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Moisture control strategies of habitable basements in cold climates

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ABSTRACT

In many countries with a cold climate, basements are used as dwellings. This presents a major challenge concerning moisture safety design. Climate change is expected to increase the risk of moisture-related damage in basements owing to increasing amounts of stormwater, annual precipitation, and annual temperatures. This study examines the primary moisture control strategies for habitable basements in western cold climate countries by identifying the main differences and similarities in national building recommendations for new buildings. Using Norwegian design guides as a baseline, we identified ten key challenges and compared them with four other cold climate countries' recommendations given by experts in the field of building physics (building science). The results showed that other countries' recommendations differ from those of Norway in various key challenges. However, similar but varying recommendations pertaining to ground surface slopes, drainage layers, drainage pipes, capillary breaking layers in floors, avoiding thermal bridges, airtightness, and ventilation were noted. The key differences pertained to the exterior damp proofing of walls, use and position of dimpled membranes and vapour barriers, and use of permeable thermal insulation. The outcome is that countries emphasize the ten key challenges differently. Although the recommendations have many similarities, the weighting (or prioritizing) distinguishes the five countries' moisture control strategies.

1. Introduction

Moisture control is a fundamental aspect of building design; it involves avoiding the damage caused by moisture and the decay and extra heat loss caused by wet materials. Most importantly, it aims to ensure occupants' health and comfort.

Climate change scenarios predict more frequent and more intense precipitation events with heavy rainfall and rainfall-induced floods in many geographical regions with cold climates [1]. Precipitation during the year might also be distributed differently compared to the current situation. To endure increasing amounts of stormwater alongside the increasing annual precipitation, buildings must be adapted to these loads.

Habitable basements can provide many advantages, e.g., reduced heating- and cooling-demands, maximizing the main living area and providing increased weather protection at exposed sites. In Norway, especially in densely populated areas, utilizing basements for more than just storage is desirable. Moisture-related damages, however, are a major challenge in basements, and likely to increase with climate change [2]. The risk is associated with the increasing amounts of stormwater alongside the increasing annual precipitation and annual temperatures. In many municipalities in Norway, restrictions have also been introduced on roof water runoff, meaning that water no longer can be carried to the municipal stormwater grid, but should be infiltrated/delayed on site.

Norwegian recommendations for moisture control in habitable basements are provided in the SINTEF Building Research Design Guides [3]. They comply with the performance-based requirements in the Norwegian building code [4] and are an important reference to documented solutions in the technical regulations. The design guides adapt experience and results from practice and research into practical benefits to the construction industry. However, due to both increasing moisture

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loads and increasing insulation thicknesses in basements, new knowledge, methods, and tools are needed to substantiate and improve current recommendations. These design guides constitute the baseline for an international comparison of cold climate strategies for habitable basements.

The aim of this study is to provide an overview of main moisture control strategies for habitable basements in cold climate countries, investigate differences and identify main learning potential.

The study includes: (1) recommendations for moisture control in habitable (heated) basements in new buildings above the groundwater level, (2) recommendations for the terrain surface next to the building, (3) recommendations for exterior drainage (drainage outside basement walls, floor or foundation), (4) recommendations for thermal insulation, airtightness, damp proofing and moisture protection of walls, floor and the transition in-between and (5) recommendations for the ventilation of indoor air in the basement (as this affects the moisture conditions in the basement envelope). More specifically, ten centres of interest have been identified throughout this research, see Table 1.

To address these general inquiries, the following research questions are raised:

1. Using Norwegian guidelines as a baseline, how do the western cold climate countries building recommendations differ with regard to habitable basements?
2. What main differences and similarities can be identified?
3. What main learning potential can be identified?

1.1. Limitations

Given the extent of the research field, certain limitations are determined. We do not address: (1) recommendations for rehabilitation, refurbishment, and restoration, (2) recommendations for structures exposed to permanent water pressure, (3) recommendations for interior walls and intermediate floors, (4) recommendations for interior lining (aesthetic recommendations) beyond what concerns the moisture protection/air sealing as this affects the moisture protection, (5) recommendations for excavation, ground stabilization and other groundwork outside the draining layer and (6) recommendations concerning the structural elements beyond what concerns the moisture conditions, i.e. the elements normally contain moisture that must be able to dry inwards, outwards or both.

The main national recommendations for habitable basements provided in Appendix A-E are independent of the design of the structural elements unless otherwise specified in the tables. Figs. 5–9 illustrates how basements can be designed to meet the national recommendations, hence the structural elements in these figures are just one of several different solutions.

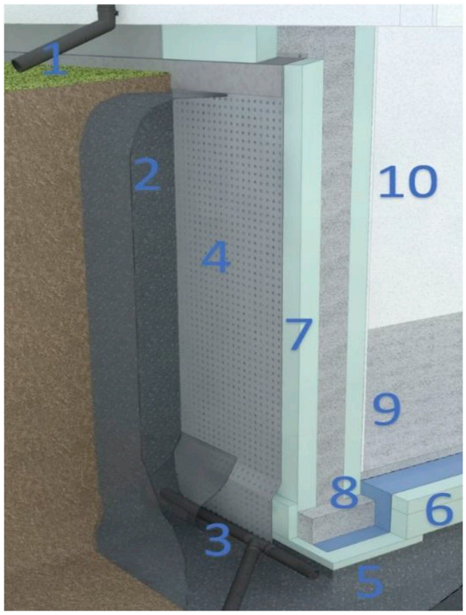
2. Theoretical framework

The main focus of this chapter is to establish an understanding of moisture control strategies for habitable basements in cold climates based on international research. Arriving at such an understanding is not a straightforward task because:

- recommendations for basements vary according to several factors, e.g. local building practice, local climate, local ground conditions, national regulations, material availability, and economy.
- the basement envelope system consists of several elements that separate the indoors from the outdoor environment, both above and below grade, e.g. basement walls (both above and below ground), basement floor slab, joints, intersections, and drainage.
- the basement envelope elements consist of several sub-systems, materials, and components that have many different and sometimes contradicting performance requirements to fulfil.

Table 1
International research sorted on the ten key challenges for habitable basements.

Key challenges	International research for habitable basements
1. Water from rain and snowmelt	- Roof drainage systems [14] (ch. 1, p. 34–35) - Site drainage [14] (p. 28–31) - Site grading [5] (ch. 4.1) [15], (ch. 4.1.1.2) - Infiltration [15] (ch. 4.1.1.3) [16], - Modelling of stormwater management [17] - Flood protection [18]
2. Water pressure on exterior walls below the ground	- Drainage [15] (ch. 4.1.1.4) - Draining backfill [19] - Draining insulation [19] - Moisture in drainage layers [20] - Foundation drainage [14] (ch. 1, p. 34–35)
3. Water pressure against the construction from raising of groundwater	- Drain pipes [15] (4.1.1.4) - Ground conditions [19,21] - Water content distribution beneath building foundations [22] - Flood Risk Associated with Basement Drainage [23]
4. Water from the terrain surface or from the ground that reaches the surface of the wall	- Capillary breaking layer, wall [15] (ch.4.1.3.5) - Draining insulation [15] (ch. 4.1.3.5) [24], - Drainage and Capillary Rise in Glass Fibre Insulation [25] - Moisture transfer [26] (ch. 2.4) - Vapour transfer [26] (ch. 2.3)
5. Capillary rise of moisture from the ground through the floor and foundations	- Capillary breaking layer, floor [15] (4.1.1.5) - Moisture transfer [26] (ch. 2.4) - Soil material properties [19] - Capillary rise in concrete floors [27]
6. Transfer of water vapour from the ground through the floor	- Vapour barrier, floor [15] (3.4.1 and 4.1.2.1) - Heat, air, and moisture conditions of slab-on-ground [28] - Vapour transfer [26] (ch. 2.3) - Thermal performance [10,29,30]
7. Moisture condensation on, and drying capacity of the basement walls	- Thermal insulation below grade [15, 31–34] (ch.4.1.3) - Basement Condensation [14] (p. 34–35) - Moisture transfer [26] (ch. 2.4) - Moisture diffusion [35] - Coupled heat and moisture transfer [36] - Moisture/air/vapour/soli gas barrier/retarders [5] (ch. 2.7 & 2.8.) - Surface condensation and drying [26] (ch. 2.3.6.3.) - Heat and moisture flow in soil [37]
8. Thermal bridges	- Dynamic modelling of thermal bridges - Thermal bridges [26] (ch. 1.2.3.4 & 1.5.4) [38], (ch. 3.4.1.) - Performance of Rigid Polystyrene Foam Insulation [39]
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor)	- Radon barriers [40] - Radon and moisture infiltration [15, 15] (ch. 4.1.1.7) - Air transfer [26], (ch. 2.2) - Air transfer through the building envelope [38] (ch. 4.2.) - Factors influencing airtightness and airtightness modelling (review) [41] - Dynamic wall system [42] - Radon transport [43,44]
10. High indoor moisture supply from cloth drying, cooking, showering.	- Ventilation of a building [38] (ch. 4.3.) [45], - Ventilation strategies [46,47] - Indoor moisture supply [48,49] - Moisture supply [50,51]



1. Water from rain and snowmelt (including down-pipes).
2. Water pressure on exterior walls below the ground.
3. Water pressure against the construction from a rise of groundwater.
4. Water from the terrain surface or from the ground that reaches the surface of the wall.
5. Capillary rise of moisture from the ground through the floor and foundations.
6. Transfer of water vapour from the ground through the floor
7. Moisture condensation on, and drying capacity of, the basement walls.
8. Thermal bridges.
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor).
10. High indoor moisture supply from cloth drying, cooking, showering etc.

Fig. 1. Key challenges in habitable basements.

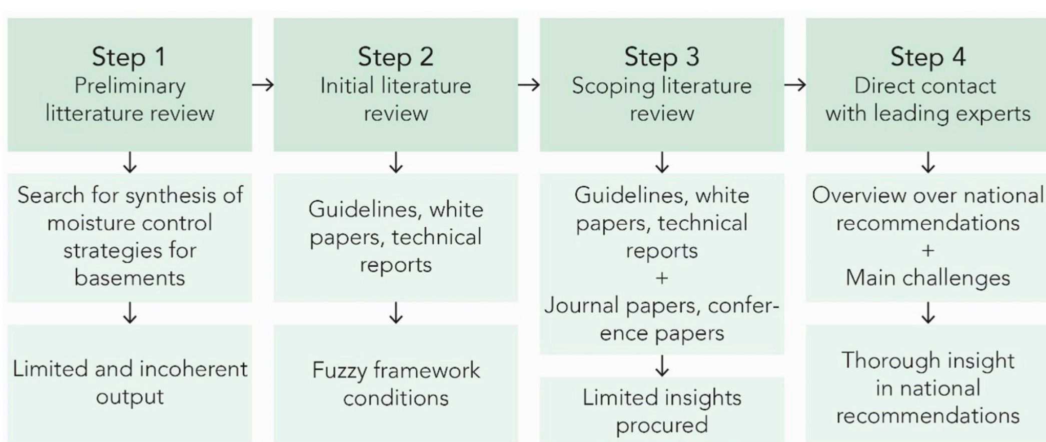


Fig. 2. Research procedure.

Our strategy has been to understand the acknowledgment and weighing of different factors concerning such building elements. The main idea is to articulate how moisture resilience in habitable basements is sought and ensured in five cold climate countries. The vocabulary outlined is based on a thorough analysis of the Norwegian SINTEF Building Research Design Guides [3] and what challenges are found to be the most important there. These design guides do not, however, constitute any significant limiting factor to the analysis. Rather, they serve as a point of departure on which the analysis can be made useful. The key challenges can be defined as in Fig. 1.

1. Water from rain and snowmelt (including down-pipes).
2. Water pressure on exterior walls below the ground.
3. Water pressure against the construction from a rise of groundwater.
4. Water from the terrain surface or from the ground that reaches the surface of the wall.
5. Capillary rise of moisture from the ground through the floor and foundations.
6. Transfer of water vapour from the ground through the floor
7. Moisture condensation on, and drying capacity of, the basement walls.
8. Thermal bridges.
9. Air leakages (moist air and radon gas) from the ground to the structure and indoor air (walls and floor).
10. High indoor moisture supply from cloth drying, cooking, showering etc.

The literature sources regarding the key challenges differ. More existing literature was found on the subject of relatively narrow technical fields. These are explained in Table 1. Certain studies cover the topic in a more general manner [5–9]. These broader studies are to a certain extent included in the table but are also discussed more extensively below. Some other studies are more concerned with thermal conditions [10–13].

Although much research has been done on all the identified key challenges, little work seems to have been done so far on their interrelations. For assessments, national recommendations within chosen cold climate countries have been subjected to scrutiny.

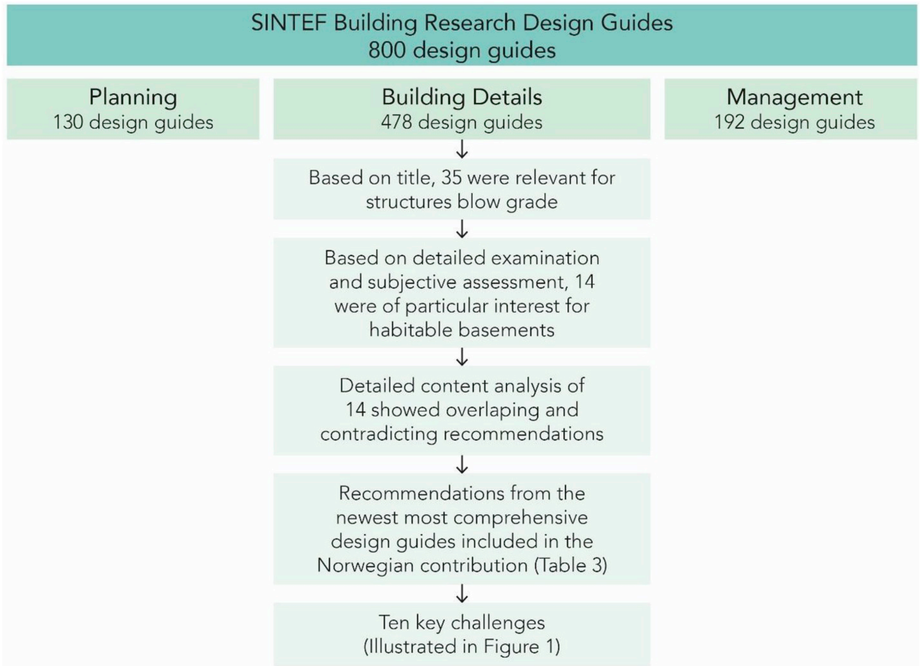


Fig. 3. Illustration of the sorting process used for content analysis and final table (Table 1).

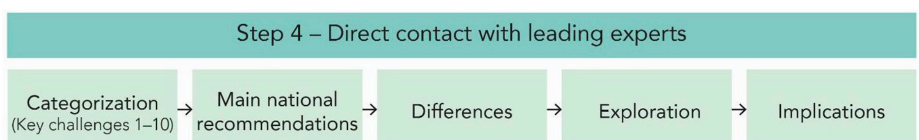


Fig. 4. Detailed illustration of the involvement of international experts.

3. Methodology

3.1. Research procedure

The methodological approach for the study has been somewhat complex (Fig. 2). Related literature articles could not be found; thus, we established an overview through initial literature review from February to May 2017. The literature review proved challenging because little research was found about the subject field. To advance the work, a thorough scoping literature review was carried out, systematically examining the leading journals within the field although the outcome was disappointing. The limited insights achieved indicated the need for a more direct approach. Leading experts from cold climate countries were directly contacted. These were challenged to provide overviews over main recommendations within the field for their respective countries. The analysis exposed in this article is mainly based on these insights provided.

In the following section, we distinguish between three main sources of information concerning the overall strategies on the subject of moisture control strategies for habitable basements. The first is regarding the description of common practice within the different countries examined. The second concerns the main recommendations for practice from authoritative sources. The last concerns descriptions of special cases. The analysis of international literature did not yield information to be characterized as a proper source of information.

3.2. Preliminary literature review

A preliminary literature review was carried out in February 2017. We first attempted to identify literature articles about the subject field; the lack of such work initiated an attempt to establish such an overview through an initial literature review. Search words, search engines and databases included in the preliminary literature review are given in Table 2.

Studies concerning moisture in building parts other than basements, heat and moisture transport in general, and damage caused by moisture were easily found. Scientific studies dealing directly with moisture control strategies or recommendations for new and habitable basements were harder to find.

3.3. Initial literature review

Considering the limited and incoherent results from the preliminary literature review, a more thorough literature review focusing on official guidelines, white papers, and technical guidelines/reports was carried out in the spring of 2017. In addition to basements, this review has also included recommendations for crawlspaces and slab on the ground.

The publications identified proved to be highly heterogeneous. From Science Direct, the results were quite limited, i.e. mainly focusing on special foundation cases, new material tryouts or building defects. Using Google and Google Scholar, examples of actual practice were easily found, e.g. drawings and recommendations from material manufacturers. Overall recommendations, however, proved hard to find for most countries. The exception was Denmark where design guides regarding moisture in basements could be found [52,53].

Search words, search engines and databases included in the initial literature review are given in Table 2. The search focused on the following countries;

Norway, Sweden, Denmark, Netherland, Belgium, USA, Canada, and Germany.

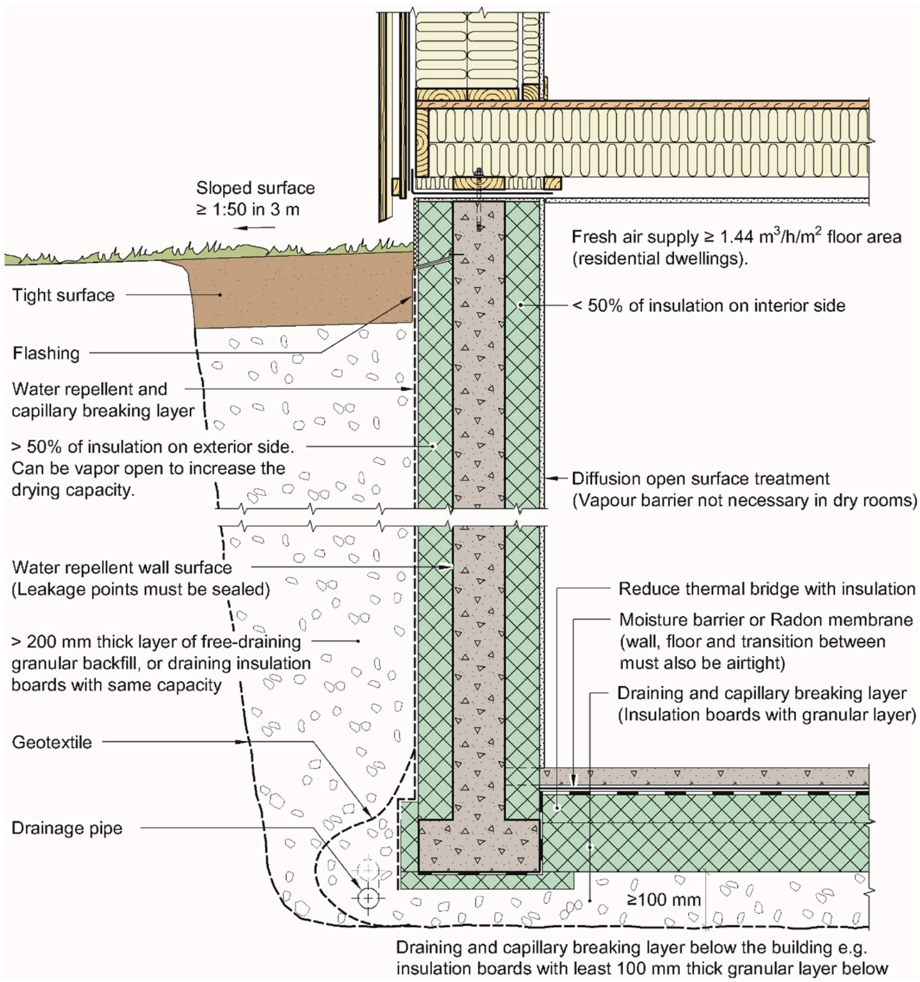


Fig. 5. Main recommendations for habitable basements in Norway.

3.4. *Scoping literature review*

Given the unclear national legacy of the results in the initial literature review, a more thorough literature review of scientific publications, reports, drawings, internet pages, and design guides was carried out spring of 2017. The review was carried out as a scoping study according to the prescriptions [54]. As commented by these authors, scoping studies differ from systematic reviews in that they typically do not assess the quality of included studies. This might be considered a significant disadvantage, however, as is further underlined by these authors [55:1], “scoping studies may be particularly relevant with disciplines with emerging evidence”.

The review was conducted to obtain an overview of recommendations for the moisture control of habitable basements in cold climate countries (Norway, Denmark, Sweden, Belgium, Netherland, Germany, Canada, and the USA.). However, the review showed that it was hard to find relevant information regarding general national recommendations in other countries than in Norway and Denmark. One particular reason for this was that they do not have design guides such as the SINTEF Building Research Design Guides [3], DBRI Guidelines [56] and BYG-ERFA [57]. USA and Canada equally stand out since they have national guidelines covering the topic [5,14].

Scientific papers and journal articles generally address special cases (i.e. specific projects and new solutions, measurements, calculations, details), and are therefore not a good source of more general national recommendations. Google and Google Scholar searches were also performed, and it yielded more relevant results; however, the information was of variable quality and thus was not optimal to provide an adequate overview of national recommendations.

A particular challenge entailed identifying recommendations and guidelines in languages not familiar to the researchers (e.g. Dutch).

Search words, search engines and databases included in the scoping literature review are given in Table 2.

3.5. *Assessing the main challenges within the Norwegian context*

To identify the main challenges for moisture control of habitable basements, a desktop study of recommendation within the Norwegian context was conducted. The object of the study was the SINTEF Building Research Design Guides [3], which provides authoritative guidelines for industry practice.

The guidelines are very comprehensive in nature, covering almost all the fields of buildings. Providing a sample found relevant for the study was based on a detailed selection process. First, planning and building details titles were distinguished. The building detail series was subsequently scrutinized in detail. For the analysis, habitable basements and year of publication were chosen as selection criteria. This process is illustrated in Fig. 3 and resulted in the development of the ten key challenges illustrated in Fig. 1.

3.6. *Involvement of international experts*

The scoping literature survey was conducted to obtain an overview of the recommended solutions. This did not, however, provide a sufficient knowledge base for understanding national recommendations. Therefore, experts within the field of building physics (building science)

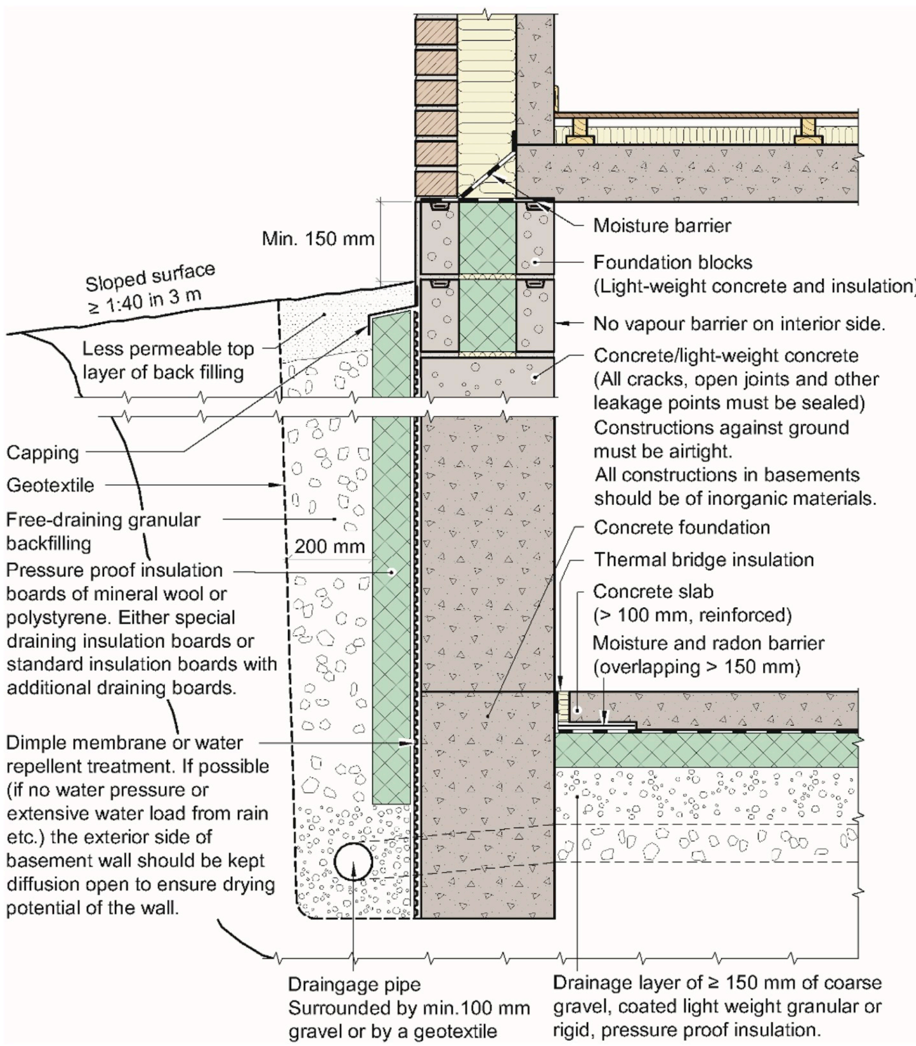


Fig. 6. Main recommendations for habitable basements in Denmark (adapted from Figures 35 and 36 in Ref. [61]).

from countries characterized by cold climates were invited to contribute with detailed information on recommended building practice.

Based on the ten key challenges identified in the analysis [3], experts were asked to contribute, with detailed information on recommended building practice in their respective countries, to the following three requirements:

1. Describe the key elements and recommendations to achieve optimal moisture safety for habitable basements in new buildings in your country.
2. Attach 1–2 detailed figures that exemplify how these recommendations can be built.
3. Write a short introduction to the use of basements in your country.

The experts were also given a Norwegian exemplification of the required contribution. The Norwegian exemplification is based on a content analysis [3] according to the prescriptions [58].

The involvement of international experts in the research process is illustrated in Fig. 4.

3.7. Choosing leading experts

Results and implications are based on contributions from the invited experts.

When deciding on what experts to involve in the work, selection criteria were established.

First, 5 countries, Finland, Denmark, Sweden, Estonia, and Canada, were chosen based on the following selection criteria;

1. Geographical location.
2. Climatic conditions.
3. Availability.

Secondly, one expert from the field of building physics (building science) from each respective country was selected according to prior knowledge of their contribution within the field from the originators of the research. The experts were contacted and invited to participate in the analysis. Of the five selected experts, one did not submit his contribution.

3.8. Limitations to the analysis

Several limitations to the analysis have to be acknowledged. Firstly, within each country, there might exist other main recommendations than those that the expert have included in their contribution. If we could have asked more than one expert from each country, perhaps this source of error could have been less. Secondly, the ten key challenges in the Tables are based on the content analysis [3] and what Norwegians experience as challenges. Initially, we thought other countries would make their own list of challenges, but they all based their contributions on the Norwegian challenges and added none of their own. If we had made the table differently, we might have left one box at the bottom

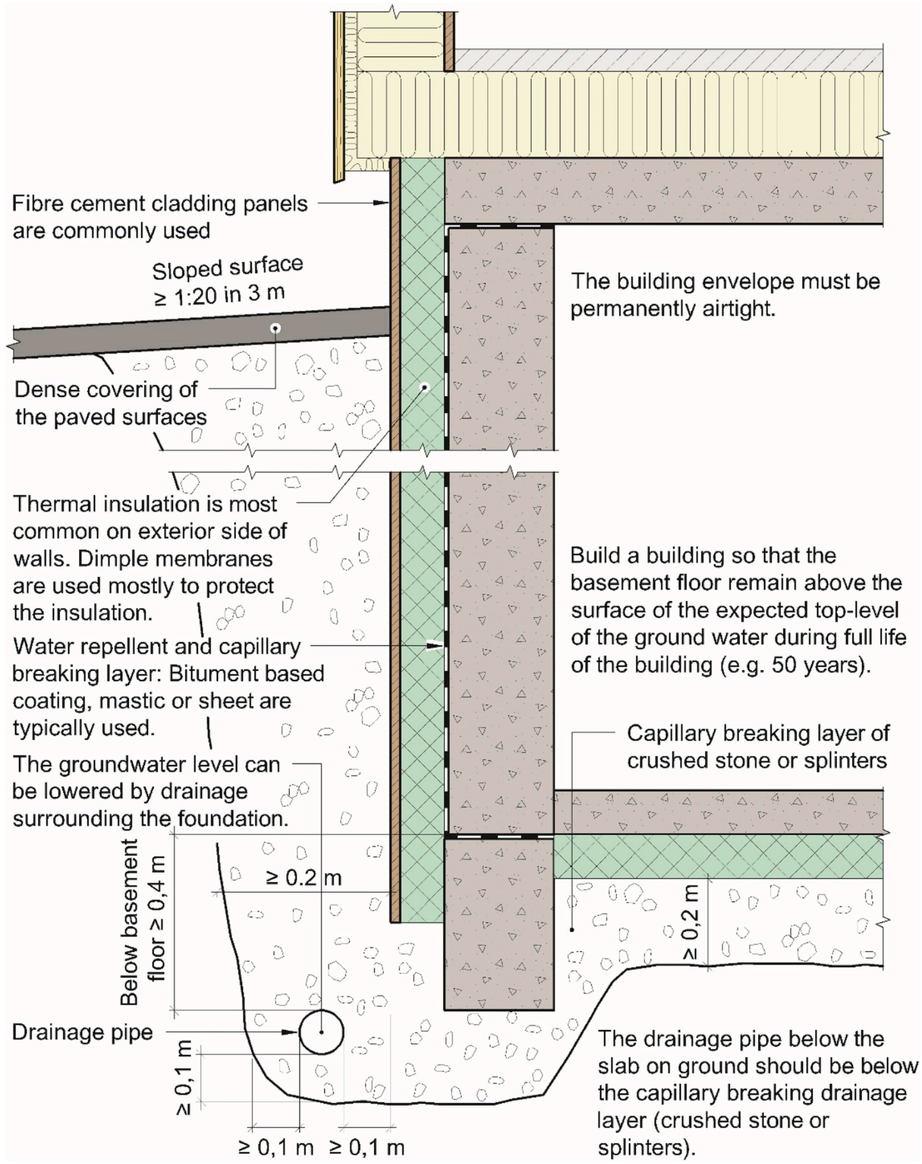


Fig. 7. Main recommendations for habitable basements in Estonia (adapted from Ref. [63]).

open and asked the experts to add their own challenge(s) if they had any. Thirdly, the expert might have misinterpreted the content of the Norwegian Table.

Whilst all these limitations might have some bearing on the analysis, their influence does not seem sufficient to significantly undermine the main conclusions presented in this article.

4. Results

4.1. Summary of main findings

In the following section, the main results sorted by the ten key challenges, see Fig. 1, are presented.

#1: Canada recommends that the building shall be located so that water will not accumulate at or near the building. Norway, Denmark, Sweden, and Estonia additionally recommend that the ground surface next to the building is levelled with a slope at a distance of 3 m. Differences in the size of the slope are from 1:20 to 1:50. Norway recommends the sleekest slope (1:50). Denmark additionally recommends that the top layer of the ground should be less permeable than the draining layer on the exterior side of the insulation. Estonia recommends a dense covering of the paved surfaces.

#2: All countries recommend a drainage layer on the exterior side of the basement walls. Norway, Sweden, and Canada recommend free-draining granular backfill or draining insulation. Denmark recommends both. Norway, Denmark, and Sweden additionally recommend a geotextile to protect the draining layers against fine-grained material from the ground. The recommendations for the type and thickness of the drainage layer also has interesting variations. Estonia recommends a drainage layer $\geq$200 mm thick. Sweden recommends a drainage layer $\geq$200 mm thick composed of sand or gravel. Norway recommends either at least 200 mm free-draining granular backfill or draining insulation with the same capacity. Canada recommends either at least 100 mm free-draining granular backfill or $\geq$19 mm mineral fibre insulation. Denmark recommends either special draining insulation boards or standard insulation boards with additional draining boards and an additional layer of $>$200 mm backfilling with good draining capacity.

#3: All countries recommend drainage pipes with some differences in the given details e.g. use of geotextile, pipe-dimension, and position. Norway recommends drainage pipe surrounded by gravel and enclosed by a geotextile, while in Denmark one of these options can be chosen. Sweden recommends drainage pipes with an internal diameter $\geq$70 mm

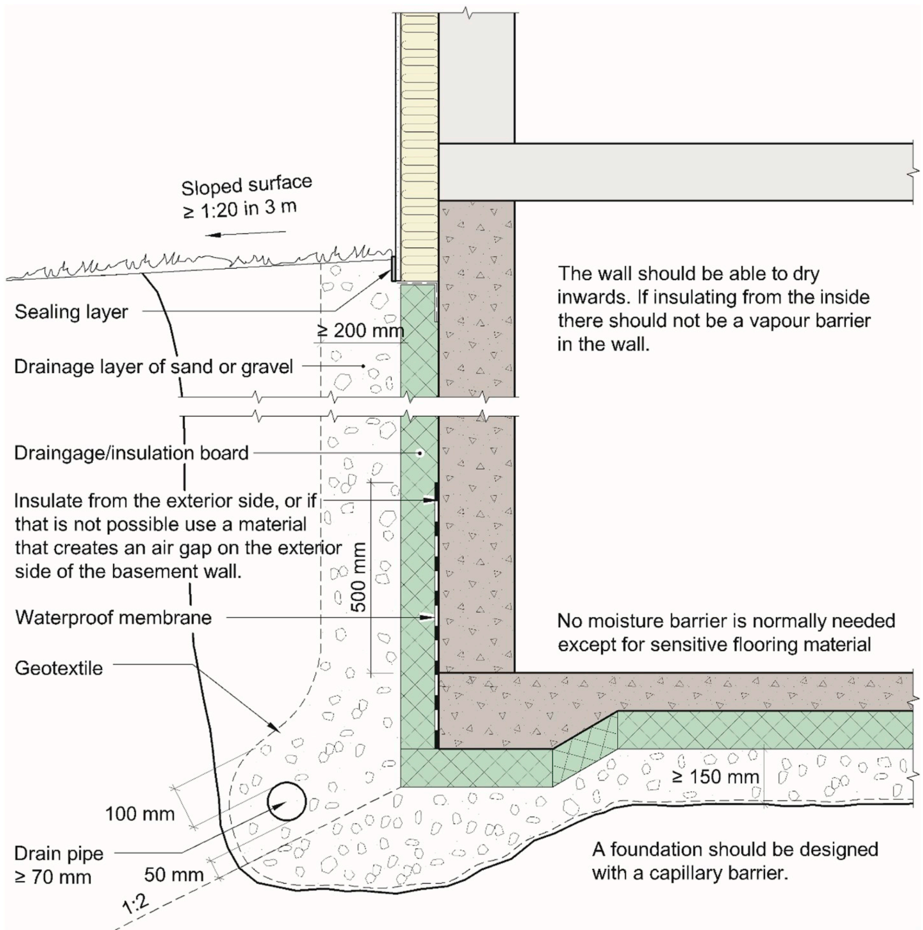


Fig. 8. Main recommendations for habitable basements in Sweden (adapted from Figure 35 in Ref. [24], Figure 4.1.36 and 4.1.34 in Ref. [15] and Figure 11 and Typritning nr. 5 in Ref. [68].

with drainage layers around and a geotextile to protect the draining layer. Canada specifies drainage tile or pipe of ≥100 mm diameter with top and side covered with ≥150 mm gravel. Estonia recommends that the highest point of the drainage pipe must be at least 0.4 m below the lower surface of the slab on ground and that the drainage pipe below the slab on the ground should be below the capillary breaking drainage layer (crushed stone or splinters) and below the lower surface of the basement wall.

#4: All countries have one or several different recommendations regarding this challenge. They all recommend a water repellent capillary breaking layer of some kind, on the exterior side of the wall or on the exterior side of exterior insulation. However, the material, design, and position vary among the countries. The capillary breaking layer can either be dimpled membranes, some kind of water repellent treatment/ rendering or both, or it can be bitumen-saturated membrane. Canada recommends a water repellent layer on the exterior wall surface and a bitumen-saturated membrane where hydrostatic pressure occurs. Denmark recommends that if possible (if not water pressure or extensive water load from rain), the exterior side of the basement wall should be kept diffusion open in order to ensure the drying potential of the wall. Norway recommends dimpled membranes on the exterior side of exterior vapour permeable thermal insulation. In Estonia, dimpled membranes are used more for the protection of insulation. Sweden recommends an additional waterproof membrane from the bottom of the concrete slab and 500 mm up on the outside of the wall.

#5: All the countries recommend a capillary barrier of some kind in the floor to avoid capillary rise of moisture from the ground, but the type, thickness, and position vary. Sweden recommends a layer of coarse crushed stone material ≥150 mm thick and a geotextile. Canada recommends ≥100 mm coarse clean granular material beneath the floor. Norway recommends both insulation and ≥100 mm thick granular layer below the building and a geotextile if there is a risk of rising groundwater or very soft building ground. Denmark recommends ≥150 mm coarse gravel, coated lightweight granular or rigid, pressure-proof insulation. Estonia recommends ≥200 mm thick layer of crushed stone or splinters and a geotextile below that layer if the base ground is clay or silt,.

#6: All the countries have different recommendations regarding water vapour from the ground through the floor. In Denmark, no moisture barrier is needed for the typical construction with reinforced concrete slab, unless moisture-sensitive flooring materials are used. Norway recommends a moisture barrier between the insulation and concrete floor. Canada recommends damp proofing below the floor of ≥0,15 mm PE. If a separate floor is provided over a slab, damp-proofing is permitted to be applied to the top of the slab. In Estonia, it is either recommended to use a moisture barrier between the insulation and the concrete floor (typically PE foil), or not to use a foil to allow dry out the concrete toward the ground. Sweden recommends thermal insulation below the whole concrete slab to protect the foundation from water vapour from the ground. A moisture barrier is normally not recommended except for sensitive flooring material.

#7: All the countries recommend thermal insulation, but the thickness and position vary among the countries. Recommendations to use or not to use vapour/moisture barriers also vary. In Norway, no moisture barrier is necessary on the interior walls (in normal dry rooms) as long as least 50% of the insulation is on the exterior side of the exterior walls. It

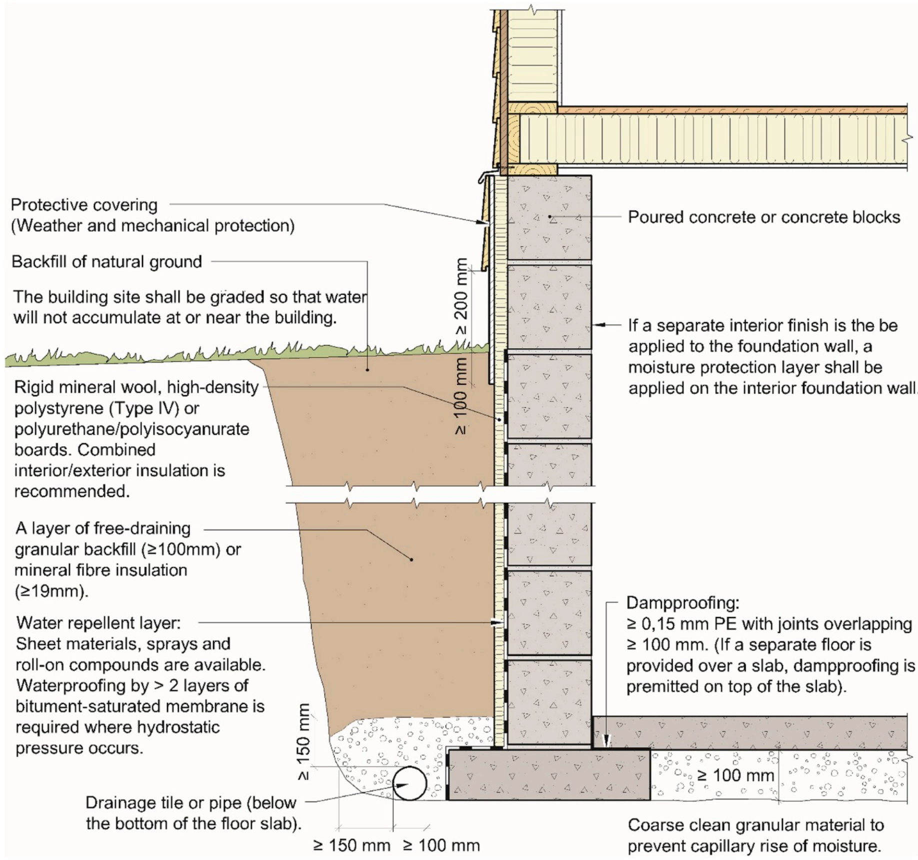


Fig. 9. Main recommendations for habitable basements in Canada (adapted from Ref. [70]).

Table 2
Search words and combinations included in the literature review.

<table>
<tr><th>Literature review</th><th>Search engines and databases</th><th colspan="5">Search words</th></tr>
<tr><td>Preliminary (Step 1)</td><td>- Science Direct
- Oria (Norwegian library database)
- Google
- Google scholar</td><td colspan="5">basement* (basement, basements), cellar* (cellar, cellars), "foundation wall*" (foundation wall, foundation walls), moisture, moisture safety, "moisture control strateg*" ("moisture control strategy", "moisture control strategies"), design guide*, (design guide, design guides) guideline*, (guideline, guidelines) recommend* (recommend, recommending recommendations).</td></tr>
<tr><td>Initial (Step 2)</td><td>Same as Step 1</td><td colspan="5">basement, "basement wall below ground", "basement wall below grade", "basement wall below-grade", "foundation wall", crawlspace, "slab on ground", "insulated basement", "exterior insulated basement".</td></tr>
<tr><td>Scoping (Step 3)</td><td>Same as Step 1 and Step 2
+
Tailor & Francis Online</td><td colspan="5">Different searches combining one search term from each column</td></tr>
<tr><td></td><td></td><td>Search term 1</td><td>AND</td><td>Search term 2</td><td>AND</td><td>Search term 3</td></tr>
<tr><td></td><td></td><td>basement*(basement, basements)</td><td></td><td>moisture</td><td></td><td>design guide* (design guide, design guides)</td></tr>
<tr><td></td><td></td><td>cellar* (cellar, cellars)</td><td></td><td>moisture safety</td><td></td><td>guideline* (guideline, guidelines)</td></tr>
<tr><td></td><td></td><td>"foundation wall*"
"wall* below ground"
"wall* below the ground"
"wall* below grade"
"wall* below-grade"
"building* below ground"
"building* below the ground"
"building below grade"
"building below-grade"</td><td></td><td>"moisture control strateg*" ("moisture control strategy", "moisture control strategies")</td><td></td><td>recommend*(recommend, recommending recommendations)</td></tr>
</table>

is recommended to put the dimpled membranes on the exterior side of exterior vapour permeable insulation to optimize outwards drying. Denmark recommends that all constructions in basements be of inorganic materials and no vapour barrier is recommended in order to ensure drying capacity of the construction. Canada recommends combined interior/exterior insulation for basement walls and if a separate interior finish is to be applied to the foundation wall, a moisture protection layer shall be applied on the interior foundation wall surface to minimize the ingress of moisture from the foundation wall. The common practice in Estonia is to use insulation on the exterior side of the basement wall. Sweden recommends that walls with moisture from the construction process be given the opportunity to become dry by exterior insulation, dimpled membrane or combination of both, and do not recommend a vapour barrier on the interior side of the wall.

#8: In Canada, thermal bridges in new houses basements are not a common issue, but they tend to be more significant in those basements that are converted in residential spaces to accommodate the increasing urban density and house shortage. Sweden has not given any specific recommendations. Estonia points out the recommended temperature factor to avoid a risk of mould growth [59]; however, it does not give specific recommendations on measures to achieve this. Norway has provided specific recommendations on how to avoid the thermal bridge in the transition between wall and foundation (either minimum of 50 mm insulation below the concrete foundation or applying insulation between wall and floor). Denmark recommends placing insulation on the exterior side of the construction and to reduce the thermal bridge on top of the basement wall by ensuring an overlap of >200 mm for wall insulation and insulation on the exterior side of basement walls.

#9: All the countries recommend airtightness for constructions against terrain (moisture, heat loss and radon).

#10: The recommendations for ventilation in basements vary among the countries. In Norway, the recommended fresh air supply for basements is the same as residential dwellings is general, e.g. minimum 1.44 m^3 each hour per m^2 of floor area. The ventilation rates shall be adapted to the contamination and moisture load and can thus be higher. In Sweden, the minimum outlet airflow is a bit lower: 1.26 m^3 per m^2 floor area (converted from 0.35 l/s per m^2 of floor area). In Denmark, ventilation in basements must fulfil normal requirements for air change in dwellings. In Canada each habitable room shall be assigned a fan capacity of 5 L/s (18 m^3/h) apart from the master bedroom which needs 10 L/s (36 m^3/h). To compare with other national recommendations, two examples are provided;

- Habitable room (floor area from 10 to 30 m^2): fan capacity from 1.8 to 0.6 m^3/h per m^2 floor area.
- Master bedroom (floor area from 10 to 20 m^2): fan capacity from 3.6 to 1.8 m^3/h per m^2 floor area.

4.2. Habitable basements in Norway

In Norway, 50% of the residential building stock consists of single-family dwellings. An additional 9% are houses with two dwellings and 12% are row houses, linked house or other small houses [60]. A large proportion of these homes is built with a living space in the basement. Such basements are normally built above the groundwater level with a concrete foundation on a free-draining layer of "gravel". The densest parts of Norway are characterized by frequent freeze-thaw conditions.

The identified recommendations for Norway are based on the SINTEF Building Research Design Guides [3]. These consist of 800 design guides that have been produced and continuously updated since 1958. The design guides are the most used planning and design tool amongst Norwegian architects and engineers because they comply with the performance-based requirements in the building code and are an important reference to documented solutions in the technical regulations.

The main national recommendations for habitable basements in Norway are depicted in Fig. 5 and described in detail in Appendix A. According to the view of the authors, Fig. 5 and Appendix A present the key elements to optimal moisture safety in habitable basements in Norway.

4.3. Habitable basements in Denmark

In Denmark, habitable rooms and kitchens must be above ground and therefore no habitation is allowed in basements. For special site conditions, e.g. sloping site, it is possible to have habitable rooms in a basement if the floor lies above ground level along at least one wall with a window. When part of the room is below the ground, a special focus must be paid on the constructions against the ground regarding penetration of moisture and radon.

In general, basement walls are made of concrete or light-weight concrete blocks. The basement floor is always a concrete slab. Thermal insulation must be placed on the exterior side of the construction and the backfilling must be suitable for draining and preventing capillary rise.

The main national recommendations for habitable basements in Denmark are depicted in Fig. 6 and described in detail in Appendix B. The basic guidelines about moisture safe construction principles are found in DBRI Guideline 224 Moisture in buildings [53]. The other guidelines referred to in Appendix B can be found [56].

4.4. Habitable basements in Estonia

In Estonia, residential buildings comprise up to 60% of the total building stock [62]. Apartment buildings account for 51% (34 282 × 10^3 m^2) of the total net area of dwellings. The second large group of dwellings is detached houses with 41% (26 447 × 10^3 m^2) of the total net area of dwellings. The groundwater level is high in Estonia; in most cases, the basement is below. There are no official statistics about buildings with or without a basement. Based on common knowledge nowadays:

- Detached houses and row houses are mainly built without a basement, mainly because the inhabitants do not need so much storages in the basement; construction below the ground is more expensive, and the foundation does not need to go deeper because solutions exist to prevent frost rise.
- Apartment buildings and offices typically use basements for garage, technical rooms or for storage.

In Estonia, good recommendations and guidelines as in Norway (SINTEF) and in Finland (RT-cards) do not exist. Instead, Estonian designers use quite a lot of Norwegian and Finnish guidelines. It is designer's responsibility and target to fulfil essential requirements on construction and building.

The main national recommendations for habitable basements in Estonia are depicted in Fig. 7 and described in detail in Appendix C.

4.5. Habitable basements in Sweden

The Swedish building stock consist of 1.2 million single-family houses and 166,000 multi-family buildings. Of the single-family houses, 30% have a basement, as do 50% of the multi-family buildings. The average U-value for basement walls below grade is 0.74 W/(m^2K) and for basement walls above the ground, it is 1.65 W/(m^2K). Of the single-family houses, 29% suffered some kind of damage; of the multi-family buildings, 8% suffered damage [64]. Around 8% of all basements in Sweden have mould odours [65]. Before the 1970s, basements were mainly used for storage and not heated, but today it is common to furnish the basement.

The Swedish building regulations have been performance-based since the end of the 1980s. This means the contractor is free to suggest and choose any solutions and construction techniques as long as the basic performance criteria are fulfilled: 'Buildings shall be designed to ensure moisture does not cause damage, odours or microbial growth, which could affect human health'. If the critical moisture level is not well-researched and documented, a relative humidity (RH) of 75% shall be used as the critical moisture level. The requirements can be met and verified using moisture safety planning and monitoring of the design to ensure that the intended moisture safety is achieved. When planning, designing, executing and monitoring moisture safety, the industry-standard ByggaF – method för fuktsäker byggprocess (ByggaF – method for moisture safe building process) can be used as guidance [66]. Buildings, construction materials, and construction products should be protected from precipitation, moisture, and dirt during the construction period [67]. The main national recommendations for habitable basements in Swedish are depicted in Fig. 8 and described in detail in Appendix D.

4.6. Habitable basements in Canada

Residential construction in the Greater Toronto Area (GTA) has been booming over the last few years. The majority of these houses have been constructed by large "tract" homebuilders in accordance with the Ontario Building Code (OBC). Under such production conditions, the emphasis is placed on achieving the lowest initial capital cost. Many researchers in Canada have looked at detailed construction cost data and floor plans for popular models to assess the value of insulating the basement properly or "upgrading" from Ontario Building Code minimum standards to the R2000 standard. These currently mean:

- Ontario Building Code: R-6 basement wall insulation to a depth of 0.6 m below grade (obligation)
- R2000: R-12 full height basement wall insulation (no obligation).

Unfortunately, the primary problem in Ontario (and the Greater Toronto Area) is housing booming. Given housing costs, basements are now no longer just used as storage spaces but are often utilized as part of the interior space. Poor moisture management across these walls often leads to mould and mildew growth and poor air quality in basement spaces [69].

Nova Scotia does not have a provincial building code. Instead, this province relies on the National Building Code of Canada (NBC). However, the National Building Code does not mandate a minimum value of thermal insulation.

The main national recommendations for habitable basements in Canada are depicted in Fig. 9 and described in detail in Appendix E.

5. Discussion

5.1. Recommendations for habitable basements

In this study, we set out to investigate the differences and similarities in national building recommendations for habitable basements. The Norwegian design guides were used as a baseline to identify main learning potentials concerning moisture control strategies. Ten key challenges (#1–10) have been identified and used in the comparison of the main national recommendations in five western cold climate countries, see Fig. 1.

5.2. Norwegian recommendations compared to other cold climate countries

This study shows that the main national building recommendations in the western cold climate countries differ from the Norwegian at different key challenges, see Fig. 10.

Danish recommendations have the most in common with the Norwegian, but there are differences regarding (#1), (#5) and (#7) and contradicting recommendations regarding (#6). Sweden has differences regarding (#1), (#4), (#5) and (#7) and contradicting

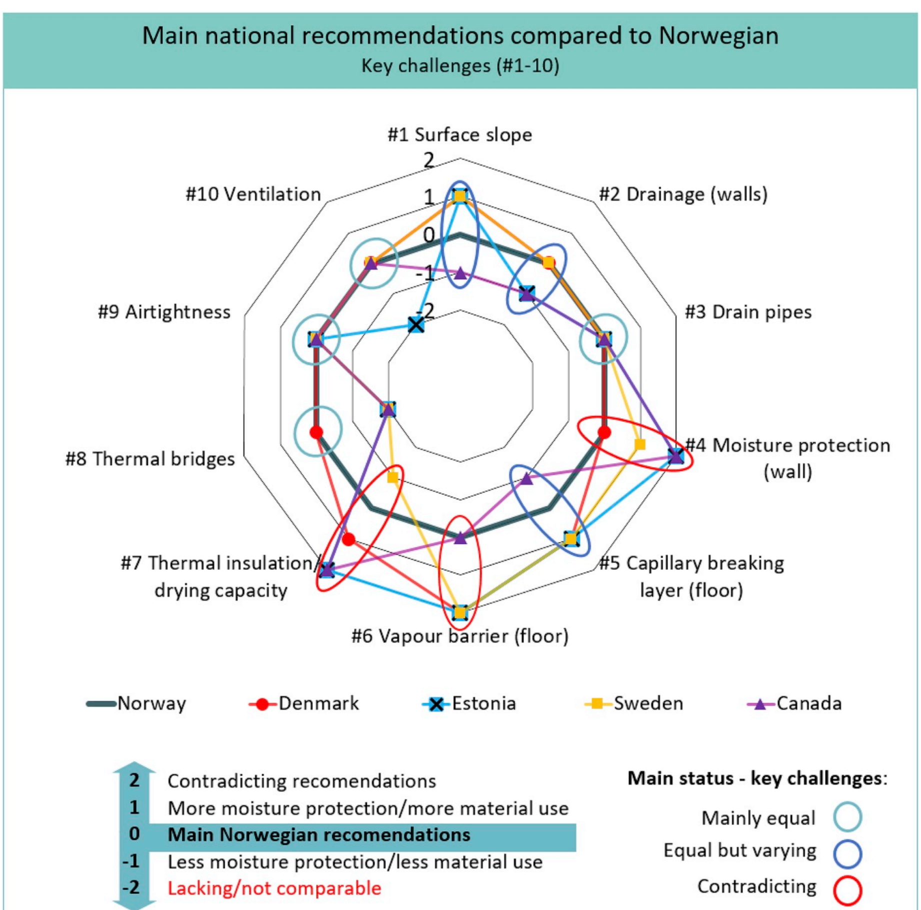


Fig. 10. Main national building recommendations for habitable basements in cold climate countries (red, blue, yellow and purple) compared to Norwegian (grey at level 0) for each of the ten key challenges (#1–10, see Fig. 1). Recommendations are sorted as either the same as Norway (level 0), more moisture safe (level 1), less moisture safe (level −1), contradicting (level 2) or lacking (level −2). The figure shows, for each key challenge, where the main recommendations are mainly equal (white circle), equal but varying (blue circle) or contradicting (red circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

recommendations regarding (#6). Canadian recommendations mainly differ regarding (#1), (#2) and (#5) and had contradicting recommendations regarding moisture protection in walls (#4) and thermal insulation and vapour barrier in walls (#7). Estonian recommendations differ regarding (#1), (#2) and (#5) and are contradicting regarding the use of dimpled membranes (#4), vapour barriers in floors (#6) and dry out capacity (#7).

Norway also stands out by recommending a diffusion open exterior wall surface, vapour permeable thermal insulation and dimpled membrane positioned on the exterior side of the exterior thermal insulation (#7). This is recommended in order to increase the drying potential of the construction against the exterior [71]. Denmark also recommends that, if possible, the exterior side of the basement wall should be kept diffusion open in order to ensure the drying potential of the wall. However, according to the Danish illustration, the dimpled membrane is positioned between the wall and exterior insulation. Estonia typically uses bitumen-based coating, mastic or sheet on the basement wall surface to prevent water transfer from the ground and into the wall. Dimpled membranes are used mostly to protect the thermal insulation. Estonia also stands out by not having national recommendations such as Norway, but generally base their recommendations on practice.

Considering only the comparable recommendations provided, the countries have similar and varying but not contradicting recommendations regarding the ground surface slope (#1), drainage layers (#2), drainage pipes (#3), capillary breaking layers in floors (#5), thermal bridges (#8), airtightness (#9) and ventilation (#10). The most interesting variations are found for #1: recommended ground surface slope varying from 1:20 (Sweden and Estonia) to 1:50 (Norway) #2: recommended drainage on exterior side of walls vary from ≥19 mm mineral fibre insulation (Canada) to special draining insulation boards or standard insulation boards with additional draining boards and a layer of >200 mm backfilling with good draining capacity (Denmark) and #5: recommended capillary breaking layer beneath floor vary from ≥100 mm coarse clean granular material (Canada) to 200 mm thick layer of crushed stone or splinters (Estonia) and from ≥100 to ≥150 mm with additional insulation (Norway/Denmark).

5.3. Contradictions

The main recommendations have interesting differences regarding water that reaches the surface of the wall (#4), water vapour from the ground through the floor (#6) and partly (#7) moisture condensation on, and drying capacity of, the basement walls. Not surprisingly, this applies to use and position of foundation boards, moisture/vapour barriers/membranes and type, thickness and vapour permeability of thermal insulation in walls and floors.

More precisely, Norway and Denmark recommend a diffusion open basement wall surface to ensure drying outwards, while Canada and Estonia mainly recommend damp proofing (#4). Sweden recommend a waterproof membrane from the bottom of the concrete slab and 500 mm up on the outside of the wall. Canada recommends interior moisture protection, while Norway and Denmark recommend no interior vapour barrier (#7). Norway and Canada recommend a vapour barrier in the floor structure, while in Estonia, some designers recommend no foil and Denmark recommend no moisture barrier unless moisture-sensitive flooring materials are used (e.g. wooden floor) (#6).

The countries included might have other main national recommendations not included in the expert contributions. This source of error could have been reduced if more than one expert from each country had submitted their version of the main recommendations.

5.4. Further research needs

Basements used as dwellings represent a major challenge concerning moisture safety design. The risk of moisture-related damage in these constructions is also expected to increase due to climate change. This study shows that cold climate countries recommend different strategies for moisture control in basements. The ten key challenges identified can be considered a basis on which future strategies for optimization of basements can be developed and evaluated.

This study shows that recommendations concerning ground surface slope (#1), drainage layers in walls (#2) and capillary breaking layers in floors (#5) vary. The risk of moisture damages in vulnerable structures, in particular, might be reduced by combining the strictest of the varying recommendations presented in the study, e.g. steeper surface slope next to the building and thicker draining and capillary breaking layers adjacent and underneath the building.

It is mainly the recommendations for key challenge #4, #6 and #7 that distinguish the moisture control strategies from each other. This is quite intriguing because barely any research was found in the literature concerning a holistic consideration of their correlation. After comparing the five countries' recommendations, new insight has substantiated the need to answer some general concerns. These include (1) are vapour permeable thermal insulation preferable? (2) can convection or moisture in exterior vapour permeable thermal insulation significantly reduce the heat resistance? (3) can exterior thermal insulation perform as a capillary breaking layer and thus replace the traditional dimple membrane? and (4) what thermal insulation thickness, position, and permeability are favorable?

Not only can research concerning such subjects provide significantly improved technical solutions; but also, they can imply significant pecuniary reductions.

6. Conclusion

A significant part of this work has been the development of the research methodology to be able to study moisture control strategies in habitable basements in different cold climates countries. Hence, we identified ten key challenges that should be included in national moisture control strategies for such constructions. The study shows that the main national building recommendations in western cold climate countries differ from the Norwegian at different key challenges.

Considering only the comparable recommendations provided, the countries have similar recommendations regarding drainage pipes (#3), thermal bridges (#8), airtightness (#9) and ventilation (#10). Interesting variations are found regarding the ground surface slope (#1), drainage layers in walls (#2) and capillary breaking layers in floors (#5). Contradicting recommendations are found regarding moisture protection of walls (#4), vapour barriers in floors (#6) and thermal insulation and drying capacity (#7).

The main learning potential from the review is that the five cold climate countries emphasize the ten key challenges differently. The recommendations have many similarities, but it is this weighing (or prioritizing) that distinguishes the five countries' moisture control strategy from each other. As an example, if a basement wall is protected against water intrusion with a bitumen-based watertight membrane on the exterior surface, exterior drainage might not need to be as efficient. Likewise, one might not have the same need to seal the wall surface if good site drainage, ground surface slope, thick draining layers and exterior vapour permeable thermal insulation provides good drying conditions.

Yet another consequence of these diverging national recommendations is a challenge for importing/exporting commercial and "well-known" solutions.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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