Canadian Journal of Civil Engineering

Hygrothermal performance of New Zealand wall constructions – meeting the durability requirements of the New Zealand Building Code

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2018-0589.R1
Manuscript Type:	Article
Date Submitted by the Author:	15-Jan-2019
Complete List of Authors:	Overton, Greg; BRANZ
Keyword:	WUFI, mould growth, condensation, timber-framed construction, durability
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1 Hygrothermal performance of New 2 Zealand wall constructions – meeting 3 the durability requirements of the 4 New Zealand Building Code

5 G. Overton,^a

6 ^aBRANZ Ltd, 1222 Moonshine Road, Judgeford, New Zealand

7 **Corresponding author:** G. Overton (greg.overton@branz.co.nz)

8 6850 words

9   **ABSTRACT**

10   The New Zealand Building Code (NZBC) is performance based. From a durability
11   perspective, compliance requires a practitioner to demonstrate that materials will remain
12   functional for the minimum periods specified. The NZBC also states that buildings must be
13   constructed to avoid the likelihood of fungal growth or the accumulation of contaminants on
14   linings and other building elements. Currently, there is no recognised method for
15   practitioners to use to demonstrate that a wall system can meet this requirement for the
16   required design life. In this paper, we consider how hygrothermal modelling, in conjunction
17   with the VTT mould index, may be used to form the basis of such a method. In the past,
18   there has been a discrepancy between predicted failures and field evidence, but the VTT
19   mould index appears to correlate much better with the successful in-service history of typical
20   New Zealand construction.

21   **Keywords:** WUFI, mould growth, condensation, durability, timber-framed construction

INTRODUCTION

Background – moisture problems in walls

A third of all residential building failure inspections in New Zealand are moisture related, but historically, condensation issues in walls are rare. Fig. 1 gives a breakdown of over 7000 moisture investigations in houses by BRANZ advisors and accredited technical advisors during the period 1975–2000 (Bassett et al, 2015). Indoor moisture and rainwater leakage through the envelope are clearly the most common problems, while condensation accumulation within walls was only witnessed on a handful of occasions.

Since the data in Figure 1 was collected, New Zealand has endured a systemic leaky building crisis, which has led to the widespread adoption of drainage cavities behind claddings. BRANZ also no longer has as much access to building failure statistics. From a condensation perspective, however, there is anecdotal evidence of problems of mould within wall spaces, but nothing more substantial than that. Despite this, the question of whether specific vapour control layers are needed in typical wall construction continues to be asked in New Zealand.

The issue of vapour control and condensation is the topic of this paper: Is the typical New Zealand construction style prone to supporting interstitial condensation and/or mould growth within the wall? How can industry practitioners prove that their designs will meet the requirements of the NZBC?

Results from a recent BRANZ study are presented and compared with failure criteria of ASHRAE 160 (ASHRAE 2009a, 2016), including the newer VTT mould index (Ojanen et al. 2010). The resulting discussion will highlight areas where more research is being undertaken at BRANZ to provide the New Zealand building industry with the tools they need to provide buildings that stand the test of time.

New Zealand Building Code and typical residential construction

New Zealand employs a performance-based code as opposed to a prescriptive code, that is, the NZBC states how a building must perform in its intended use rather than describing how the building must be designed and constructed. It covers aspects such as structural stability, fire safety, access, moisture control, durability, services and facilities, and energy efficiency. Of relevance in this paper are NZBC clauses B2 *Durability* and E3 *Indoor moisture* (MBIE 2017a, 2017b).

To demonstrate that a planned construction will comply with the NZBC, the applicant can use Acceptable Solutions, which are specific construction methods that are deemed to comply with the NZBC, or Verification Methods, which are methods of testing or calculation that, if passed, are deemed to comply. Anything that differs from these is an alternative method, where the applicant must prove that their design meets the requirements of the NZBC. If accepted by the consenting authority, this then becomes an Alternative Solution.

From a durability perspective, compliance requires a practitioner to demonstrate that materials will remain functional for the minimum periods specified (5, 15 or ≥ 50 years), depending on the criticality and accessibility of the building element. For the building elements within a wall, this typically means a durability requirement of 15 years, unless the element provides structural stability, in which case, the requirement is 50 years.

The Verification Method for NZBC clause B2 comprises proving the durability of a building element by one of more of the following:

- In-service history.
- Laboratory testing.
- Comparable performance of similar building elements.

The issue of condensation or mould growth within walls and roofs sits within NZBC clause E3 *Internal moisture*. The functional requirement is that buildings must be constructed to

71 avoid the likelihood of fungal growth or the accumulation of contaminants on linings and
72 other building elements.

73 Currently, there is no recognised method practitioners can use to demonstrate that a wall
74 system can meet the requirement of clause E3 for the required design life. However, many
75 New Zealand residential walls follow the same basic construction as shown in Fig. 2, and
76 since there has been little evidence of any systemic issue with this practice, compliance is
77 essentially demonstrated via history of use. The fact remains though that it would be
78 desirable to demonstrate 15 or 50-year durability via a robust analysis technique. Such a
79 method would allow for new design strategies, which may not have the same history of use
80 as traditional methods, to be assessed for compliance in a more consistent and fairer
81 manner.

82 Typical New Zealand residential wall construction comprises insulated timber framing
83 (typically 90 mm thick), lined on the inside with gypsum plasterboard (typically 10 or 12 mm
84 thick). Outboard of the framing, there is typically a flexible wall underlay (or weather-resistive
85 barrier) which has a very low vapour resistance. In recent years, there has been a significant
86 uptake of rigid underlays (akin to sheathing in North American construction), which may be
87 used in conjunction with a flexible underlay or on their own. Outboard of the underlay, there
88 is typically a 20 mm drainage cavity that is vented at the bottom of the wall, and outboard of
89 that is cladding.

90 In terms of vapour control, nothing specific is included in the typical construction, but the
91 internal linings will be painted with an acrylic paint and would therefore be akin to a Class 3
92 vapour barrier (ICC 2015a). The general advice has been that vapour barriers, in particular
93 polythene sheet, are unnecessary except in special cases, with a preference for the extra
94 drying ability provided by a low vapour resistance wall assembly. There is also no specific
95 airtightness requirement in the NZBC, but modern houses are being built more airtight than
96 ever before. This is due to changing construction practices over the years such as replacing

strip flooring with sheet flooring, aluminium joinery replacing timber joinery and so on. As a result, modern homes are likely to have an airtightness of about 4–5 air changes an hour (ach) when tested at 50 Pa (McNeil et al. 2012)

New Zealand exterior and interior climates

In this section, the exterior and interior environment are discussed. The reason for this is that the combination of indoor and outdoor conditions effectively forms the moisture load that a wall, or any other building element, has to endure.

Exterior climate

For the purposes of the NZBC, the country is split into three climate zones based on heating degree days, but Table 1 shows how New Zealand's climate would be classified using the International Energy Conservation Code (IECC) climate zones (ICC 2015b). The climate data used was generated by NIWA (Liley et al. 2008) for use in the Energy Efficiency and Conservation Authority's Home Energy Rating Scheme (HERS). The IECC employs a zone number that represents the thermal aspect of the climate (zone 1 being extremely hot and zone 8 being extremely cold) and a zone letter corresponding to the moisture classification (A = moist, B = dry, C = marine).

Based on this data, all the locations in New Zealand are either moist or marine with a thermal category ranging from 3 to 5. It should be noted that Queenstown and Lauder only just fall into the colder zone 5. The International Residential Code contains guidance on the use of Class 3 vapour barriers, and based on the climate zones in Table 1, the typical New Zealand construction falls within those guidelines.

Interior climate

New Zealand houses are typically spot heated. The living room may be heated by a woodburner or other source, but all other rooms may be unheated, with occupants relying on extra clothing for personal comfort in other rooms. This rudimentary approach to heating, combined with the fact that many houses have inadequate insulation levels, means indoor

temperatures are low. A BRANZ report measured temperature and relative humidity across 83 homes in New Zealand in 2016 (Plagmann et al. 2018, Draft Report, BRANZ). Fig. 3 and Fig. 4 show temperature and humidity distributions from bedrooms in that study. The red line in Fig. 3 corresponds to the WHO minimum recommended temperature of 18°C. The median temperature for the sample was 16.4°C. The red line in Fig. 4 corresponds to the median humidity of 64%.

A significant number of New Zealand homes are likely to be underventilated as well. Another BRANZ report measured in-service ventilation levels across winter in 30 homes using a perfluorocarbon tracer gas and found that about a quarter of these had average ventilation levels below 0.5 ach. (McNeil et al. 2012).

The significance of the indoor climate, with respect to assessing condensation risk, is that there is little consensus about the conditions that should be used as part of an analysis. As will be discussed later, this is one of the topics of ongoing research at BRANZ, but it can be said that the indoor climate is both quite cool and quite humid compared to what may be used in simulations elsewhere.

ASSESSING CONDENSATION RISK IN NEW ZEALAND AND OVERSEAS

In the past, the usual way of assessing whether a structure was prone to condensation damage was to perform a dew point calculation, as typified by the Glaser method (Glaser 1959) or the ASHRAE profile method (ASHRAE 2009a) and ascertain whether condensation would occur or accumulate. These methods entail looking at the steady state temperature and vapour pressure profiles through a structure subject to some assumed indoor and outdoor conditions. In the simplest form, if the vapour pressure is predicted to exceed the saturation vapour pressure at a point, condensation occurs and the structure may be deemed unacceptable. In a more sophisticated calculation, the vapour pressure at the point

in question is set to equal the saturation vapour pressure, and the process is repeated for the rest of the structure with this new boundary condition. This enables an estimate of the rate of condensation, which can then be compared with the storage capacity of the material. A similar method is employed in various standards, such as BS 5250:2011 (BSI 2011) in conjunction with BS EN ISO 13788:2012 (BSI 2012), which look for a situation where there is no net accumulation of condensation over a year. The downside of these calculations is they do not account well for any moisture storage in materials, varying material properties, transient conditions or airflow processes.

Over the last 20–30 years, computer software has been developed to enable a more sophisticated analysis of building elements. WUFI (Künzel 1995), developed at Fraunhofer IBP, is a prime example of this software, and this has been used extensively by BRANZ (McNeil et al. 2010) and other researchers across the world. Some newer standards such as ASHRAE 160 and BS EN 15026 (BSI 2007) reflect the growing use of computer hygrothermal models, but there is often still an emphasis on the designer to ascertain adequate boundary conditions, and airflow processes are notably absent from the standards. The output of a hygrothermal analysis is typically a time series of temperature and humidity at points of interest in the structure as well as time series of the moisture content of the constituent materials. This enables the analyst to consider failure criteria other than the accumulation of condensation – for example, corrosion of components or the extent of mould growth within a structure. Until recently, the default failure criterion in ASHRAE 160 was that the 30-day average relative humidity on any surface should not exceed 80%. This criterion is specifically aimed at preventing mould growth and corrosion. It is stated in ASHRAE 160 that mould-resistant materials may be able to resist higher surface relative humidities and that other criteria as specified by the manufacturer may be used, but this is usually unavailable.

LITERATURE

The subject of this paper is the need for assessment methods that correlate with field experience of successful wall assemblies, not the history of vapour control layers. However, a brief overview of this history is presented here to illustrate that the issue of vapour control has long been a contentious subject in building physics.

Rose (2010) presents a history of condensation control in walls and highlights some of the erroneous concepts that are still in use today. In that paper, it is stated that the adoption of vapour barriers was largely on the back of work conducted by Frank Rowley (Rowley 1939; Rowley et al. 1939), who can be considered the father of vapour barrier requirements (Straube 2001). Using Rowley's results, the US Federal Housing Administration published *Minimum Property Requirements*, which contained the first numerical values for vapour barrier permeance, attic ventilation and crawl space ventilation (FHA, 1942). That publication also included the rule that a vapour barrier (resistance of 17.5 MNs/g or greater) be placed on the warm side of the thermal insulation in cold climates.

Once the use of vapour barriers became commonplace, it became very difficult to alter the status quo. Rose puts this down to the fact the prescriptive requirements were put in place prior to the science and the establishment of performance criteria. Therefore, work such as that of Hutcheon (1953) from the National Research Council of Canada, which showed that airflow explained the occurrence of condensation better than diffusion, did not have the impact it should have had in the United States.

After the initial work in the 1940s and 1950s, there have been numerous studies about the effectiveness of vapour barriers. The reader is referred to an extensive literature review conducted by the Canadian Mortgage and Housing Corporation as part of a study on the use of polyethylene vapour barriers (Wilkinson et al. 2007). This review highlights the confusion about the topic of condensation control. The summary relating to above-grade walls showed

about a dozen studies where plastic sheeting vapour barriers may cause problems and about a dozen more that suggested problems would arise if this sheeting was omitted.

More recently overseas, a study by Glass et al. (2015a) compared field measurements in walls of two test structures with one-dimensional simulations using the hygrothermal modelling software WUFI (Künzel 1995). The key parameter under investigation here was the moisture content of the oriented strand board (OSB) sheathing in walls. WUFI approximately captured the seasonal increases of OSB moisture content, but the simulated OSB moisture contents tended to be considerably lower than measured values during summer. The experimental walls with an interior kraft vapour retarder recorded lower OSB moisture contents than the walls without any vapour retarder.

There has been research on condensation in New Zealand as well. Trethowen (1972) presents a theory of condensation and mildew that has a legacy that lives on today in the form of NZBC Acceptable Solution E3/AS1. The paper has useful data about moisture emission sources and uses simple principles to illustrate that ventilation is the major process removing internal moisture rather than diffusion. Trethowen (1976) discussed adequate design values for interior humidity and used a simple mass balance equation and energy considerations to conclude that the winter vapour pressure difference between indoors and outdoors would rarely be above 4 mbar in New Zealand, which was in line with measured values from eight houses. The paper called for a design method that took the moisture storage capacity of materials into account, because this could have a controlling effect on the room vapour pressure in normal structures. In a later paper, Trethowen (1979) discussed the relatively common occurrence of surface condensation in New Zealand (affecting 25–50% of homes) compared with the very low number of cases of interstitial condensation causing damage. In that paper, the Kieper diagram was used to illustrate that even trace quantities of ventilation behind the cladding were enough to outweigh the effects of the diffusion properties of the materials. Trethowen (1987) again reiterated that focusing on the use of vapour barriers was unnecessary, apart from where moisture conditions really are

forced (as in cold stores or swimming pool halls). In other cases, the structure itself would moderate vapour pressure difference between indoors and outdoors by absorbing and releasing moisture. That paper also refers to the discrepancy reported between laboratory work, which continues to forecast increasing moisture problems, and field evidence, which persistently shows this does not happen (Lieff and Trechsel 1980). A variety of studies are referenced that show that structural condensation is not a general problem whether winter is mild or severe, vapour barriers are present or not or insulation is present or not.

In October 2015, Lstiburek (2015) discussed some of the challenges faced by hygrothermal modelling software and, in particular, presented a possible way of simulating wall flows using the source-sink models in WUFI by using coupled air spaces.

In terms of failure criteria, Glass et al. (2017) describe a recent addendum to ASHRAE 160 (Addendum e), which is based on using a mould growth model developed by VTT in Finland (Ojanen et al. 2010). As well as a description of the mould index model, Glass's paper describes a number of experiments on walls and roofs whereby the existing 80% humidity rule predicted failed assemblies, but there was no evidence of mould growth. In contrast, the VTT mould index model, which is a 6-point scale indicating the severity of mould growth, aligned more satisfactorily with the field observations, including when mould was present. Using the VTT mould index, an index of 3, corresponding to visible mould growth is usually used as the threshold between a pass and a fail. Saber, Lacasse and Moore (2017) considered how the VTT mould index compared with the Canadian RHT (relative humidity and temperature) index, which is also a measure of the risk of mould formation or wood rot. That paper looked at the simulated performance of a reference, code-complaint wall assembly when subjected to water intrusion. Although the focus in that paper was to determine which of the analysed climates was most severe, the average mould index was found to exceed the value of 3 in a number of locations, suggesting that the reference wall would not pass the criterion whilst presumably having a track record of performance, although the study did assume a degree of ongoing water entry into the wall.

EXPERIMENTAL PERFORMANCE OF NEW ZEALAND

WALLS

Across 2014 and 2015, a study was conducted at the BRANZ research facility, with the overall aim of updating BRANZ's advice on the role of vapour control layers in New Zealand. For full details, refer to Overton (2016). The desire to update advice came from the fact that modern homes are being built more airtight than previously, despite there being no focus on air barriers per se, and with higher levels of insulation. There is also evidence that a significant percentage of houses are underventilated (McNeil et al. 2012). Together, these changes mean the risk of interstitial condensation may have increased. There is a higher moisture load due to reasonably airtight but poorly ventilated construction, and there are colder temperatures outboard of the insulation because of the higher level of insulation.

The aim of the study was to generate a range of representative computer models of walls in New Zealand that were benchmarked by experiment. These models were to then be used to:

- provide an up-to-date answer regarding the role of vapour barriers in New Zealand construction
- for the range of New Zealand climates, define the various tipping points at which current construction trends will result in a moisture accumulation problem
- provide specific guidance in cases where there are multiple layers of insulation within the wall, for example, fibreglass batts in conjunction with a polystyrene sheathing – this is relatively uncommon in New Zealand, and so no specific advice from BRANZ existed.

Experimental method

The experiment consisted of constructing a number of wall specimens and installing them in a test building. The walls were instrumented with thermocouples and humidity probes, and the conditions in the walls were monitored from 1 May 2014 until the end of 2016. The interior space of the test building was heated and occasionally humidified. In addition to the

instrumentation, a borescope camera was used to inspect the inside face of the sheathing/underlay in the walls during humidification periods.

These results were then used to benchmark WUFI simulations of the walls. These simulation models were then used to investigate wall performance in areas other than the BRANZ site and subjected to different indoor conditions. The following sections describe both the experimental approach and the analysis method in more detail.

Wall specimens and test building

The wall specimens in this study were all 1.2 m wide x 2.4 m high to allow installation into a test building on the BRANZ site. The test building (see Fig. 5) had 24 separate openings for wall specimens – 10 on each of the north and south elevations and two on the east and west elevations. For this study, five of the openings on the south elevation and one on the north elevation were used.

Fig. 2 shows a typical cross-section through a wall specimen. The framing layout was slightly different to typical New Zealand construction but was in accordance with previous studies at BRANZ. Studs were located 300 mm from each side. Nogs were located at 800mm centres in the central portion of the frame and at 1,200 mm centres in the two outer spaces. The wall specimens were all clad with fibre-cement sheet over timber cavity battens. This cladding was preprimed on the exterior face and then had two coats of acrylic paint applied to the exterior face. The interior lining of the wall specimens was 13 mm thick gypsum plasterboard.

Once installed into the test building, a 10 mm hole was drilled through the interior lining to allow a borescope to be inserted through a precut slit in the insulation and view the condition of the sheathing. This hole was sealed with tape up when the borescope was not being used.

Table 2 contains details of the wall specimens. Where the wall specimens had a flexible underlay, it was generally a separate component in the wall. However, wall 8 had a sheet thermal break that had a flexible wall underlay bonded to its exterior surface. This is referred

to as an integrated underlay in Table 2. The original test specimens (year 1) were all steel-framed with various sheet thermal breaks. This was because the experimental design was initially focused on the use of multiple layers of insulation in walls. Of those walls, walls 7 and 8 were expected to be the worst cases because of the combination of a relatively thin layer of XPS and an unpainted internal lining. With the majority of the wall's vapour resistance on the cold side of the wall, it was likely that relatively moisture laden air would be cooled to the point where condensation occurred. For walls with thicker XPS, the temperature on the inside of the sheathing would be warmer, thus lowering the probability of condensation. In year 2, it was decided to also investigate timber-framed walls and so some of the test specimens were replaced. The worst-case wall from year 1 (wall 8) was retained. Year 2 was split into two parts, representing where the specimens were again modified. Walls 6 and 9 had insulation with a higher R-value installed to try and cause condensation. Wall 8 had the interior lining painted to see if this was enough to stop condensation forming. Where a smart vapour retarder (SVR) was included in a test specimen, it was located adjacent to the interior lining.

Fig. 6 shows some representative data for the vapour resistance of several materials used in the experiment. Note the plywood used in this experiment was 12 mm thick and sourced from New Zealand. The data shown in the graph is intended to be representative only, for example, not all smart vapour retarders will have the profile shown in Fig. 6.

Instrumentation

For each wall, the temperature and humidity were recorded at 15-minute intervals in the following locations:

- At the interface between insulation and internal lining (or SVR).
- At the interface between insulation and sheathing.
- In the drainage cavity.

In addition, surface temperatures were measured on the interior and exterior of the walls.

Type-T thermocouples were used to measure the temperatures, and Honeywell HIH-4000-001 sensors were used to measure the relative humidity. The humidity sensors have a standard accuracy of $\pm 3.5\%$ RH and were calibrated using an on-site humidity generator. A standard linear relationship between output voltage and relative humidity was used for relative humidity values up to 90%. A quadratic polynomial was used to fit the data between relative humidities of 90% and 96%. This approach was used to gain more accurate measurements when the relative humidity was in excess of 90%. Temperature corrections were applied in accordance with the manufacturer's data sheet using the data from the corresponding thermocouple.

The temperature and humidity inside the test building were controlled using heaters and humidifiers in conjunction with simple on/off controls. Heating was activated if the indoor temperature was less than 20°C, and humidification was activated if the room relative humidity was less than 70%. Two pedestal fans were used to ensure the indoor air was reasonably well mixed. The humidification was not always sufficient to raise the relative humidity to 70%, but the precise value of relative humidity was not considered crucial. The main intention was that it was measured and was sufficient to lead to interstitial condensation in some of the wall specimens at certain times.

The outdoor climate was measured using a weatherstation on the BRANZ site. Longwave and shortwave radiation sensors were used to enable the full radiation balance calculation to be performed in WUFI.

Photographic evidence of condensation

Most of the walls recorded a humidity of 100% at the plane of the sheathing/underlay at some point during the experiment. However, only a limited number accumulated moisture to the point that it could be seen as droplets on the sheathing. This section contains images from the worst-case walls (walls 7 and 8) and the typical timber-framed wall (wall 9).

Walls 7 and 8 (2014)

These two walls were almost identical in construction, the main features being a 10 mm XPS sheathing and an unpainted interior lining. Condensation was seen on the sheathing throughout the humidification period from 17 July 2014 to when humidification stopped on 6 August. Liquid droplets remained visible until 12 August (Fig.).

Wall 9 (2015)

Wall 9, with a flexible underlay, showed no evidence of liquid droplets during the first phase of year 2 (2015). During the second phase, where a higher R-value insulation was installed, liquid droplets were visible occasionally in wall 9, as shown in Fig. 8. Note that this was with an unpainted interior lining, had the lining been painted, as is usually the case in practice, these drops may not have formed under these conditions.

WUFI simulation and analysis method

BRANZ has access to a number of the WUFI simulation tools. The approach used in this study was to start with the most simple models possible and then refine them as necessary.

It was thought that these simple models would be significantly different to the measured results and then aspects such as wall ventilation or moving from one-dimensional models to two-dimensional models would be employed to hopefully improve this agreement.

The reason for using the simplest model possible was that a desired outcome of the study was to have a range of trusted working models that could be used to explore a range of climates. The reasonably simple one-dimensional models lend themselves to this kind of parametric study more so than two-dimensional models.

Models of the experimental walls

The models of the experimental walls relied quite heavily on the material data available in the WUFI database. Measurements of the vapour permeability and thermal conductivity of the XPS sheathing were conducted as well as vapour permeability of unpainted and painted

plasterboard and the fibre-cement cladding. These measurements were in line with existing materials in the WUFI database and so these were generally used as a basis for the models in this study. One point in particular to note is that the ASHRAE 1018-RP data (Kumaran et al. 2002) for the moisture storage function of the fibreglass insulation was chosen rather than the default moisture storage function used in WUFI, which corresponds to mineral wool.

WUFI modelling of experimental walls

The results in this section show a comparison between the measured data and a numerical simulation of the walls using WUFI Pro V5.3. For clarity, data from wall 8 is shown, though the agreement in this case is representative of all the walls.

All of the results in this section relate to one-dimensional models, so the effect from any framing is not included. No ventilation or driving rain are included in these models. These aspects and the use of two-dimensional models are discussed later.

Fig. a) to e) shows the 24-hour averaged measured and simulated results for wall 8 in year 1. The shaded regions are when humidification was active. These graphs show that the temperatures are predicted reasonably well throughout the wall. The relative humidity is significantly different at the sheathing during non-humidification periods and is significantly different in the cavity throughout the experiment

SIMULATED PERFORMANCE OF NEW ZEALAND WALLS

The results in the previous section pertain to the conditions in the BRANZ test building, where the humidity was such that condensation conditions were forced upon the walls. Accepting the difference between the experimental data and the WUFI models of the walls, which will be discussed later, the WUFI models were then used to explore the behaviour across different locations in New Zealand.

Boundary conditions

Exterior climate

The outdoor climates used in the analysis were those built into WUFI, which in turn are those from the HERS scheme and discussed previously. These climate files do not therefore represent worst-case data, but rather a typical meteorological year.

Indoor climate

There is no recognised standard indoor climate for New Zealand homes. Various standards around the world have guidance for what should be used as the indoor climate, but it is unknown how representative these are for New Zealand. The approach used in this study was to use a modified version of the intermediate method in ASHRAE 160.

In the intermediate method, the indoor humidity is a function of the 24-hour running-average outdoor vapour pressure, the moisture generation rate inside the building and the ventilation rate inside the building. It is worth noting that, as implemented in WUFI, the humidity has an upper cut-off at 70%. There appears to be no physical reason why this would happen in reality other than by user intervention, i.e. ventilating more when humidity is high.

The indoor temperature is a function of the 24-hour running-average outdoor temperature, the heating setpoint and the indoor temperature shift (the difference between indoor and outdoor temperature without any purchased heat). In ASHRAE 160, the setpoint is 18.3°C, and the temperature shift is 2.8°C.

In the absence of any agreed temperature and humidity profile for New Zealand, the heating setpoint was chosen to be 16°C with a temperature shift of 3°C for this analysis. Results are also shown for when the indoor humidity is allowed to exceed 70%.

The other parameters assumed for this analysis were an air change rate of 0.5 ach, a building volume of 450 m³ and a moisture generation rate of 1.16×10^{-4} kg/s, corresponding to a three-bedroom house, in ASHRAE 160.

Results

Fig. and Fig. show the relative humidity at the plane of the sheathing/underlay in a typical New Zealand timber-framed wall, a wall with 10mm XPS sheathing, a wall with 10mm plywood sheathing and a wall with an SVR installed adjacent to the interior lining. The older ASHRAE 160 80% RH criterion and the VTT mould index model results are also shown. The simulations are of south-facing (i.e. cold) walls in Auckland and Queenstown. Auckland was chosen because it is the largest population centre. Queenstown was chosen because this is where the anecdotal perception of condensation problems is most evident.

For comparison, Fig. shows the results for Auckland when the indoor relative humidity cut-off is 70%, as is usual ASHRAE 160 practice. Note the reduction in the mould index for each type of wall.

Of the results shown here, the only wall to pass the older ASHRAE 160 80% criteria is the wall with an SVR, located in Queenstown. When we look at the newer VTT mould index criteria, a very different picture is shown. In Queenstown, the only questionable assembly would be the XPS sheathing case. In Auckland, the typical wall with a flexible underlay would be borderline acceptable, with mould only really being strongly predicted for the wall with plywood sheathing. When the indoor relative humidity is limited to 70% (by human intervention), all but one of the simulated walls pass the mould index criterion.

DISCUSSION

Agreement between hydrothermal models and real walls

Agreement between the experimental data and the WUFI simulation is not as good as it was hoped to be prior to the experiment. The reason for this appears to be related to the moisture levels in the cavities of the walls, with the measured relative humidity in each cavity being higher than expected. To illustrate this further, Fig. shows the 24-hour averaged

vapour pressure calculated from the measured temperatures and humidities for the indoors, outdoors and cavity from year 1 in wall 8.

During the humidification period (the shaded region), the indoor vapour pressure is higher than the outdoor vapour pressure due to humidification. Once humidification is finished, the indoor and outdoor vapour pressures are approximately equal, as expected. However, particularly after the humidification period, the vapour pressure in the cavity is higher than both indoors and outdoors, suggesting moisture is somehow being added to the space. This moisture source has still not been satisfactorily explained, despite investigating hygroscopic buffering and water entry. The difference between modelled and experimental data is being explored further in BRANZ's model buildings project, which is discussed below.

Failure criteria for New Zealand walls

Historically, the failure criteria used by BRANZ for the condensation risk within walls has been the accumulation of liquid moisture. Overton (2016) was the source of the experimental data in this current paper and, using Queenstown as an example, concluded that moisture accumulation would only occur in the presence of extreme indoor environments – for example, ventilation rates below 0.3 ach in the indoor space. The same paper noted, and this is reinforced here, that the vast majority of wall constructions employed in New Zealand would fail the older ASHRAE 160 80% criteria. Therefore, although accumulation of condensate was unlikely to be a common failure mechanism in New Zealand, almost all of the country's walls should be experiencing mould growth within the construction. The failure statistics in Fig. 1 suggest this is not the case. Also of note is the severity of the humidity and mould index in Auckland compared with Queenstown. Queenstown is usually perceived to be of higher condensation risk than Auckland (a cold climate versus a marine climate), but the analysis shows that the opposite is actually true. This is due to the fact that the climate is warmer and more humid in Auckland across the year, so the conditions suitable for mould growth are more common.

As shown in Fig. 10 to Fig. 12, the mould index shows that mould growth inside New Zealand walls should be relatively uncommon, which does agree with our knowledge of failed buildings. Therefore, this would seem to be a more suitable basis for any future verification methods for NZBC clause E3.

The results shown in this paper are indicative of the effect of moving to the newer criterion of ASHRAE 160, but there is still work to do to make a truly satisfactory assessment method. The VTT mould index seems to agree with our field experience of successful walls, but it would be desirable to obtain agreement with higher mould indices and failed walls as well, in the same way as observed by Glass (2017). In addition, data on the sensitivity to mould for New Zealand materials would be of benefit, as would a realistic New Zealand indoor climate profile.

All of the shortcomings are being addressed by future BRANZ research initiatives. We have a range of surveys planned, from highly detailed monitoring in our model buildings project, to less detailed but more widespread monitoring as part of the 2018 NZ General Social Survey, which is coordinated by Statistics New Zealand. Among other things, that work should help inform us as to the range of indoor climates provided by our housing stock.

CONCLUSIONS

The NZBC and the need for a means for demonstrating durability of wall assemblies has been described. New Zealand walls do not typically have specific vapour control layers for limiting condensation risk. However, based on a comparison with overseas climates and the International Residential Code, New Zealand practice would fall within IRC guidelines. Despite this, questions on the use of vapour control layers continue to be raised in New Zealand.

An earlier BRANZ study (Overton, 2016), which aimed to provide updated information on the use of vapour control layers, has been described. A series of wall specimens were installed into a BRANZ test building, which was humidified periodically over a 2-year period.

Measurements within the walls showed that the humidity at the sheathing/underlay reached 100% in almost all of the walls, but this only manifested itself as liquid droplets in a minority of walls. The only walls that did not reach 100% humidity were those that had an SVR between the interior lining and the insulation in the stud space.

The hygrothermal simulation software WUFI was used to simulate the walls. It was originally expected that, for the simulation and measurements, airflow process would need to be accounted for. In general, the WUFI models agreed well with the experiment without this addition, with the main exception being the moisture level in the cavity. This difference is still being investigated.

WUFI was then used to simulate the behaviour of a range of wall assemblies in Auckland and Queenstown. Queenstown is usually perceived to be of higher condensation risk than Auckland (a cold climate versus a marine climate), but the analysis shows that the opposite is actually true. Also of note is the fact that all but one of the walls shown in this paper would fail the older ASHRAE 160 80% criteria for mould growth. The newer VTT mould index suggests the wall constructions would perform much better, which aligns with our field experience. The VTT mould index would therefore be a prime candidate for the basis of any verification method in the NZBC in relation to indoor moisture.

Acknowledgements

This work was funded by the Building Research Levy.

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620

621 **Fig. 1.** Moisture failure investigations in New Zealand.

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623 **Fig. 2.** Section through a typical New Zealand wall construction.

624 **Fig. 3.** Temperatures in New Zealand bedrooms.

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626 **Fig. 4.** Humidities in New Zealand bedrooms.

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628 **Fig. 5.** Test building on the BRANZ site – weatherstation shown in foreground.

629 **Fig. 6.** Vapour resistances of layers within the test walls.

630 **Fig. 7.** Walls 7 and 8 – condensation visible for sustained periods.

631 **Fig. 8.** Wall 9 – no condensation visible in part 1 of year 2. Condensation visible on flexible underlay
632 with higher level of insulation (and unpainted) lining.

633 **Fig. 9.** Measured and simulated data for wall 8 in year 1.

634 **Fig. 10.** Performance of a range of wall assemblies in Auckland, New Zealand.

635 **Fig. 11.** Performance of a range of wall assemblies in Queenstown, New Zealand.

636 **Fig. 12.** Performance of a range of wall assemblies in Auckland (max. indoor RH = 70%).

637 **Fig. 13.** Vapour pressure from temperature and humidity measurements in wall 8.

638

639

640 **Table 1.** IECC climate classification based on HERS climates.

Location	IECC climate classification
Auckland	3C
Christchurch	4A
Dunedin	4C
Hokitika	4A
Kaitaia	3C
Lauder	5C
Napier	3C
Nelson	3C
New Plymouth	3C
Queenstown	5A
Tauranga	3C
Wellington	4C

641

642 **Table 2.** Details of wall specimens.

	Wall number (position in building)	Framing (90 mm deep)	Sheathing	R-value of fibreglass insulation (m ² .°C/W)	Underlay	SVR	Interior lining	Orientation
Year 1 (winter 2014)	5	Steel	30 mm XPS	R2.8	Separate	No	Painted	South
	6	Steel	30 mm XPS	R2.8	None	No	Painted	South
	7	Steel	10 mm XPS	R2.8	Separate	No	Unpainted	South
	8	Steel	10 mm XPS	R2.8	Integrated	No	Unpainted	South
	9	Steel	10 mm XPS	R2.8	Separate	No	Painted	South
	20	Steel	10 mm XPS	R2.8	Separate	No	Unpainted	North
Year 2 (winter 2015) Part 1	6	Timber	Plywood	R1.8	Separate	No	Unpainted	South
	7	Timber	None	R1.8	Separate	Yes	Unpainted	South
	8	Steel	10 mm XPS	R2.8	Integrated	No	Unpainted	South
	9	Timber	None	R1.8	Separate	No	Unpainted	South
	20	Timber	None	R1.8	Separate	Yes	Unpainted	North
Year 2 (winter 2015) Part 2	6	Timber	Plywood	R2.8	Separate	No	Unpainted	South
	7	Timber	None	R1.8	Separate	Yes	Unpainted	South
	8	Steel	10 mm XPS	R2.8	Integrated	No	Painted	South
	9	Timber	None	R2.8	Separate	No	Unpainted	South
	20	Timber	None	R1.8	Separate	Yes	Unpainted	North

643

59x55mm (220 x 220 DPI)