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# Field Temperature and Moisture Loads from a Building Envelope as the Basis for Accelerated Aging of Barrier Membranes

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# Abstract

Temperature and relative humidity (RH) data within the building envelope of a single family home at the National Research Council of Canada's Canadian Centre for Housing Technology were collected over five years. We report on the distribution, rate of change and the limits of temperature and moisture variations for south easting wall and south facing wall and roof systems to better understand the in-situ environmental conditions to which building materials and components typical of homes in North America may be subjected. Over an average year, wall temperature varied from –25 °C to +45 °C, and temperature followed a bimodal distribution, with maxima at 0 °C to 5 °C and 15°C to 20 °C. Each maxima represented about 1100 hours of field exposure. Roof temperatures, which spanned a temperature range of –35 °C to 75 °C, did not show a Gaussian distribution, but was characterized as being multi-modal. From values of temperature and RH, absolute moisture contents within the building envelope were found to range between 1 and 55 g/m$^3$, the most common values being 6 to 8 g/m$^3$. The application of this information is discussed and related to the development of realistic accelerated aging conditions to obtain a more accurate durability assessment of building envelope materials used in Canadian dwellings.

**Keywords:** Building envelope; building materials; construction; temperature; humidity; accelerated aging.

# 1. Introduction

Construction products age due to weathering in-service. Their durability, the time during which the product performance is adequate, depends on product composition and in-service environmental conditions. Granted adequate design in consideration of in-service conditions and proper installation, construction products can last for several decades. The National Building Code of Canada (NBC) sets out the minimum requirements and quality standards for materials and components used in building envelope assemblies. To this effect, building envelope materials (BEMs) must meet standards referred to in various parts of the NBC (**Table 1**). However, the NBC does not explicitly state a minimum durability or service life for different BEMs, but guides for the durability of buildings, and their components are referenced in the NBC, specifically, the CSA S478-95 (R2007) Guideline on Durability in Buildings.

Apart from the standard products, producers of construction materials submit innovative products for performance assessment to NRC's Canadian Construction Materials Centre (CCMC) to obtain an opinion on possible product performance with regards to the requirements of the NBC, and for which within this assessment process there is an implicit requirement for durability. The CCMC evaluates products against performance-based criteria. This implies that the new products are to be tested both before and after accelerated aging in laboratory conditions representative of field conditions. Standards such as CSA S478 (1995) and ISO 15686-2 (2012) provide a general framework for accelerated aging, from which aging conditions ought to be considered in respect to in-service conditions; for products as might be used across Canada, these may be subjected, for example, to typical Canadian climatic conditions as provided in **Table 2**. On this basis, however, laboratory aging can vary significantly in terms of exposure conditions for different climates, including for instance, the time, temperature, and exposure to humidity, and whether or not these aging factors must be applied over a constant or cyclic period. It is also not uncommon to find prescriptive products aging methods with unclear links to durability. For instance, CAN/ULC-S741 (2008) requires heat aging of air barrier membranes at 50 °C during 16 or 32 days, but there is no established relationship to service-life. It is preferable to have performance-based laboratory aging conditions designed on the basis of actual service loads. Unfortunately, the actual service loads are seldom recorded because it is both expensive and time consuming to do so. Average air temperatures and relative humidity can be obtained from the weather records for most Canadian cities, but these conditions do not translate into actual aging conditions for BEMs. Having temperature data as may occur within the building envelope, such as expected values within roof and attic assemblies, are critical consideration to ensure proper aging conditions for laboratory accelerated aging tests (Winandy et al. 2007).

The goal of this work is to provide field data that can be used to fill the existing knowledge gap of actual values for temperatures and moisture in-situ conditions within the building envelope during in-service conditions, and from which to establish accelerated aging conditions for laboratory evaluations specifically for wall and roof membranes and barriers. The in-situ data reported includes temperatures for south facing walls and roof assemblies of a brick masonry-clad house located in Ottawa, Canada, and as well, moisture data for an east facing wall. The south facing orientations are the warmest and as a result this is where thermal aging is fastest. The usefulness of the data is provided in examples for accelerated heat aging, and also accelerated aging from exposure to moisture. The reported data can be beneficial to building scientists and engineers having interest in the development of accelerated aging methods (Nelson 1990) and to improve methods of service life assessment of BEMs (ISO 13823, 2008).

# 2. Methodology

## 2.1. Test house and its construction

The source of wall and roof temperature data is a two-story 210 $m^2$ (2,260 $ft^2$) single family home with a brick façade at the Canadian Centre for Housing Technology (CCHT)[1], located on the campus of the National Research Council in Ottawa, Canada. The home was built in 1998 to the R-2000 standard, a voluntary standard developed by Natural Resource Canada that went above and beyond minimum code requirements at that time (NBC 1995) to include energy-efficient building practices. The CCHT house was built with brick cladding and featured instrumented exterior wall cross-sections for which data was recorded on an hourly basis from 2004 to 2009. The CCHT house features include: wood-frame construction, RSI 3.5 (R20) fiberglass batt insulation in the walls, RSI 8.6 (R50) attic insulation, 12 mm thick Oriented Strand Board (OSB) sheathing, wood stud with nominal size of 50 mm × 150 mm (2-inch by 6-inch), asphalt shingles, high efficiency forced-air heating and cooling, and low air leakage (~1.5 Air Change per Hour, ACH). **Figure 1** shows a photograph of the CCHT house upon its completion with the location of sensors relevant to this work. **Figure 2** and **Figure 3** are representations of the layered wall and roof structures of the CCHT house along with the placements for the sensors, respectively. The data reported in this study is for a south-facing wall, and roof, and also an east-facing wall. The south face of the house was oriented 13° to the east, and the slope of the roof was 40°.

[1] The Canadian Centre for Housing Technology is a partnership between the National Research Council Canada, Natural Resources Canada, and the Canada Mortgage and Housing Corporation.

### 2.2. Instrumentation

On the basis of sensor readings in the walls and roof (**Figures 2 and 3**), temperature, relative humidity, and moisture content are reported for the building envelope. Temperature data is reported for the OSB surface temperature on the south facing wall, sensor position 31 in **Figure 2**, and for the OSB surface sheeting immediately under the roofing underlayment and the shingles for the south facing roof (**Figure 3**). OSB is the most common wood sheathing in Eastern Canada. Temperature and relative humidity is also reported in the air gap onto brick siding on the east-facing wall, sensor position 30 in **Figure 2**. All thermocouples were type T with +/- 0.2 ºC precision, whereas the precision for RH sensor was +/- 5 %. The attic space for the house was unconditioned, and consequently its temperature could be in excess of 50 °C in summer due to solar gains.



### 2.3. Weather data

Data from the CCHT house was compared to the data from the year 2005 collected from weather stations number 24287 in Vancouver, number 94810 in Windsor, and number 4772 in Ottawa. A Microsoft Excel Visual Basic application was developed to calculate running averages from hourly weather data from each city. Averages were calculated for 1-day, 1-week, 1-month, and 1-year.

## 3. Results

### 3.1. Temperature, South-facing Wall

Temperature was measured every 5 minutes, 24 hours a day, for 6 years, from 2004 and 2009. In this work, the 5-minute data was averaged into hourly data, and then the frequency of occurrence was collected into 5 °C intervals, e.g., 5 to 10 °C and 10 to 15°C, which would respectively be written as >5 °C and >10 °C in graphs and tables. Further averaging into monthly and yearly averages were also calculated.

The monthly temperature distribution of the south-facing wall can be seen in **Table 3**. Although the hourly temperature data varied from –25 °C to +45 °C, the monthly averages only changed from about –2.5 °C to 25 °C. The yearly average for the 6 years was about 12 °C.

**Table 4** shows the time distribution for the temperature in the south-facing wall in 5 °C temperature intervals between –25 °C and +45 °C. The minimum temperatures were between –25 °C and –20 °C for about 17 hour per year (h/y), and the maximum temperatures were between 40 °C and 45 °C for about 24 h/y. Temperatures of 15 °C to 20 °C were the most common, with a cumulative average of 1214 h/y. **Table 4** also includes the normalized time distribution for the years 2004-2009. This normalisation was required because some data sets were shorter than 8760 hours, a full year, due to spring or autumn maintenance. The data was normalized to fit a distribution for a full year (8750 hours) by calculating the percentage of time at each interval, and increasing the absolute time to fit a full year.



**Figure 4** shows the normalized time percentage for the yearly data in **Table 4**, and **Figure 5** shows the overall normalized time distribution. From **Figures 4** and **5**, two aspects are noteworthy: a) the percent of time each material is exposed to various temperatures is most often between about 12 and 16% of the total exposure time (**Figure 4**), with 66% of the temperatures being between 0 and 25 °C (**Table 4**), and b) the curves are not Gaussian in shape and they show some form of bimodality.

Data in **Figure 5** was plotted as an overlap of two data sets in **Figure 6**; the two sets were chosen to be “hot” months and “cold” months. The hot months were defined as April to September, and the cold ones, as October to March. **Figure 6** highlights the most common temperatures for cold and hot at 0 °C to 5 °C, and 20 °C to 25 °C, respectively.

To determine if the bimodality arose from the building itself or the weather patterns, the data in **Figure 6** was plotted alongside the air temperature from Ottawa's Macdonald-Cartier Airport weather station. **Figure 7** shows the overlap for the year 2007. The temperature data had a similar bimodal distribution, which demonstrated that the modulation in the temperature data collected from the CCHT house was driven by the weather and the temperature variations in Ottawa, and that it was not intrinsic to the wall design or caused by the heating and cooling cycles of the test house. In other words, the temperature distribution in the exterior side of the wall is closely related to the distribution of outdoor temperatures.

A brief investigation into weather data for other Canadian cities indicated that bimodality in weather data is not common to all cities. Windsor, Ontario, was found to have a bimodal distribution with maxima near 0 °C and 20 °C, close to those for Ottawa, but Vancouver, British-Columbia, only showed a unimodal distribution with a maximum near 5 °C.



### 3.2. Temperature, South-facing Roof

The temperatures and the time of exposure to various temperatures for the south-facing roof were measured for 4 years from 2006 to 2009 similar to the south-facing wall. The difference, however, was in the proximity of the thermocouple to the exterior material plane that directly exposed to weather. On the roof, the thermocouple was onto the surface of the wood panel immediately under the bituminous covers, and there was no air gap like the one for the wall (compare **Figure 2** and **Figure 3**).

**Table 5** shows the time distribution for the temperature intervals in the south-facing roof. The temperature range varied from –35 °C to 75 °C. This range agreed with that measured by Winandy and Hatfield in Wisconsin (2007), from Ottawa. **Figure 8** provides a visual perspective of the temperature distribution with respect to time. The most common temperature was around 0 °C to 5 °C, with an average of 1087 h/y. Temperatures from –5 °C to +20 °C were most common, totalling just over 4087 h/y, 58% of the year. The distribution then tails off to just about 4 h/y for temperatures of 70 °C to 75 °C (**Table 5**).

As with the wall, the temperature distribution of the roof was not Gaussian (**Figure 8**). Its bimodal distribution is shown in **Figure 9**, which helped to highlight the most common winter temperatures, –5 °C to –10 °C, and the most common summer temperatures, 15 °C to 20 °C. In **Figure 9**, the temperature distribution for both the cold and hot months is also asymmetric and not quite Gaussian, with a long tail to the higher temperatures. In contrast to wall temperature distributions (**Figure 6**), this suggests that the roof temperature distributions may be broken down further to seasonal variations and average seasonal temperatures, if required.



### 3.3. Rate of Temperature Change

To determine the actual rates of temperature change in the field, values of $\Delta T/\Delta t$ were calculated for hourly changes of average temperatures between years of 2004 to 2009 and 2006 and 2009, for the south-facing wall and the south-facing roof, respectively. The results are shown in **Figure 10**. Rates of cooling at night, near 1 °C/h are much the same for the wall and the roof, as recognized from the parallel slopes form 0 to 7 hour. In the day time, from 8 to 14 hour, the heating rate of the roof was about three times larger than the wall, with maximum rates of 2.1 °C/h for the wall and 7.1 °C/h for roof. For the practical purpose of accelerated aging tests, these rates would be rounded off to 2 °C/h and 7 °C/h. After mid-day, cooling took effect, and cooling was more rapid for the roof than the wall.

### 3.4. Humidity, East-facing Wall

The temperature and relative humidity in the wall cavity was acquired over three years, 2004 to 2006, and their trend for an average year is shown in **Figure 11**. When temperature varied from –5 °C to +30 °C relative humidity varied from about 30 % to 90%. As a general rule, relative humidity decreases in the spring when temperatures rise, and the opposite occurs in the fall. Temperature and relative humidity cycles are thus inversely related. In contrast, temperature and absolute water content, in grams of water per cubic meter of air, follow the same trend (**Figure 12**). Higher temperatures contain more moisture than cold air, and as will be discussed later, this is an important issue in accelerated aging.



**Table 6** shows time-centric absolute moisture content, that is to say, the time per year in hours in the range of 1 g/m$^3$ and 55 g/m$^3$, including averages normalized to a full year (8760 days). **Figure 13** shows the absolute moisture content distribution for three years between 2004 and 2006: The median moisture concentration, the mid-point in the distribution, is 14 g/m$^3$ to 16 g/m$^3$, and the average of the range is near 27 g/m$^3$. However, the moisture data is not normally distributed, it is skewed to the lower values in the range. Thus, the average moisture content of 27 g/m$^3$ is a false measure of central tendency. The time-centric representation in **Figure 13** readily shows the mode at 6 g/m$^3$ to 8 g/m$^3$, that is, the most common absolute moisture content.

## 4. Discussion

### 4.1. Applications to building envelope products

In this work, the temperature and humidity data in the air space area of a building envelope with brick cladding, and onto a roof panel under the shingles and underlayment are reported. These conditions are relevant to the aging of different barriers or membranes that may be in the envelope (**Table 7**). The temperature and humidity data is most useful to develop accelerated aging methods for these materials. In accordance with established guidelines on testing and design for construction materials durability (CAN/ULC-S741 and ISO 13823), product composition and structure must be considered in such tests so that possible degradation pathways can be anticipated. However, in rare occasions will there be efforts to proceed with a strict service life predictions (SLP) of a building envelope product because of high expenses related to SLP, and failure is not catastrophic and does not put lives at risk. For the case of building envelope products and materials, it is generally sufficient to determine a minimum service life, the limit being 25 years for non-structural products used for small buildings as implied from the Part-9 of the National Building Code of Canada (Di Lenardo 2017). This is where the data produced in this research study is most useful: it allows for the development of more realistic test conditions to establish a lower limit to the service life, but without the provision for true SLP. Three specific examples of test conditions are detailed next: heat aging, moisture aging, and cyclic aging.

### 4.2. Heat aging

Building officials expect walls and roof membranes and barriers to last at least 25 years. To validate such durability, standard CAN/ULC-S741 (2008) calls for 32 days of heat aging of a water-sheathing membrane at 50ºC. The reported data, for instance in **Table 3**, helps to determine the suitability of these accelerated aging conditions in the estimation of a minimum service life.

The basis for heat aging and the time-temperature equivalence between laboratory and field aging is based on the relationship between the thermal oxidation rate k of the product and temperature T (Kelvin) as expressed by the Arrhenius relationship shown as Equation 1 (Pickett et al. 2008).

$$k = A\,e^{\left(\frac{-E_a}{RT}\right)} \quad (1)$$

where A is a pre-exponential factor, $E_a$ is the activation energy (Joules), which represents the ease with which the thermal barrier to thermal degradation is crossed, and R is the gas constant (8.314 $J.K^{-1}.mol^{-1}$). The relative rate of heat aging in the laboratory at temperature $T_2$ when compared to field aging at $T_1$ is given by Equation 2, which also defines the laboratory acceleration factor $A_F$.

$$A_F = \frac{k_2}{k_1} = e^{\left[\left(\frac{E_a}{8.314}\right)\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]} \quad (2)$$



In the simplest case, $T_1$ is the average field temperature and $T_2$ is an aging temperature selected such that it is lower than a material phase temperature or thermal transition, if any. As an example, $T_1$ can be considered as the overall yearly average temperature in the south-facing wall from **Table 3**, so $T_1$=12 °C, and $T_2$ can be taken as 50 °C from CAN/ULC-S741 (2008). As many water-sheathing membranes are made of high-density polyethylene (HDPE), a value of $E_a$= 72 kJ/mol can be applied to the calculation. The activation energy is material dependent. This $E_a$ is drawn from a study of the thermal oxidation of HDPE in the temperature range of the interest here (Yang 2006). On this basis, aging at 50 °C provide for the acceleration factor, $A_F$, of 36. So, as per standard CAN/CULC S741 (2008), 32 days of aging at 50 °C represents 36 × 32 days in the field, or 3.2 years. This is very much shorter than the service-life sought out for water-sheathing membrane. With **Equation 2**, it can be calculated that 14 days of heat aging at 90 °C would be an improved method to assess membrane performance. Indeed, with $T_2$=90 °C, $A_F$= 681, so that 681

× 14 days of aging in the laboratory is about 26 years of simulated field aging, which is consistent with a minimum service-life of 25 years.

The use of Equation 2 can of course be expanded to account for the fact that temperatures vary in the field, and thus $T_1$ is not constant. For instance, **Table 8** shows $A_F$ for aging temperatures $T_2$ from 90 °C to –25 °C with field temperatures $T_1$ = –25 °C, and also $T_1$ = 12 °C, and $E_a$=72 kJ/mol. The larger the gap between $T_1$ and $T_2$, the larger the acceleration factor. With $T_2$ at 90 °C and $T_1$ at –25 °C, the acceleration is a whopping value of 63036, but with $T_1$ at 12 °C, it is a more reasonable value of 681.

The challenge with a list of acceleration factors like those in **Table 8** is to decide which one to use to calculate the correspondence between laboratory aging time and service exposure time. i.e., the best $T_1$ and $T_2$ to use. The value for $T_2$ is always set to the laboratory aging temperature, say 90 °C, which must be high enough to provide for accelerated aging. Its upper bound may be set by a phase or a thermal transition, beyond which $E_a$ would no longer be representative of field aging (Flynn 1995). Similarly, a very large difference between $T_1$ and $T_2$ may lead to accelerated aging not representative of field aging (Flynn 1995, Celina 2005), this is to say, a different failure mechanism.



The selection of $T_1$ will depend on the intent of the test. For a general assessment of the effect of heat aging, $T_1$ can be selected based on data likes those in **Table 3** or **Figure 5**, where $T_1$ reflects the average field temperature, 12 °C for the data at hand. In contrast, the intent may be to compare the seasonal effect of thermal aging, in which case a bimodal temperature distribution like that in **Figure 6** can be used for the selection of $T_1$ values (either 0 ºC or 20 ºC, the maxima in the bimodal distribution in **Figure 6**). With $T_2$=90 °C and Ea = 72 kJ/mol, $T_1$ values of 0 ºC and 20 ºC respectively provide for $A_F$ = 2584 and $A_F$= 297. On the basis of these acceleration factors, 90 days of field aging in a single winter or summer would respectively be simulated by 20 hours and 175 hours in the laboratory at 90 ºC. If needed, these aging times could be used in elaborated cyclic aging methods that involve humidity variations or wetting/drying cycles, representative of winter and summer conditions.

### 4.3. Aging from exposure to moisture

The humidity data in **Table 6** and **Figure 13** suggest the important point that the wall cavity is rarely ever dry. Generally, accelerated heat aging of BEMs is done in a ventilated oven, and humidity is close to zero (CAN/ULC-S741). Based on the field humidity data presented in this study, for realistic aging conditions, the heat aging must always be coupled to humid aging. For consistency and comparison of the effect of different heating levels, the humid conditions must be maintained constant. Inattention in experimental design could prescribe heat aging at, say 40 °C, 60 °C, and 70 °C at a constant 50% RH. In these conditions, however, the absolute moisture contents are not constant. They are 25.5 g/m$^3$, 65 g/m$^3$, and 83 g/m$^3$, respectively. This is a great variation in humidity considering that degradation by hydrolysis depends on water concentration (Bélan et al. 1997). In these conditions, the effect of heat aging could not be compared on the same basis because both temperature and moisture contents are changing. **Figures 11 and 12** draw the attention to the different trends between RH and absolute moisture content in air with temperature change. The confusion brought about by the absolute moisture content in air versus the relative humidity is a long lasting one (Greaves 1881).

On the basis of the data in **Figure 13**, the absolute moisture content in heat aging should normally be set to a value of 6 to 8 g/m$^3$, the most common level, when designing the thermal aging conditions for BEMs. We suggest a value of 6.8 g/m$^3$, that is, 100% RH at 5 °C. **Table 9** shows the relative humidity required at different temperatures to maintain this absolute moisture content in air. Accelerated moisture aging could also be done at higher moisture contents, to further accelerate aging, but this is a subject beyond the scope of this paper.

### 4.4. Cyclic (dynamic) aging

Building envelope products are most often composite materials, where a significant interface exists between the components. The cyclic exposure to temperature or humidity variations can lead to differential expansion and contraction between the components, which may lead to adhesive failure at the interface: ASTM D1183 (2003), for instance, provides a method to study the durability of adhesives in cycling aging. In this procedure, samples are quickly exposed to a cold and then a hot temperature, a situation not likely to occur in service, and which may lead to interfacial failure due to thermal shock. Such thermal shock is also possible in the accelerated aging of bituminous materials by method ASTM D4798 (2011) when cycles B1 or B2 are used. **Figure 10** provides data to improve laboratory practices with heating or cooling rate representative of day-time heating or night-time cooling at rates of 2 °C/h and 7 °C/h for wall and roof materials, respectively.



### 4.5. Construction and climate issues

The CCHT house temperature and humidity data only hold for brick cladding. Red brick has a low thermal conductivity (λ) of 0.4 W/K/m (Kumaran 2001), which is not the case with all claddings. Polymer-based cladding with polyvinyl chloride (PVC) or polypropylene (PP) is in common use today; it is thin and its thermal conductivity is much higher than that of brick with a value near 11 W/m/K with 30 % talc (Weidenfeller et al. 2004). It is therefore expected that polymer-based cladding will allow for a greater average temperatures behind cladding than that reported here, and as a result the absolute moisture content may be lower. The same trend will apply to wood fibreboard or pine cladding, but to a lesser than with polymer cladding because of their greater thicknesses and low thermal conductivity of the wood products, $\lambda$ =0.05-0.1 W/m/K (Kumaran 2001). This implies that thermal aging will be slowest behind brick cladding than behind the other claddings. In accelerated aging tests, $T_1$ values somewhat greater than 12 °C may be considered for such cases.

Further consideration must also be given to the effect of climate change. Data reported here was collected a decade ago when $CO_2$ levels were about 385 ppm (WMO 2018). The $CO_2$ levels are greater than 400 ppm (WMO 2018) today, with a rise near 4 %, and they will keep rising to levels projected between 500 ppm to 970 ppm later this century (Incropera 2016). The years 2013-2017 have been the warmest on record to date, with an average temperature rise of 0.85 °C over Canada compared to the 1980-2010 average (WMO 2018). Given that dwellings are constructed to last for more than 50 years, further temperature rise due to climate change must be considered in the use of the reported data and the development of accelerated aging methods for BEMs.

## 5. Conclusion

Temperature and moisture concentration within the building envelope of a single family home having brick cladding and located in Ottawa, ON, was measured over five years, from 2004 to 2009.

The monthly temperatures for a south-facing wall varied from –25 °C to +45°C for the years 2004-2009, and the normalized average temperature showed a bimodal distribution, the peaks representing hot and cold months. The yearly average temperature was about 12 °C, but temperatures of 15 °C to 20 °C were most common, with a cumulative average of 1214 h/y. The temperature data obtained for the roof system had a larger range compared to that collected for the wall, specifically ranging between -35 °C and 75 °C. Similar to the results obtained for the wall, the roof temperature distribution showed bimodality, this being related to the outside temperature in Ottawa.

Daily temperature profiles were used to determine the extreme values for hourly rate of change in temperature. This was done for both the south-facing wall and roof systems. The maximum rate of change for the wall and the roof were calculated, respectively, as 2.1 °C/h and 7.1 °C/h. These results clearly indicate that the rate of change in roof temperature is much higher than that for a wall. This is a key factor to consider in respect to the accelerated aging of construction materials when undertaking durability tests in the laboratory.



The absolute moisture content was calculated from the relative humidity and temperature values for an east-facing wall during the years of 2004 to 2006. Relative humidity fluctuated from 40% to 90% over a typical year, with an average near 70%. The absolute moisture content in air was calculated to be 1 to 55 g/m$^3$ (grams water/m$^3$ of air) in the year, with the most common values being 10-16 g/m$^3$ occurring between June and September. During half of the year, the absolute moisture content in the envelope was about 7 g/m$^3$. This perhaps is the basic moisture content to consider for accelerated aging methods of components within wall assemblies.

The work described in this paper provides some basic field data for the future development of improved accelerated aging methods for BEMs. In this respect, time of exposure to average and maximum temperatures, average and maximum moisture contents, heating and cooling rates are important parameters to consider for aging methods. Several examples are provided to show how the field data can be applied to develop more realistic test conditions to estimate the service life of barrier membranes, i.e. test conditions for heat aging, aging due to exposure to moisture, and cyclic aging tests.


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# Figure legends

Figure 1. CCHT test house. Sensors location on wall and roof are indicated with a star.

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# Tables

**Table 1: Building envelope materials (BEMs), their basic functions, and NBC section relevant to standard requirements**

| Material | Function | NBC section |
|---|---|---|
| Siding | Structural weather protection | 9.27.2 to 9.27.12 |
| Drainage gap | Ventilation for drying undue water ingress | A-9.27.3.1 |
| Sheathing membrane | Protect wood frame from water and wind driven rain | 9.27.3.2 |
| Exterior sheathing | Provide support to water sheathing membrane, act as air barrier, and reinforce wood frame | 9.23.17 |
| Insulation | Enhance thermal comfort of occupant by reducing heat transfer through the wall | 9.25.2 |
| Vapour barrier | Protect wall insulation from undue moisture coming from the inside of the house | 9.25.4 |
| Interior sheathing | Protect the wood frame from fire | 9.29.5 to 9.29.9 |

445 **Table 2: Typical Canadian climatic conditions**

| Climate | Typical locations |
| --- | --- |
| Cold and wet | British Colombia coast, Maritimes |
| Cold and dry | Yukon, Northwest Territories, Nunavut |
| Hot and humid | Ontario peninsula |
| Hot and dry | Interior of British Colombia, Prairies |

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**Table 3: Average monthly temperatures (ºC) of the south-facing wall**

| Year | Jan | Feb | March | April | May | June | July | Aug | Sept | Oct | Nov | Dec | Yearly avg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2004** | -8.4 | 1. 8 | 5.7 | 10.9 | 17.7 | 22.0 | 24.3 | 23.3 | 22.6 | 13.4 | 6.5 | -3.2 | 11.4 |
| **2005** | -2.6 | 1. 8 | 6.6 | 12.8 | 16.1 | 25.9 | 26.2 | 25.8 | 22.7 | 13.2 | 5.3 | 0.3 | 12.8 |
| **2006** | 0.4 | 0.6 | 7.2 | 13.5 | 18.8 | 23.4 | 26.9 | 25.6 | 19.0 | 11.4 | 7.7 | 3.1 | 13.1 |
| **2007** | 0.5 | -0.8 | 4.6 | 10.9 | 19.7 | 23.6 | 23.7 | 25.3 | 22.8 | 15.5 | 6.0 | -2.1 | 12.5 |
| **2008** | -0.1 | 0.0 | 4.4 | 14.4 | 16.5 | 24.1 | 24.3 | 24.4 | 21.2 | 13.9 | 6.6 | -2.5 | 12.3 |
| **2009** | -5.1 | 1.7 | 7.2 | 12.1 | 16.3 | 22.4 | 22.3 | 24.9 | 21.2 | 11.2 | 9.5 | -0.7 | 11.9 |
| **Avg.** | -2.5 | 0.9 | 6.0 | 12.4 | 17.5 | 23.5 | 24.6 | 24.9 | 21.6 | 13.1 | 6.9 | -0.9 | 12.3 |
| **Sd. †** | 3.6 | 1.1 | 1.3 | 1.4 | 1.5 | 1.4 | 1.7 | 0.9 | 1.5 | 1.6 | 1.5 | 2.3 | 0.6 |

† Sd.: Standard Deviation

**Table 4: Time distribution in hours for temperature intervals of the south-facing wall**

| Year | < -25 | > -25 | > -20 | > -15 | > -10 | > -5 | >0 | >5 | >10 | >15 | >20 | >25 | >30 | >35 | >40 | >45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2004** | 0 | 63 | 107 | 265 | 502 | 691 | 1103 | 1103 | 1033 | 1216 | 1105 | 689 | 426 | 112 | 15 | 0 |
| **2005** | 0 | 29 | 52 | 222 | 487 | 825 | 1042 | 1164 | 990 | 1099 | 1096 | 785 | 567 | 280 | 40 | 0 |
| **2006** | 0 | 0 | 12 | 106 | 290 | 710 | 1341 | 1294 | 1114 | 1108 | 1018 | 746 | 521 | 223 | 9 | 0 |
| **2007** | 0 | 0 | 60 | 238 | 495 | 777 | 1073 | 1008 | 1062 | 1216 | 1068 | 780 | 505 | 243 | 32 | 0 |
| **2008** | 0 | 0 | 43 | 192 | 517 | 822 | 1220 | 940 | 999 | 1338 | 1152 | 763 | 438 | 134 | 26 | 4 |
| **2009** | 0 | 11 | 64 | 244 | 521 | 684 | 1010 | 1230 | 1212 | 1308 | 1137 | 657 | 395 | 151 | 22 | 0 |
| **Avg.** | 0 | 17 | 56 | 2111 | 469 | 752 | 1132 | 1123 | 1068 | 1214 | 1096 | 737 | 475 | 191 | 24 | 1.0 |
| **Sd.*** | 0 | 25 | 31 | 57 | 89 | 65 | 126 | 134 | 84 | 99 | 49 | 52 | 66 | 67 | 11 | 2 |
| **Normalized avg. hrs** | 0 | 18 | 58 | 216 | 479 | 768 | 1158 | 1149 | 1093 | 1242 | 1121 | 753 | 486 | 195 | 24 | 1 |

* Sd.: Standard Deviation

**Table 5: Time distribution in hours for temperature intervals of the south-facing roof**

| Year | <-30 | >-25 | >20 | >-15 | >-10 | >-5 | >0 | >5 | >10 | >15 | >20 | >25 | >30 | >35 | >40 | >45 | >50 | >55 | >60 | >65 | >70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2006** | 0 | 39 | 124 | 217 | 543 | 1029 | 1291 | 963 | 1012 | 871 | 555 | 386 | 306 | 264 | 224 | 201 | 199 | 142 | 97 | 27 | 8 |
| **2007** | 7 | 113 | 165 | 494 | 642 | 849 | 997 | 873 | 961 | 873 | 620 | 381 | 326 | 266 | 264 | 204 | 218 | 160 | 91 | 44 | 3 |
| **2008** | 0 | 43 | 172 | 429 | 742 | 1043 | 1094 | 765 | 912 | 960 | 572 | 417 | 306 | 259 | 249 | 206 | 194 | 131 | 68 | 22 | 5 |
| **2009** | 29 | 84 | 200 | 478 | 675 | 880 | 967 | 984 | 973 | 934 | 608 | 443 | 304 | 283 | 256 | 182 | 158 | 117 | 63 | 22 | 4 |
| **Avg.** | 9 | 70 | 165 | 405 | 651 | 950 | 1087 | 896 | 965 | 910 | 589 | 407 | 311 | 268 | 248 | 198 | 192 | 138 | 80 | 29 | 5 |
| **Sd.*** | 14 | 35 | 31 | 128 | 83 | 100 | 146 | 100 | 41 | 45 | 30 | 29 | 10 | 10 | 17 | 11 | 25 | 18 | 17 | 10 | 2 |

* Sd.: Standard Deviation

**Table 6: Number of hours at each absolute moisture content interval by year**

| Year | >0 | >2 | >5 | >10 | >15 | >20 | >25 | >30 | >40 | >50 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2004 | 306 | 1314 | 3910 | 2017 | 650 | 145 | 68 | 18 | 0 | 0 | 8428 |
| 2005 | 147 | 1327 | 4041 | 2206 | 851 | 105 | 1 | 0 | 0 | 0 | 8678 |
| 2006 | 34 | 796 | 3822 | 2097 | 1201 | 362 | 120 | 48 | 9 | 2 | 8491 |
| **Normalized avg. hrs** | 167 | 1176 | 4029 | 2162 | 925 | 210 | 65 | 23 | 3 | 1 | 8760 |

**Table 7. Barrier or membrane types**

| | |
|---|---|
| **Wall** | Plant-applied laminate & tape over panel joints (adhesive*) |
| | Fastened water-sheathing membranes & tape over laps (adhesive) |
| | Self-adhered water-sheathing membranes (adhesive) |
| | Liquid-applied membranes, flashing & caulks |
| | Exterior insulation panel (adhesive) |
| **Roof** | Bituminous overlayment |

* Adhesive is the secondary polymeric component

**Table 8. Acceleration factors $A_F$ from Equation 2 for different aging temperatures, $T_2$, with respect to field temperature $T_1$**

| $T_2$/°C | $A_F^{-25*}$ | $A_F^{12**}$ |
|---|---|---|
| 90 | 63036.45 | 680.72 |
| 70 | 15702.45 | 169.57 |
| 50 | 3293.26 | 35.56 |
| 30 | 562.05 | 6.07 |
| 10 | 74.72 | 0.81 |
| 5 | 43.12 | 0.47 |
| 0 | 24.39 | 0.26 |
| -5 | 13.50 | 0.15 |
| -10 | 7.31 | 0.08 |
| -20 | 1.99 | 0.02 |
| -25 | 1 | 0.01 |

* $T_1$ = –25 °C, $A_F^{-25}$

** $T_1$= 12 °C, $A_F^{12}$

**Table 9. Relative humidity values to maintain absolute moisture content of 6.8 g/m$^3$ at different temperatures.**

| T/ °C | 5 | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RH*/%** | 100 | 72 | 53 | 39 | 30 | 22 | 18 | 13 | 10 | 8 | 7 | 5 | 4 | 3 | 3 | 2 | 2 | 2 | 2 | 1 |

* RH values rounded off to the nearest unit.


Figure 1. CCHT test house. Sensors location on wall and roof are indicated with a star.

235x170mm (300 x 300 DPI)

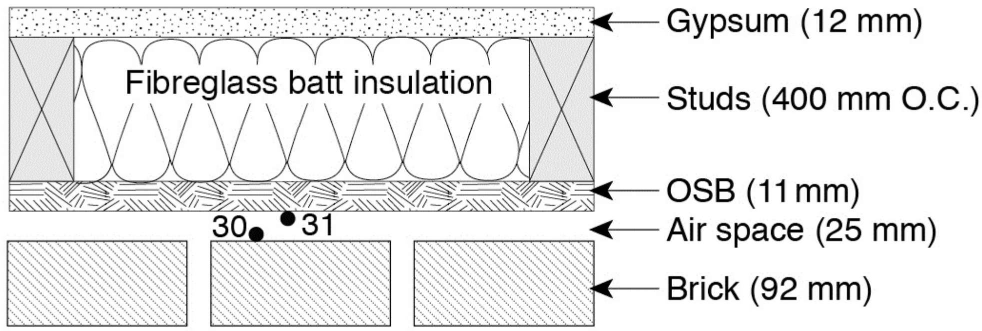


Figure 2: Layered wall structure for the CCHT house. Dots refer to sensor locations and numbers refer to sensor identity. Gypsum on top is on the interior side of the house and the exterior masonry was typical clay fired brick.

88x44mm (300 x 300 DPI)

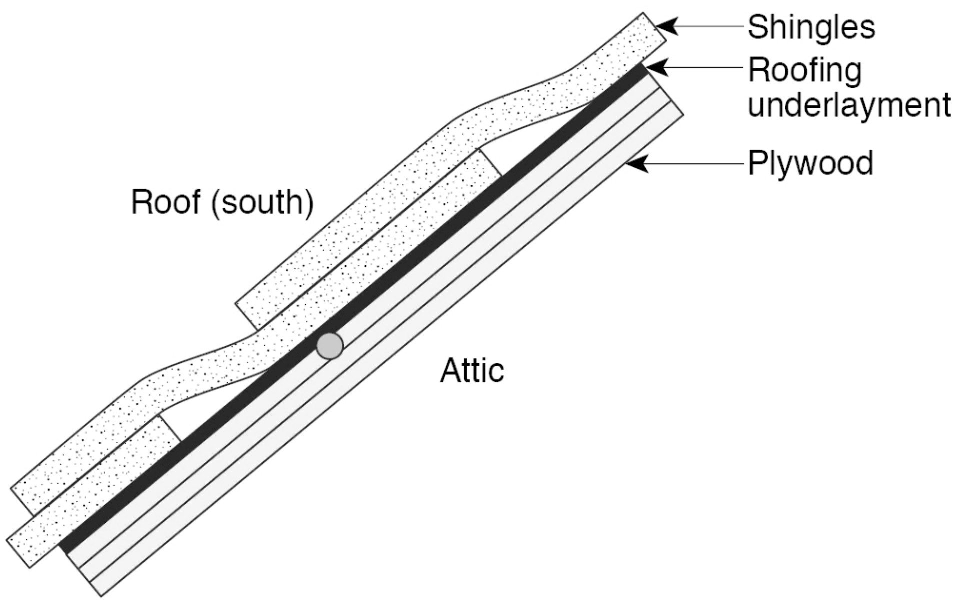


Figure 3: Layered roof structure for the CCHT house. The dot refers to the sensor location.

88x76mm (300 x 300 DPI)

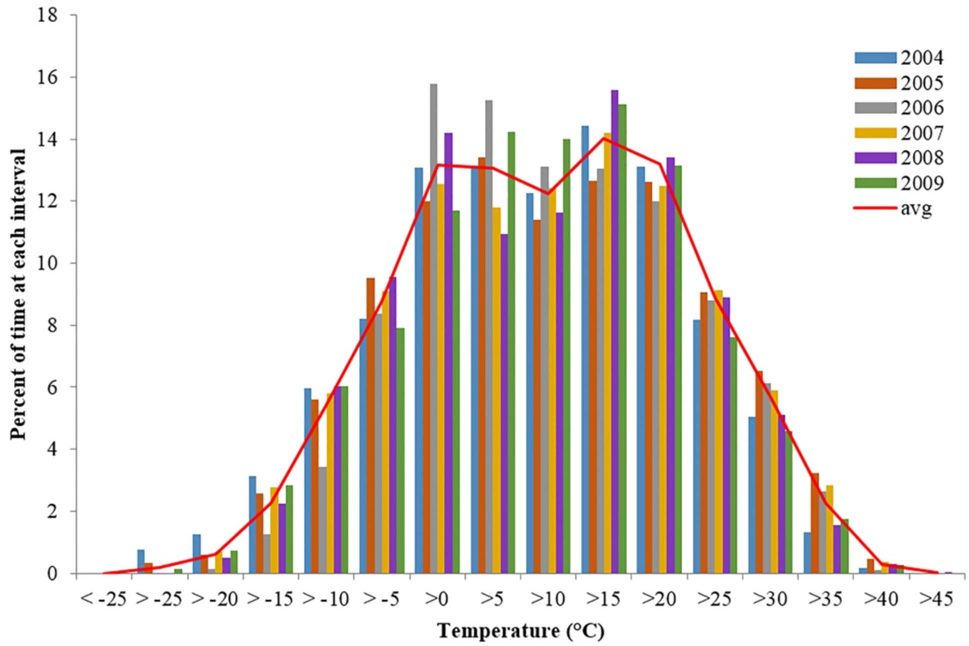


Figure 4: Normalized time percentage of temperature distributions for the south-facing wall over the years of 2004 to 2009 and the average of the years; bars from left to right at each temperature interval are in chronological order, 2004 to 2009.

258x172mm (300 x 300 DPI)

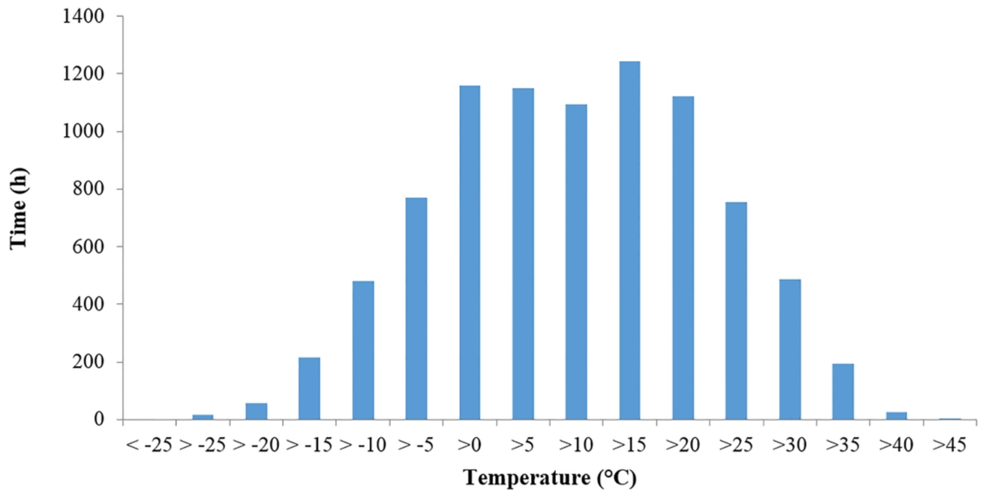


Figure 5: Average temperature distribution in normalized number of hours per temperature range for the south-facing wall.

294x152mm (300 x 300 DPI)

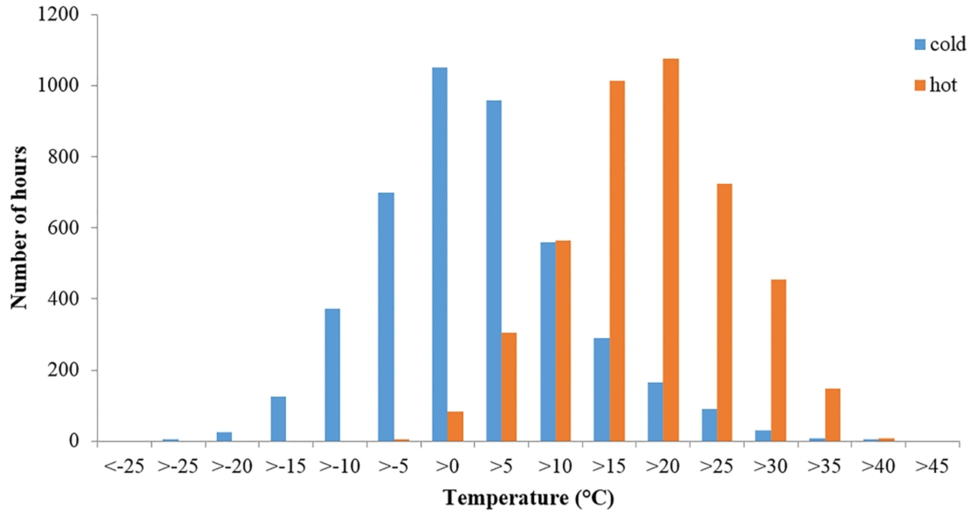


Figure 6: Average temperature distribution of the south-facing wall, data separated into hot months (April to September) and cold months (October to March).

298x163mm (300 x 300 DPI)

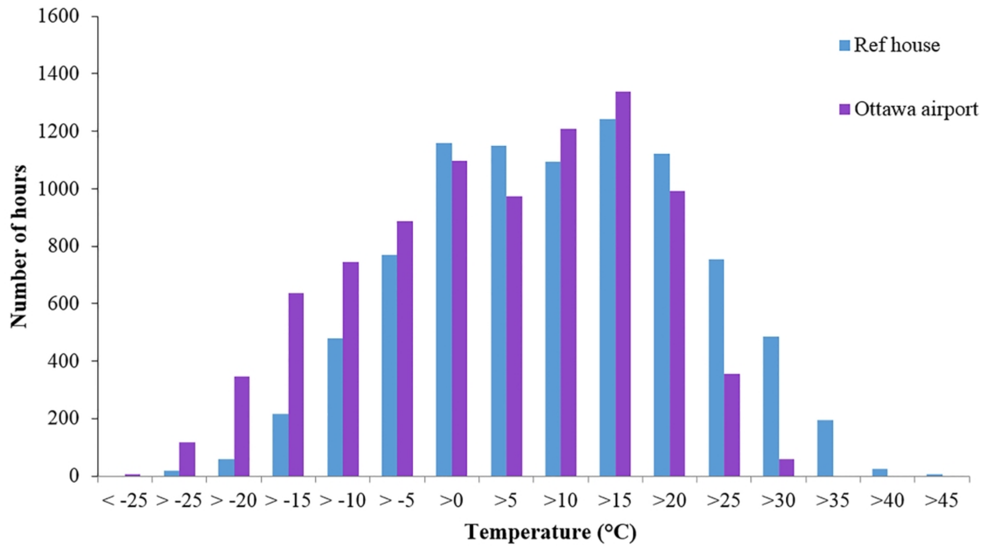


Figure 7: Comparison of temperature distribution in the south-facing wall of the CCHT house with the Ottawa's Macdonald-Cartier Airport weather station for 2007.

297x171mm (300 x 300 DPI)

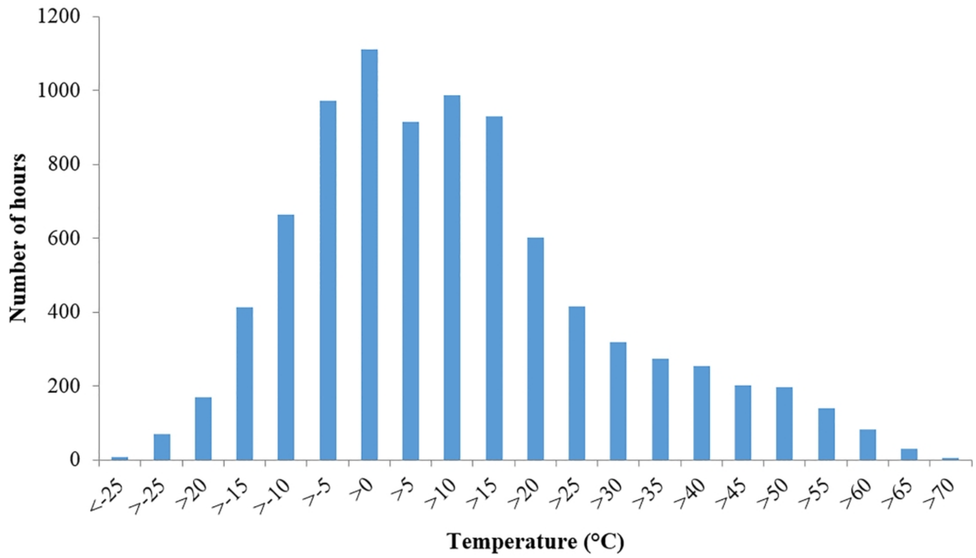


Figure 8: Temperature distribution in normalized number of hours per temperature range for the south-facing roof.

288x170mm (300 x 300 DPI)

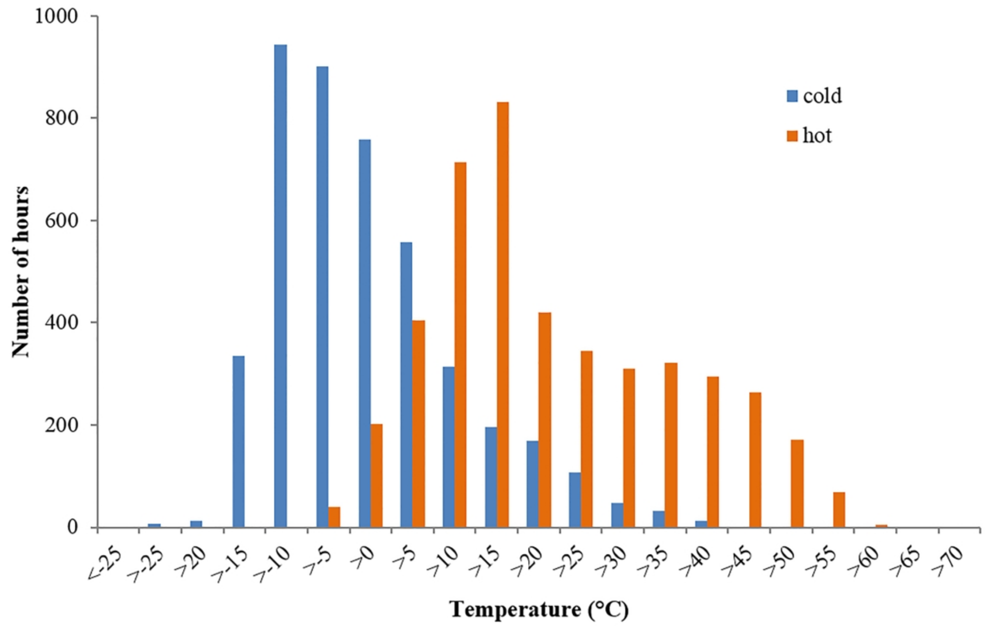


Figure 9: Temperature distribution of the south-facing roof, data separated into hot and cold months.

268x175mm (300 x 300 DPI)

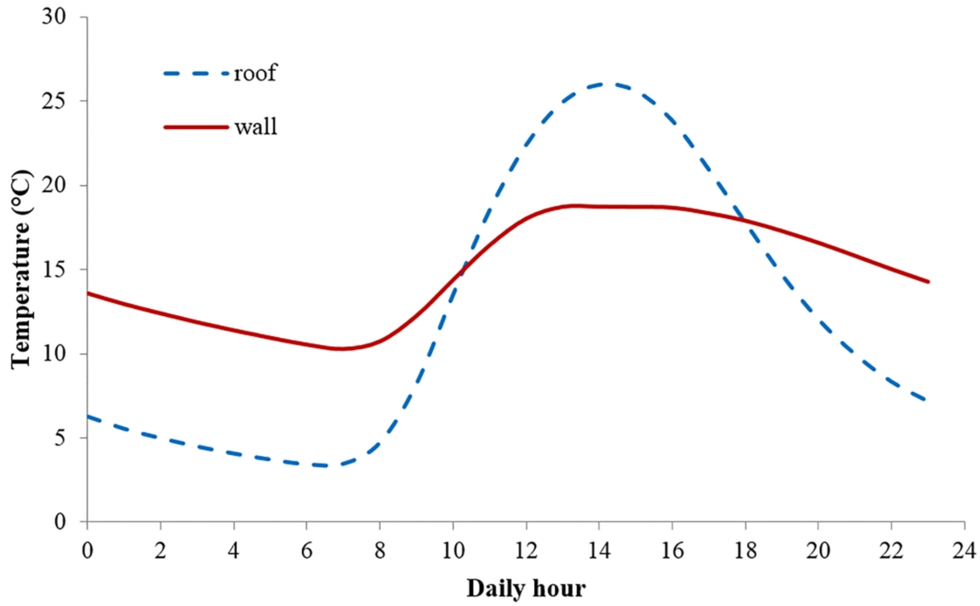


Figure 10: Average hourly temperature data for south-facing wall and roof.

255x164mm (300 x 300 DPI)

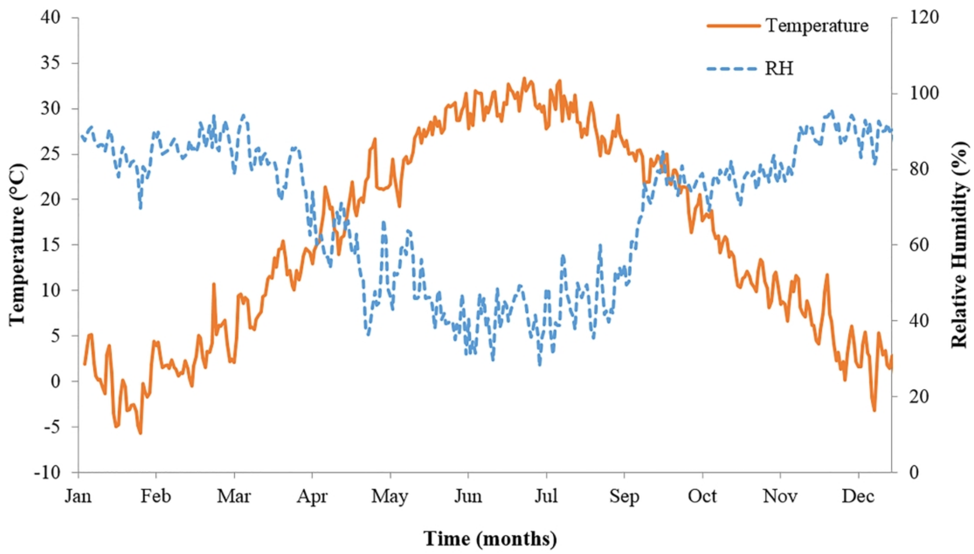


Figure 11: Temperature and RH for an average year using daily averages.

313x178mm (300 x 300 DPI)

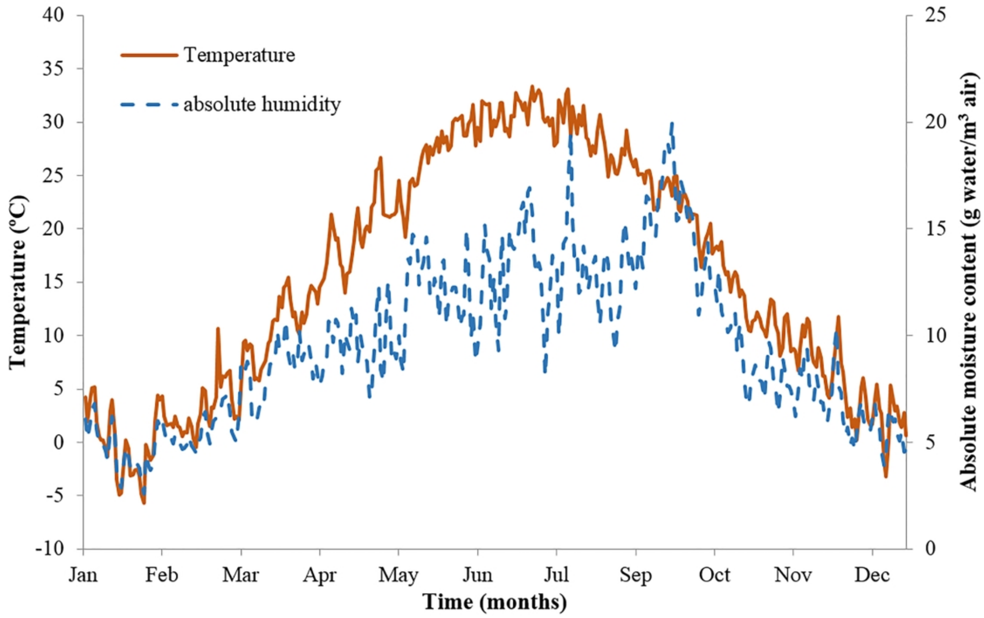


Figure 12: Temperature and absolute moisture content for an average year using daily averages.

289x181mm (300 x 300 DPI)

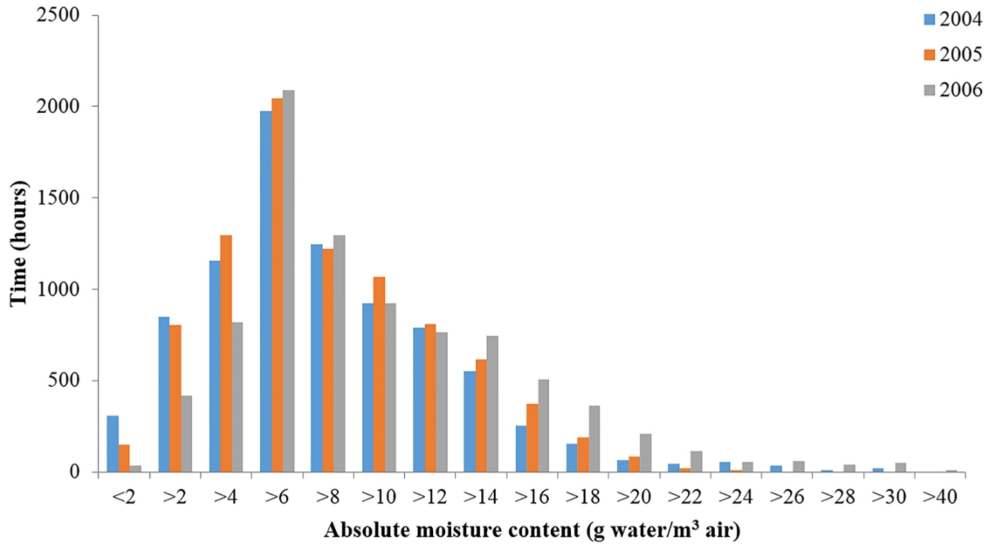


Figure 13: Distribution of absolute moisture content in the east-facing wall from 2004 to 2006.

291x168mm (300 x 300 DPI)