given region (Figure 3.1).

To permit this:

- A quality assurance inspector must be on site at all times.
- Testing of the seams must be performed on-site on the same day, under the supervision of a third party (i.e., the QA Inspector) in full conformance with the test method, i.e., under controlled environmental conditions and after complete cooling of the seam, typically a few hours.
- The QA inspector present on site at all times must have the authority to approve the subgrade and the installed layers immediately.

Figure 3.1: Example of GBR covered by a 500 mm snowfall before completing installation (Courtesy FC Geosynthetics)

3.2 Conformance testing of geosynthetic materials

To avoid delays caused by conformance testing for weather-sensitive and therefore time-sensitive construction schedules, quality control of the materials should be completed before the rolls are delivered to the site. This may be achieved using one of the two following methods:

- Sampling the products in the plant or distributor's storage location and testing sufficiently ahead of time to permit installation immediately after reception of the material on-site. The sampling activity must then be coordinated with the manufacturer before the production is initiated.
- Using products holding an appropriate certification involving third-party testing, when available.

3.3 CQA Report – GBR-P seams

GRI Test Method GM9 provides guidance on Quality Assurance, reproduced below with permission.

- The report should include hourly temperatures during cold weather seaming which include the actual temperature of the surface of the geomembrane (using a pyrometer) and the ambient air temperature measured approximately 1 m (3 ft.) above the geomembrane.
- The method of removing frost from the area to be seamed (if any is present), as well as drying and cleaning of the surfaces involved, should be described.
- The condition of the subgrade beneath the area being seamed should be assessed. If a rub sheet is used during the seaming process, this should be noted.
- Complete identification of the field seaming system used, including material, methods, preheat, seaming rate, use of tents or enclosures and other details of the procedure should be documented.
- The type, nature, number, condition, and details of trial seams, as well as the results of such tests, should be detailed.
- The type, nature, number and details of destructive samples and disposition of sections of the sample should be described. Proper identification is required to identify results of CQA laboratory testing in the final as-built plans of the project.
- Any unusual condition with respect to personnel, equipment, sampling and/or testing that may be attributable to the cold weather should be described and documented.

3.4 Electrical leak location of GBR-P and GBR-B

Considering the higher risk of damage, electrical leak location (ELL) should be part of the acceptance strategy for the project. However, frozen soils exhibit an electrical conductivity typically much lower than unfrozen soils, which limits the use of ELL to time periods where the temperature of the lining system is above freezing temperature. A temperature below freezing brings several challenges:

- Testing exposed GBR can only be performed using a spark test, with the condition that an electrically conductive layer is available below the GBR: either a conductive layer co-extruded to the GBR, or a conductive geotextile laid under the GBR. Feasibility of spark testing may be affected by the presence of snow or ice of the surface of the GBR, sometimes requiring laborious surface preparation.
- Leak detection after backfilling, using the dipole method, can only be performed when environmental conditions permit. This may be as soon as the cover soil is defrosted, when a conductive layer is available under the GBR-P; or as soon as both the cover soil and the subgrade are defrosted when electrical leak location relies solely on the electrical conductivity of the soils.

4 STATUS OF EXISTING INFORMATION ON INSTALLATION REQUIREMENTS FOR SEALING PRODUCTS (GBR-P, GBR-B AND GBR-C) UNDER NORDIC CONDITIONS: KEY CONCLUSIONS

4.1 Sealing requirements on service conditions

The service conditions will contribute to the definition of performance criteria applicable to the selection of an adequate lining system. Three classes of service were defined. Each of them reflects a type of stress that may affect the selection of the geosynthetic barrier, and/or that may be mitigated by implementing particular measures during transportation / storage, installation, and backfilling:

- <u>Class 1 – Exposed applications</u>, where the geosynthetic barrier system is intended to be left permanently exposed in a Nordic region, therefore experiencing extreme temperatures, temperature cycles, ice and snow but may NOT be confined while in service.
- <u>Class 2 – Shallow cover</u>, where the geosynthetic barrier is intended to be permanently covered by a shallow layer of soil providing a uniformly distributed or almost uniformly distributed (in some cases the fill cover may change from 300 mm to e.g., 700mm etc.) confining stress on the geosynthetic barrier or lining system but will still experience almost similar freeze / thaw conditions as for Class 1.
- <u>Class 3 – Fully covered applications</u>, where the geosynthetic barrier is intended to be covered by a thick layer of soil (or confining material) and will therefore not be exposed to extreme environmental conditions once the project is completed.

Requirements for Class 1 are more stringent than for Class 2, which are also more stringent than for Class 3.

4.2 Sealing requirements on geosynthetic properties

The GBR properties are selected to make sure the product will survive installation and perform as requested during its entire service life. The issues to consider when selecting a geosynthetic barrier that will be installed under freezing temperatures are:

a) The GBR must preserve its integrity during transportation and storage.
b) It must be possible to unroll the GBR in place under freezing temperatures, on a frozen soil subgrade, without damaging it.
c) Worker safety must not be affected by a behaviour of the GBR.
d) Welding of GBR-P or GBR-B to assemble panels or to repair a tear must be possible under the anticipated environmental conditions.
e) The GBR must not be affected by the installation of the next layer, such as the soil cover (when applicable).
f) The long-term performance of the GBR must not be affected by the installation process.
g) The (installed) GBR must exhibit adequate long-term properties when exposed to cold temperature during service.

When a product cannot meet one of these requirements, it is sometimes possible to modify the installation process or require that installation is made under less problematic environmental conditions, and/or to modify the design of the structure to minimize exposure of the product.

Note: requirements on installation procedure for all geosynthetics shall also be applied (see 4.3)

4.3 Requirements on installation procedure for all types of geosynthetics

The successful installation and long-term performance of a project using geosynthetics will be affected by project management and the quality of coordination between the installer, earthwork contractor and general contractor. Example of factors affecting the quality of installation include:

- Management of storage conditions and on-site handling of the products.
- Timely response at every stage of the project, and in particular for subgrade approval and authorization to cover the geosynthetics.

1 REFERENCES

Standards & Guidelines

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2 ANNEXES

APPENDIX A – Summary of the requirements applicable to GBR-P, GBR-B and GBR-C

The requirements identified in this project are summarized in the following Tables:

- Table A1: polymeric geosynthetic barriers GBR-P;
- Table A2: bituminous geosynthetic barriers GBR-B;
- Table A3: clay geosynthetic barriers GBR-C.

Table A1 – Requirements applicable to GBR-P

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
criterion 'a' – integrity of the GBR-P during transportation and storage				
Cores	The cores must be insensitive to water	Mandatory		
criterion 'b' – unrolling and placement, for GBR-P				
Lay-flat properties	$E_T/E_{23°C} \leq \sim 2$	Recommended (1) (2)		
Offer an overall better mechanical resistance	Thickness > 1.5 mm (3)	Recommended (4)		
criterion 'c' – properties influencing worker safety				
Preferred material features	Textured / non-slip surface facing up	Mandatory	(5)	
criterion 'd' – assembly and repair of geosynthetic barriers				
Preferred material features	Smooth edges	Recommended		
	Lower crystallinity of resin (LLDPE preferred to HDPE)	Recommended		
Thickness	Thickness > 1.5 mm	Recommended (6)		
criterion 'e' – installation of soil cover				
Gravel puncture during installation	Increase the mass per unit area of the geotextile cushion by 1.5x to 2x the calculated value, and at least 500 g/m²	Not applicable	Recommended	
criterion 'f' – effect of installation on long-term properties				
Low temperature flexibility	$T_{Flex} \leq T_{installation}$ (7)	Recommended		
criterion 'g' – long-term exposure to cold temperature				
Low temperature flexibility	$T_{Flex} \leq T_{service}$ (7)	Mandatory	Recommended	N/A (9)
Preferred material feature	Textured / non-slip surface facing soil	Recommended	Preferred	
Minimize sensitivity to slow crack growth and rapid crack propagation	Prefer LLDPE to HDPE	Recommended (8)		
General design consideration, e.g.: wind uplift, impact resistance, etc.	Include effects of a stiffened material in the design methods	Recommended		

(1): proposal made in absence of supporting literature.

(2): store the product at a sufficiently high temperature, install and cover the GBR when environmental conditions are favourable. The anticipated temperature of the liner once covered should not be lower than the low-temperature flexibility.

(3): this requirement mainly applies to HDPE and LLDPE.

(4): may be avoided with extremely cautious installation.

(5): using a textured / non-slippery material may be considered to improve worker safety if no other measure is taken; nevertheless, it may have an impact on the ease of welding on textured regions of the GBR and it should be considered a compromise.

(6): Using thinner products is possible but increases the risk of problems during welding or at a later date.

(7): The criterion is also applicable to the lamination/coating of GBR-C, when used.

(8): the risk of cracking is a combination of factors, which includes the material sensitivity to cracking as well as aspects related to the design and quality of installation.

(9): Class 3 is not exposed to low temperature after installation.

Table A2 – Requirements applicable to GBR-B

	Criterion	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
criterion 'a' – integrity of the GBR-P during transportation and storage				
Cores	The cores must be insensitive to water	Mandatory		
criterion 'b' – unrolling and placement, for GBR-P				
Lay-flat properties	$E_T/E_{23°C} \leq \sim 2$	Recommended (1) (2)		
Offer an overall better mechanical resistance	Thickness > 4.0 mm	Recommended (3)		
criterion 'c' – properties influencing worker safety				
Preferred material features	Textured / non-slip surface facing up	Mandatory	(4)	
criterion 'd' – assembly and repair of geosynthetic barriers				
Thickness	Thickness > 4.0 mm	Recommended (5)		
criterion 'e' – installation of soil cover				
Gravel puncture during installation	Increase the mass per unit area of the geotextile cushion by 1.5x to 2x the calculated value, and at least 500 g/m²	Not applicable	Recommended	
criterion 'f' – effect of installation on long-term properties				
Low temperature flexibility	$T_{Flex} \leq T_{installation}$	Recommended		
criterion 'g' – long-term exposure to cold temperature				
Low temperature flexibility	$T_{Flex} \leq T_{service}$	Mandatory	Recommended	N/A (6)
Preferred material feature	Textured / non-slip surface facing soil	Recommended	Preferred	
General design consideration, e.g.: wind uplift, impact resistance, etc.	Include effects of a stiffened material in the design methods	Recommended		

(1): proposal made in absence of supporting literature

(2): store the product at a sufficiently high temperature, install and cover the GBR when environmental conditions are favourable. The anticipated temperature of the liner once covered should not be lower than the low-temperature flexibility.

(3): may be avoided with extremely cautious installation.

(4): using a textured / non-slippery material may be considered to improve worker safety if no other measure is taken; nevertheless, it may have an impact on the ease of welding on textured regions of the GBR and it should be considered a compromise.

(5): Using thinner products is possible but increases the risk of problems during welding or at a later date.

(6): Class 3 is not exposed to low temperature after installation.

Table A3 – Requirements applicable to GBR-C

	Criteria	Class 1 (exposed)	Class 2 (shallow cover)	Class 3 (fully covered)
criterion 'a' – integrity of the GBR during transportation and storage				
Packaging	Water-sensitive GBR must be wrapped in adequate watertight wrapping	Preferred (1)		
Cores	The cores must be insensitive to water	Mandatory		
criterion 'b' – unrolling and placement, for GBR-C				
Lay-flat properties	Water content < 35% (2)	N/A (3)	Preferred, or (4)	
Prevent excessive moisture uptake during installation on icy, snowy, or damp soils	Use of laminated/coated GBR-C (5)		Recommended (6)	
Improve cushioning properties	minimum weight of the geotextile components: 200 g/m² nonwoven + 100 g/m² woven		Recommended (7)	
Resist mechanical stress	Strength at break: >10 kN/m		Recommended (7)	
Preserve dimensional stability during installation	Elongation at first peak (%): <30%		Recommended (7)	
criterion 'c' – properties influencing worker's safety.				
Preferred material features (this applies to coated/laminated GCL)	Textured / non-slip surface facing up	N/A (3)	Preferred	
criterion 'd' – assembly and repair of geosynthetic barriers				
(Not applicable to GBR-C)				
criterion 'e' – installation of soil cover (GBR-C)				
Gravel puncture during installation	1 - well graded particle size distribution 2 - d_{100} of the soil in contact with the GBR-C: Angular or sub-angular particles: $d_{100} \leq 16$ mm - Rounded or sub-rounded particles: $d_{100} \leq 31.5$ mm	Recommended		
criterion 'f' – effect of installation on long-term properties				
Low temperature flexibility of the coating or laminated film, when applicable	$T_{Flex} \leq T_{installation}$	Recommended		
criterion 'g' – long-term exposure to cold temperature				
Prevent accidental swelling	Never leave the GBR-C exposed overnight	N/A (3)	Mandatory	
Prevent dehydration if continuously exposed to freezing temperatures	Install a GBR-P above the GBR-C	Mandatory (3)	Recommended (8)	

(1) Use of other wrapping materials, such as cling wrap, may be considered if transportation and storage are adapted, e.g., transportation in closed trailers, onsite storage avoiding contact with snow or rain, and delaying distribution to the final location as much as possible.

(2): in case of very exposed critical conditions (e.g. truck-bed without protection) certain installers recommend a lower value of the water content (e.g., ÖNORM S 2081).

(3): GBR-C cannot be left exposed.

(4): store the product at a temperature greater than 0°C, install and cover when no frost is expected until all layers and the soil backfill is completed.

(5): laminated/coated GBR-C includes a film of polymer on one side of the product.

(6): this recommendation applies essentially to subgrades which are difficult to compact and exhibit a high content of frozen water. It may be avoided if no excessive moisture is anticipated in the subgrade or when a soil cover is installed within hours after laying the GBR-C.

(7): may be avoided with extremely cautious installation.

(8): GBR-C/GBR-P composites or laminated/coated GBR-C with the lamination/coating side up may be considered.

APPENDIX B - Concept for design of a cushioning geotextile using a test performed at room temperature.

Figure A.1: Point load caused by a gravel on the GBR. To be able to project this performance at low temperature, these tests should be performed considering a 'soil' replicated to model the anticipated properties of the frozen subgrade, and performance requirements adapted to consider the change in intrinsic properties of the geosynthetic barrier, i.e., its multiaxial elongation (EN 14151, DIN 61551 or ASTM D5617, using a diameter of at least 500 mm), which may be significantly lower at low temperature than at room temperature.

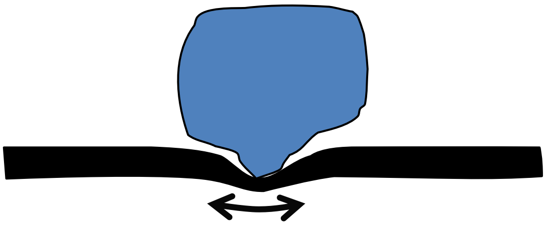

Figure B.1: Point load caused by a particle on the GBR.

Considering the difficulties associated with modelling, then performing such a test, a simplified approach may be to use design requirements used in local practice, but to consider as inputs modified soil properties, service load and performance criteria as proposed here, for GBR-P:

- Apparent particle size: the value selected should be larger than the actual particle size to account for the presence of frozen soils. This should be estimated considering the properties of the frozen soil, i.e., the particle size distribution, water content and likelihood of observing frozen agglomerates.
- Service load: the value selected should be determined considering the ground pressure of the equipment circulating on the soil cover and the thickness of the soil cover. For a cover soil thickness of 500 mm, the ground pressure of the equipment should be used directly. For a cover soil thickness greater than 500 mm, the load considered should be calculated considering the soil thickness minus 500 mm, to account for potential formation of frozen blocks in the soil cover. A minimum cover soil thickness of 500 mm is often recommended to allow circulation of low ground pressure equipment, or 1000 mm for tyre-equipped vehicles.
- The performance criteria should be based on local design practice, i.e., maximum arch elongation, no yield deformation or other. However, considering the influence of the temperature on elongation at yield, it is reasonable to modify this criterion by reducing the permissible elongation of the geosynthetic barrier by a factor A_T defined in Equation 3.

$$A_T = \frac{\varepsilon_{23°C}}{\varepsilon_T} \qquad (1)$$

Where:

- A_T: reduction factor for frozen condition
- ε_T: elongation at yield measured at the anticipated installation temperature.
- $\varepsilon_{23°C}$: elongation at yield measured at 23°C.

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