# R-values, humidity and health: Case studies from Auckland

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# Introduction

The Auckland winter is rainy season. High indoor relative humidity is a major issue for Auckland housing indoor health conditions (Figure 1). According to international and national standards, the indoor relative humidity should be lower than 60% for indoor air quality [1-5]. Most of the health effects such as bacteria, viruses, fungi, mites, etc. have increases associate with very high indoor relative humidity (Figure 2). Maintaining indoor relative humidity between 40% and 60% can minimize the indirect health effects. The abundance of two major causes of allergy, mites and fungi in New Zealand housing, increase proportionately with average indoor relative humidity [6]. New Zealand has some of the highest levels of house dust mite allergens in the world [6]. Visible mould growth on indoor surfaces is a common problem in over 30% of New Zealand houses [7]. **Auckland house thermal design not only focuses on indoor air temperatures but also the winter indoor relative humidity level.**

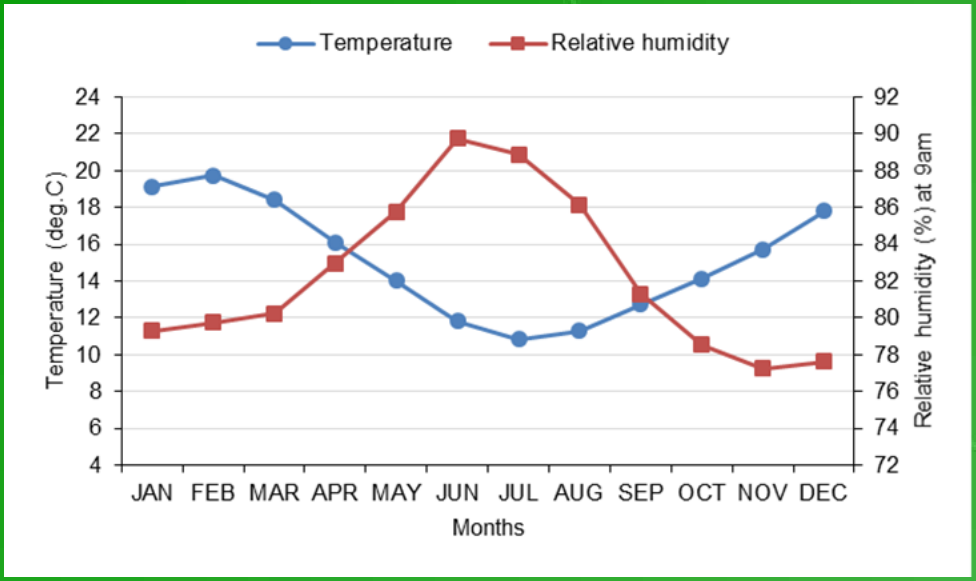


Figure 1 Auckland monthly mean temperature and relative humidity (source: NIWA)

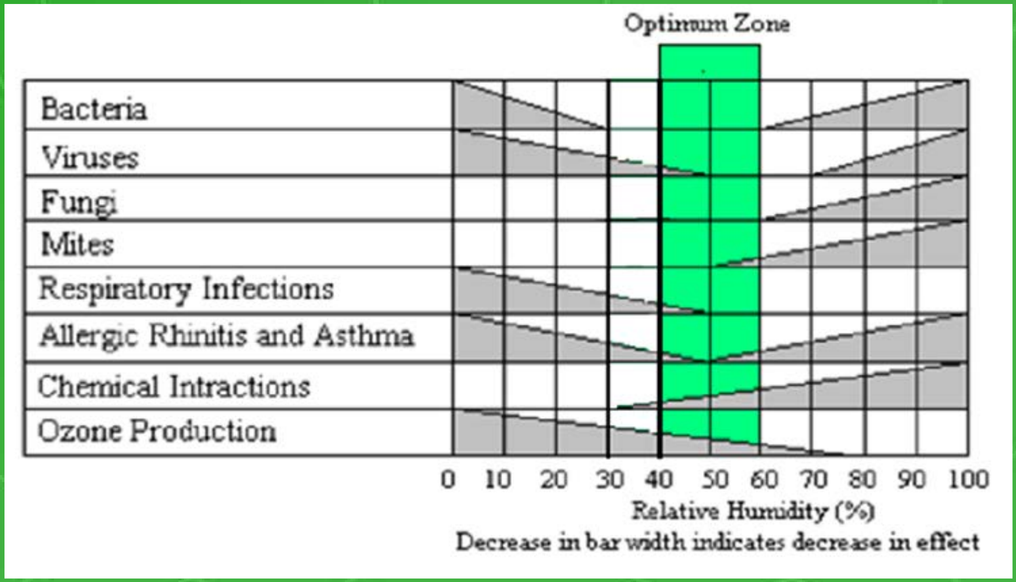


Figure 2 Health effects and indoor relative humidity (source: Arundel, et al. 1986)

# Case Study 1. Indoor Relative Humidity and Mould

**Mould growth is likely on almost any building material if the relative humidity exceeds 75-80% [8-10]. 80% relative humidity is the threshold for mould gemmation (Table 1). 60% relative humidity is the threshold for the mould survival and growth after the gemmation of mould spores [11] (Figure 2). Although visible mould growth on indoor surfaces is a common problem in over 30% of New Zealand houses [7], there are over 60% of New Zealand houses without mould problem. What is the major difference of indoor RH between houses with and without mould problem?**

**Two Auckland houses with and without mould problem were selected for the field study of winter indoor thermal conditions. House A with mould problem, built in 1962 with single glazed window, did not have any insulation in the roof and wall; House B without mould problem, built in 2000 with single glazed window, has some insulation in its envelope (R-values for Roof: 1.9, Wall: 1.5, Floor: 1.3, Single Glazing: 0.13). Both houses used temporary space heating (electronical heater) during the field study.**

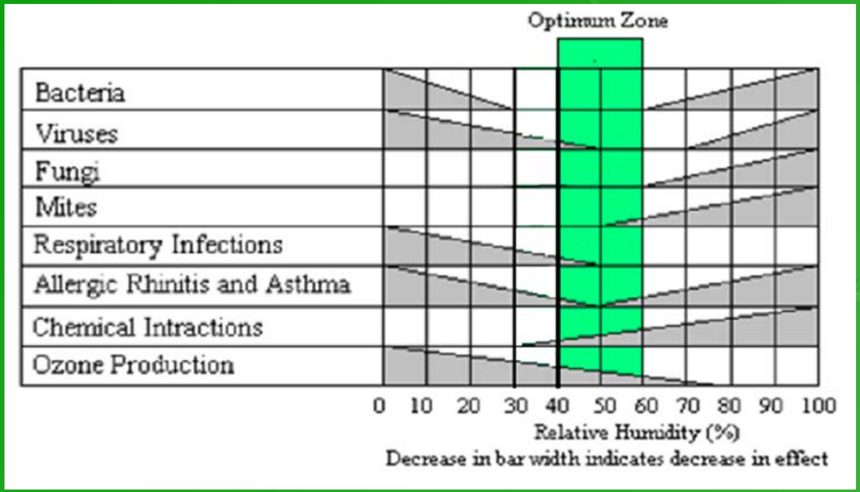


**Figure 2 Health effects and indoor relative humidity (source: Arundel, et al. 1986)**

**Table 1 Threshold for mould gemmation and time**

| Substrate | Threshold RH | Time |
|---|---|---|
| Porous and dust and fat covered non-porous | 100% | 1 day |
| | 89% | 7 days |
| | 80% | 30 days |
| Clean non-porous | 100% | - |

(Source: H.L.S.C. Hens, Minimizing Fungal Defacement [11])

# Case Study 1. Indoor Relative Humidity and Mould

## Different distribution of indoor relative humidity of houses with and without insulation

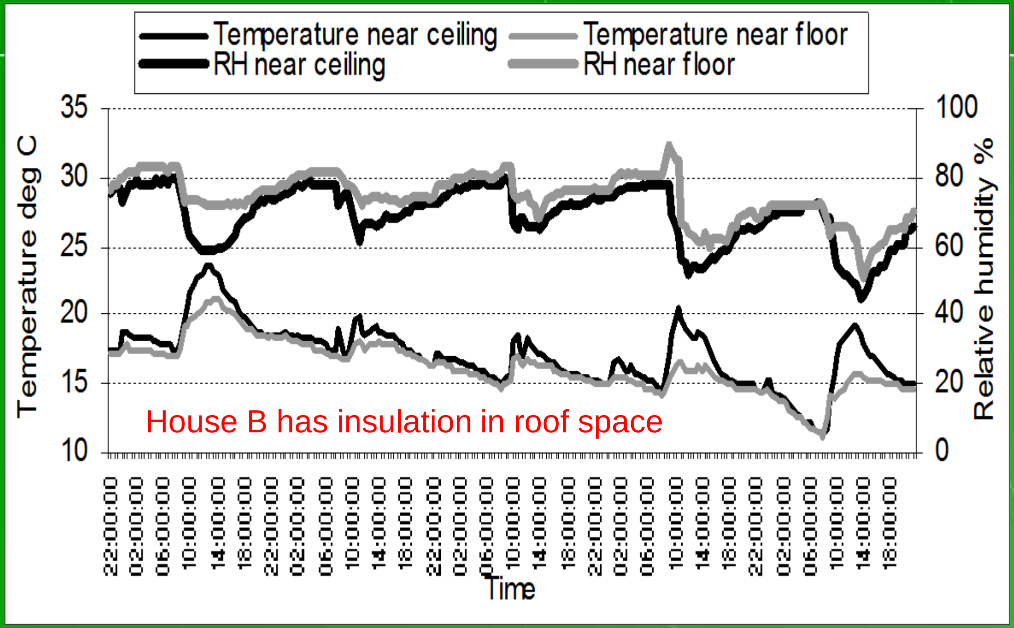


Figure 3 Air temperature and RH of House B without mould problem

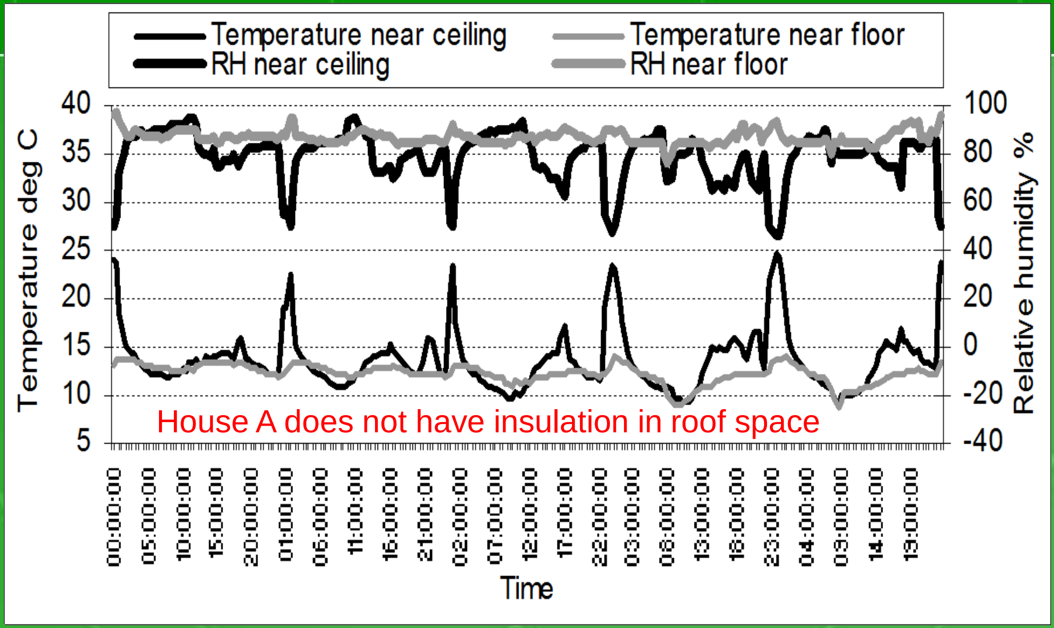


Figure 4 Air temperature and RH of House A with mould problem

**As the warm air moves up the air temperatures near the ceiling are normally higher than the floor. For House B with insulation in the roof space, the air temperatures near the ceiling are always higher than the floor and the mean air relative humidity near the ceiling is always lower than the floor (Figure 3). For House A without insulation in the roof space, the air temperature near the ceiling can be lower than the floor and the air relative humidity near the ceiling can be higher than the floor during early morning (Figure 4). Without insulation in roof space, the heat loss to the sky by long wave radiation can cause very low surface temperature of ceiling during early morning. The underside of ceiling with very low surface temperature can decrease air temperature and increase relative humidity of the air adjacent to the ceiling, which can encourage visible mould growth on the underside of ceiling. Sufficient insulation in building envelope is crucial to prevent indoor mould problem.**

# Case Study 1. Indoor Relative Humidity and Mould

## Major difference of indoor relative humidity of houses with and without mould problem

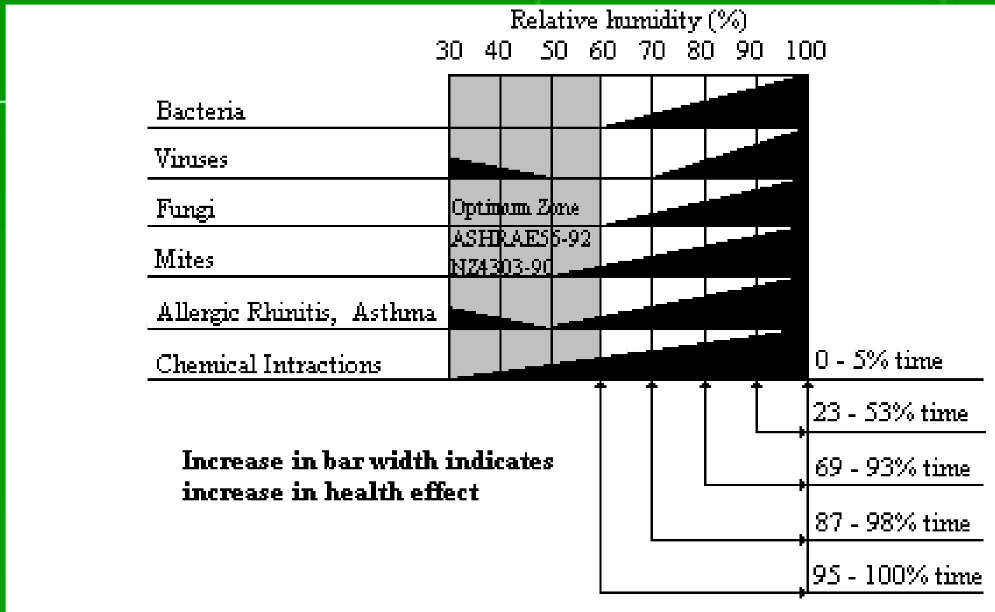


Figure 5 Percentage of winter time related to different ranges of RH near ceiling and floor of House A with mould problem

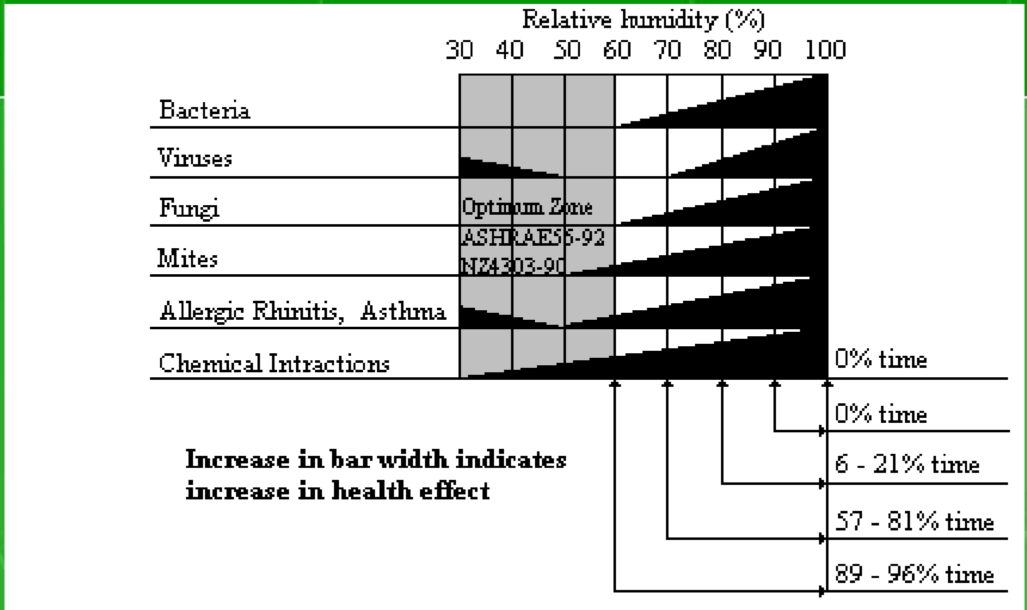


Figure 6 Percentage of winter time related to different ranges of RH near ceiling and floor of House B without mould problem

There are not significant difference of winter time when indoor relative humidity is higher than 60%, the threshold for the mould survival and growth, between House A (95 – 100% winter time) and House B (89 – 96% winter time). There are significant difference of winter time when indoor relative humidity is higher than 80%, the threshold for mould gemmation, between House A and House B. For House A, there are 69% winter time (63.5 days near ceiling) and 93% winter time (85.6 days near floor) when indoor relative humidity near is higher than 80%, the threshold for mould gemmation. For House B, there are only 6% winter time (5.5 days near ceiling) and 21% winter time (19.3 days near floor) when indoor relative humidity is higher than 80%, the threshold for mould gemmation. One option to prevent mould growth on indoor surfaces is to control the indoor RH under the threshold of mould gemmation (80% RH and 30 days) . If the mould spores never start gemmation then mould will not grow on indoor surfaces [12].

# Case Study 1. Indoor Relative Humidity and Mould

## Conclusions:

- There are not significant difference of winter time when indoor relative humidity is higher than 60%, the threshold for the mould survival and growth, between Houses with and without mould problems. There are significant difference of winter time when indoor relative humidity is higher than 80%, the threshold for mould gemmation, between Houses with and without mould problems.

- It is difficult for Auckland houses, not designed for permanent active thermal control (permanent space heating) according to the local climate conditions, to control indoor relative humidity under 60%, the threshold that the mould can survive and growth. It is possible to control the indoor relative humidity under the threshold that the mould can gemmate by passive design and temporary heating. This study proved that it is possible to limit the indoor relative humidity to under the threshold of mould gemmation (80% relative humidity) in most of the winter time for controlling the mould growth on indoor surface of Auckland houses. If the mould spores never gemmate in an Auckland house the mould never grows on indoor surfaces of the Auckland house.

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Conditions

Since 1978, continuously increasing R-value of building envelope of Auckland houses in accordance with the updated building standards mainly focus on improving energy efficiency. To investigate winter indoor thermal comfort and healthy conditions of Auckland houses with different R-values of building envelopes and different space heating methods (temporary and permeant heating), three Auckland houses with lightweight timber frame construction were selected for the field studies of winter indoor micro-climatic conditions [13, 14].

- House 1 was built in 2000 (R-values for Roof: 1.9, Wall: 1.5, Floor: 1.3, Single Glazing: 0.13). House 1 had 2 occupants and used an electronical cylinder hot water system and an electronical oil heater in the master bedroom only for the evening time during the field study.

- House 2 was built in 2012 (R-values for Roof: 2.9, Wall: 1.9, Floor: 1.3, Double Glazing: 0.26). House 2 had 2 occupants and used a gas instant hot water system but did not use any space heating during the field study, although there is a heat pump.

- House 3 was built in 2012 (R-values for Roof: 2.9, Wall: 1.9, Floor: 1.3, Double Glazing: 0.26). House 3 had 2 occupants and used a gas instant hot water system and a gas central heating system during the field study. Indoor air temperature of House 3 was set at 20°C in the downstairs living room during the field study.

Monthly electricity and gas consumption data for the three houses were collected for this study. As space heating energy is closely related to the volume of indoor space, the study uses daily mean energy consumption per cubic metre of indoor space volume (kWh/$m^3$day) as a basic energy unit.

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## Indoor air temperature and relative humidity of houses with different R-value in their envelopes

According the field study data of House 1 built in 2000 and House 2 built in 2012, increasing R-value of building envelope from 1.9 for roof, 1.5 for wall, 1.3 for floor and 0.13 for glazing, as required by the New Zealand building standards in 1996, to the 2009 requirements of 2.9 for roof, 1.9 for wall, 1.3 for floor and 0.26 for glazing significantly improves winter indoor thermal and health conditions (Table 2 and Table 3).

Although House 1 used an electronic heater in the master bedroom during the field study, indoor mean air temperature of House 2 is 1.1°C higher than House 1. The percentage of winter time in House 2, when indoor air temperatures are higher than or equate to 18°C (the minimum indoor air temperature required for indoor health conditions) [15] is 17.6% higher than House 1. Although House 1 used an electronic heater in the master bedroom during the field study, mean relative humidity of House 2 is 4.9% lower than House 1. The percentage of winter time in House 2, when indoor relative humidity is between 40% and 60%, minimizing indirect health effects, is 19.6% higher than House 1.

Table 2: Percentages of winter time and mean indoor air temperature ranges of House 1 and House 2

| | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | Mean | Max. | Min. | Fluctuation |
|---|---|---|---|---|---|---|---|---|---|---|
| House 1 | 35.3% | 3.9% | 0% | 0% | 0% | 0% | 15.5ºC | 19.8ºC | 11.4ºC | 8.4ºC |
| House 2 | 61.0% | 21.5% | 2.5% | 0.01% | 0% | 0% | 16.6ºC | 22.1ºC | 11.2ºC | 10.9ºC |
| Difference | 25.7% | 17.6% | 2.5% | 0.01% | - | - | 1.1 | - | - | - |

Table 3: Percentages of winter time and mean indoor air temperature ranges of House 1 and House 2

| RH Ranges | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | 40%-60% | Mean RH |
|---|---|---|---|---|---|---|---|---|
| House 1 | 100% | 100% | 92.2% | 37.6% | 16.5% | 1.0% | 8.8% | 68.3% |
| House 2 | 100% | 100% | 71.6% | 11.9% | 1.70% | 0% | 28.4% | 63.4% |
| Difference | 0% | 0% | 20.6% | 25.7% | 14.8% | 1% | 19.6% | 4.9% |

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## Indoor air temperature and relative humidity of houses with and without sufficient space heating

Although upgrading insulation and using double glazing windows can significantly increase 17.6% of winter time when indoor air temperatures are higher than or equate to 18°C and 19.6% of winter time when indoor relative humidity are 40% and 60%, there is still 78.5% of winter time when indoor air temperatures are lower than 18°C and 71.6% of winter time when indoor relative humidity is higher than 60% (see Table 4 and Table 5) compared with House 3.

An Auckland house with sufficient insulation and double glazing windows needs space heating to achieve winter indoor thermal comfort and health conditions (18°C for the minimum indoor temperature and 40%-60% for relative humidity).

Table 4. Percentages of winter time and mean indoor temperature ranges of the three houses with different insulation and space heating

| | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | Mean | Max. | Min. | Fluctuation |
|---|---|---|---|---|---|---|---|---|---|---|
| House 1 | 35.3% | 3.9% | 0% | 0% | 0% | 0% | 15.5°C | 19.8°C | 11.4°C | 8.4 |
| House 2 | 61% | 21.5% | 2.5% | 0.01% | 0% | 0% | 16.6°C | 22.1°C | 11.2°C | 10.9 |
| House 3 | 100% | 100% | 98.7% | 44.5% | 1.3% | 0.01% | 21.9°C | 27.3°C | 18.8°C | 8.5 |
| Difference of House 2 & House 3 | 39% | 78.5% | 96.2% | 44.4% | 1.3% | 0.01% | 5.3°C | - | - | - |

Table 5. Percentages of winter time and mean indoor relative humidity ranges of the three houses with different insulation and space heating

| | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | 40% to 60% | Mean | Max. | Min. | Fluctuation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| House 1 | 100% | 100% | 92.2% | 37.6% | 16.5% | 1.0% | 8.8% | 68.3% | 82.9% | 54.3% | 28.6% |
| House 2 | 100% | 100% | 71.6% | 11.9% | 1.70% | 0% | 28.4% | 63.4% | 81.0% | 51.1% | 29.9% |
| House 3 | 100% | 28.8% | 0% | 0% | 0% | 0% | 100% | 48.1% | 56.7% | 38.5% | 18.2% |
| Difference of House 2 & House 3 | 0% | 71.2% | 71.6% | 11.9% | 1.70% | 0% | 71.6% | 15.3% | - | - | - |

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## Indoor air temperature and relative humidity of houses with and without sufficient space heating

House 2 and House 3 have the same R-value in their envelopes. With a central heating system, House 3 has 100% of winter time when indoor air temperatures are higher 18 °C and indoor relative humidity is between 40% to 60% for all indoor spaces (Table 6 and Table 7). How much the space energy is needed to achieve indoor thermal comfort and health conditions?

Table 6: Percentages of winter time and air temperature ranges of different indoor spaces of House 2 and House 3

| | Temperature Ranges | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | Mean |
|---|---|---|---|---|---|---|---|---|
| House 2 Indoor Spaces | Living | 78.7% | 21.8% | 1.0% | 0% | 0% | 0% | 16.8 |
| | Downstairs bedroom | 28.3% | 4.9% | 0% | 0% | 0% | 0% | 14.8 |
| | Upstairs master bedroom | 71.1% | 44.9% | 18.7% | 6.4% | 0.9% | 0.1% | 17.9 |
| | Corridor | 76.2% | 30.7% | 4.0% | 0.2% | 0% | 0% | 17.0 |
| House 3 Indoor Spaces | Living | 100% | 100% | 100% | 68.2% | 1.1% | 0% | 22.2 |
| | Upstairs master bedroom | 100% | 100% | 98.6% | 62.5% | 13.3% | 1.0% | 22.6 |
| | Upstairs south bedroom | 100% | 100% | 82.5% | 19.4% | 0.1% | 0% | 20.9 |
| | Corridor | 100% | 100% | 84.7% | 12.3% | 0.1% | 0% | 20.8 |
| | Outdoor | 1.70% | 0% | 0% | 0% | 0% | 0% | 10.4 |

Table 7: Percentages of winter time and relative humidity ranges of different indoor spaces of House 2 and House 3

| | RH Ranges | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | 40% - 60% | Mean |
|---|---|---|---|---|---|---|---|---|---|
| House 2 | Living | 100% | 99.4% | 69.2% | 11.8% | 1.3% | 0% | 30.8% | 62.8% |
| | Downstairs bedroom | 100% | 100% | 95.7% | 41.4% | 12.6% | 2.5% | 4.3% | 68.6% |
| | Upstairs master bedroom | 100% | 97.5% | 58.6% | 8.0% | 0.3% | 0% | 41.4% | 61.1% |
| | Corridor mean | 100% | 100% | 69.7% | 10.8% | 1.2% | 0.04% | 30.3% | 63% |
| House 3 | Downstairs Living | 100% | 40.6% | 0% | 0% | 0% | 0% | 100% | 49.1% |
| | Upstairs master bedroom | 99.8% | 24.3% | 0% | 0% | 0% | 0% | 100% | 47.5% |
| | Upstairs south bedroom | 100% | 66.8% | 0% | 0% | 0% | 0% | 100% | 51.6% |
| | Corridor | 100% | 24.3% | 0% | 0% | 0% | 0% | 100% | 47.6% |
| Outdoor | Outdoor | 100% | 99.9% | 97.4% | 86.8% | 77.8% | 68.4% | 2.6% | 85% |

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# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## The space heating energy needed to achieve indoor healthy conditions

Table 8 Energy data (kWh/m$^3$day) of the three houses associated with different insulation and heating

| | House 1 Total energy (electricity only) | House 2 Total energy (gas and electricity) | House 3 Total energy (gas and electricity) | House 2 Gas only | House 3 Gas only |
|---|---|---|---|---|---|
| Annual | 0.04878 | 0.01919 | 0.05286 | 0.00871 | 0.04593 |
| Winter | 0.07478 | 0.02508 | 0.09955 | 0.01297 | 0.09194 |
| Summer | 0.02839 | 0.01522 | 0.01438 | 0.00570 | 0.00934 |
| Heating months May to Sep | 0.06699 | 0.02319 | 0.09354 | 0.01162 | 0.08595 |
| Other months except heating months | 0.03564 | 0.01630 | 0.02350 | 0.00661 | 0.01705 |
| Difference of heating and no heating months | 0.03135 | 0.00689 | 0.07004 | 0.00501 | 0.06890 |

Table 8 shows energy data of the three houses. As space heating energy is closely related to the volume of indoor space, the study uses daily mean energy consumption per cubic metre of indoor space (kWh/m$^3$day) as a basic energy unit. House 3 used gas for the gas central heating system, gas instant hot water system and cooking during the space heating months. House 3 used gas for the gas instant hot water system and cooking during the no space heating months. The difference of daily mean gas usage per cubic metre of indoor space between the space heating months and the no space heating months of House 3 can mainly represent its space heating energy. The difference of daily mean gas usage per cubic metre of indoor space between the space heating months and the no space heating months of House 3 is 0.0689 kWh/m$^3$day, which can mainly represent the space heating energy needed to achieve the guideline of indoor thermal comfort and health conditions (for 20°C as the minimum indoor air temperature) of a local house with lightweight timber frame construction with sufficient insulation in its envelope according to the current building code. If indoor air temperature of House 3 is set at 18°C (not 20°C) in the downstairs living room during the winter, the space heating energy can be lower than 0.0689 kWh/m$^3$day.

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## Energy for hot water and space heating

Table 8 Energy data (kWh/m$^3$day) of the three houses associated with different insulation and heating

| | House 1 Total energy (electricity only) | House 2 Total energy (gas and electricity) | House 3 Total energy (gas and electricity) | House 2 Gas only | House 3 Gas only |
|---|---|---|---|---|---|
| Annual | 0.04878 | 0.01919 | 0.05286 | 0.00871 | 0.04593 |
| Winter | 0.07478 | 0.02508 | 0.09955 | 0.01297 | 0.09194 |
| Summer | 0.02839 | 0.01522 | 0.01438 | 0.00570 | 0.00934 |
| Heating months May to Sep | 0.06699 | 0.02319 | 0.09354 | 0.01162 | 0.08595 |
| Other months except heating months | 0.03564 | 0.01630 | 0.02350 | 0.00661 | 0.01705 |
| Difference of heating and no heating months | 0.03135 | 0.00689 | 0.07004 | 0.00501 | 0.06890 |

During no space heating months, daily mean energy of House 1 (0.03564 kWh/m$^3$day) with an electronic hot water cylinder is significantly higher than house 2 (0.01630 kWh/m$^3$day) and House 3 (0.02350 kWh/m$^3$day) with gas instant hot water systems (Table 8). The previous study [16] shows that on average, across all fuel types, the space heating energy is the biggest portion (32%) of New Zealand household energy followed by hot water (29%). During no heating months energy used for hot water is the major part of energy consumption. House 1 with an electronical cylinder hot water system could use more energy for hot water than House 2 and House 3 using gas instant hot water system. There is a short time for occupants to use hot water for a shower or other purposes during the 24 hour day. Current hot water cylinders continuously heat water and maintain water temperature at a temperature of 24 hours a day whether hot water is needed or not. During the winter night when occupants do not use hot water and internal air temperature is very low, especially for those houses without sufficient insulation, heat loss from a cylinder to the cold internal space can consume some extra energy for maintaining the water temperature.

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## (Major Issues for Local House Thermal Design)

## 1. Low air temperature and high relative humidity in southern downstairs bedrooms

Table 9 Percentages of winter time and air temperature ranges of different indoor spaces of House 1 and House 2

| | Temperature Ranges | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | Mean Tem. |
|---|---|---|---|---|---|---|---|---|
| House 1 indoor spaces | Living | 34.7% | 4.6% | 0.1% | 0% | 0% | 0% | 15.5ºC |
| | Downstairs south bedroom | 11.2% | 0% | 0% | 0% | 0% | 0% | 14.2ºC |
| | Upstairs master bedroom | 69.2% | 32.7% | 6.7% | 0.1% | 0% | 0% | 16.9ºC |
| | Corridor | 34.0% | 2.9% | 0% | 0% | 0% | 0% | 15.3ºC |
| House 2 indoor spaces | Living | 78.7% | 21.8% | 1.0% | 0% | 0% | 0% | 16.8ºC |
| | Downstairs south bedroom | 28.3% | 4.9% | 0% | 0% | 0% | 0% | 14.8ºC |
| | Upstairs master bedroom | 71.1% | 44.9% | 18.7% | 6.4% | 0.9% | 0.1% | 17.9ºC |
| | Corridor | 76.2% | 30.7% | 4.0% | 0.2% | 0% | 0% | 17.0ºC |
| | Outdoor | 1.70% | 0% | 0% | 0% | 0% | 0% | 10.4 |

Table 10 Percentages of winter time and relative humidity ranges of different indoor spaces of House 1 and House 2

| | RH Ranges | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | 40% - 60% | Mean RH |
|---|---|---|---|---|---|---|---|---|---|
| House 1 indoor spaces | Living | 100% | 100% | 90.8% | 34.7% | 12.3% | 0% | 9.2% | 67.7% |
| | Downstairs south bedroom | 100% | 100% | 100% | 71.4% | 38.2% | 13.4% | 0% | 73.4% |
| | Upstairs master bedroom | 100% | 100% | 69.7% | 24.6% | 8.8% | 0% | 30.3% | 64.3% |
| | Corridor | 100% | 100% | 90.4% | 35.8% | 15.6% | 1.5% | 9.6% | 67.9% |
| House 2 indoor spaces | Living | 100% | 99.4% | 69.2% | 11.8% | 1.3% | 0% | 30.8% | 62.8% |
| | Downstairs south bedroom | 100% | 100% | 95.7% | 41.4% | 12.6% | 2.5% | 4.3% | 68.6% |
| | Upstairs master bedroom | 100% | 97.5% | 58.6% | 8.0% | 0.3% | 0% | 41.4% | 61.1% |
| | Corridor mean | 100% | 100% | 69.7% | 10.8% | 1.2% | 0.04% | 30.3% | 63% |
| | Outdoor | 100% | 99.9% | 97.4% | 86.8% | 77.8% | 68.4% | 2.6% | 85% |

Winter indoor mean air temperatures of southern downstairs bedrooms are significantly lower than other spaces in both House 1 and House 2 with different R-value in their building envelopes (Table 9), which can result in higher indoor relative humidity (Table 10). House 2 having higher R-value insulation in its envelope does not efficiently improve indoor thermal and health conditions of the southern downstairs bedroom. The southern downstairs indoor space is in cold side of house without direct sun light. Southern bedrooms are commonly smaller than the northern bedrooms and the other spaces. A southern bedroom with a smaller floor area could potentially result in big ratios of external wall area to indoor space volume or window area to floor of that room. Negative impact of a big ratio of window to floor could overrule or degrade the positive impact of higher insulation levels and double glazed windows on indoor thermal comfort and health conditions of a southern indoor space conditions.

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## (Major Issues for Local House Thermal Design)

## 2. Large fluctuations of indoor air temperature

**Fluctuations in indoor air temperatures of House 1 and House 2 are both large (Figure 7). Large fluctuations of winter indoor air temperature can result large fluctuations of indoor relative humidity (Figure 8), which can negatively impact winter indoor health conditions. In common with most Auckland houses, House 1 and House 2 are lightweight timber frame construction with internal insulation and external cladding, of break veneer in this instance. Wall insulation materials are located at the internal surface of the wall as thermal designs of House 1 and House 2 are for temporary heating, not for permanent heating. As the internal surface of the wall does not have thermal mass, the space can be heated quickly, rather than heating the building envelope first and then heating the space. For this type of lightweight building envelope without sufficient thermal mass on the internal surface of the wall, the indoor space air temperature is heated up quickly by solar radiation and rising outdoor air temperatures during winter daytime and also cooled down quickly during winter night time.**

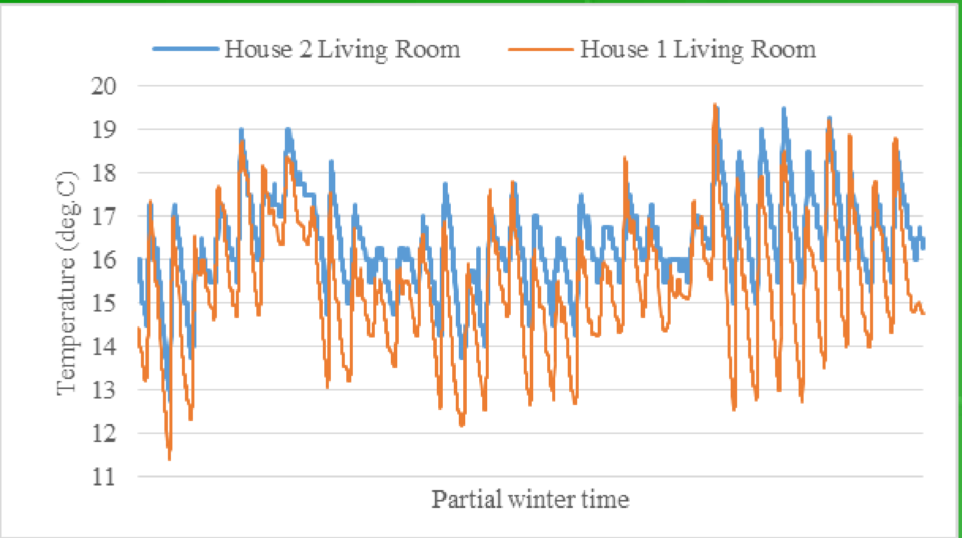


**Figure 7 Indoor air temperatures of living rooms of House 1 and House 2**

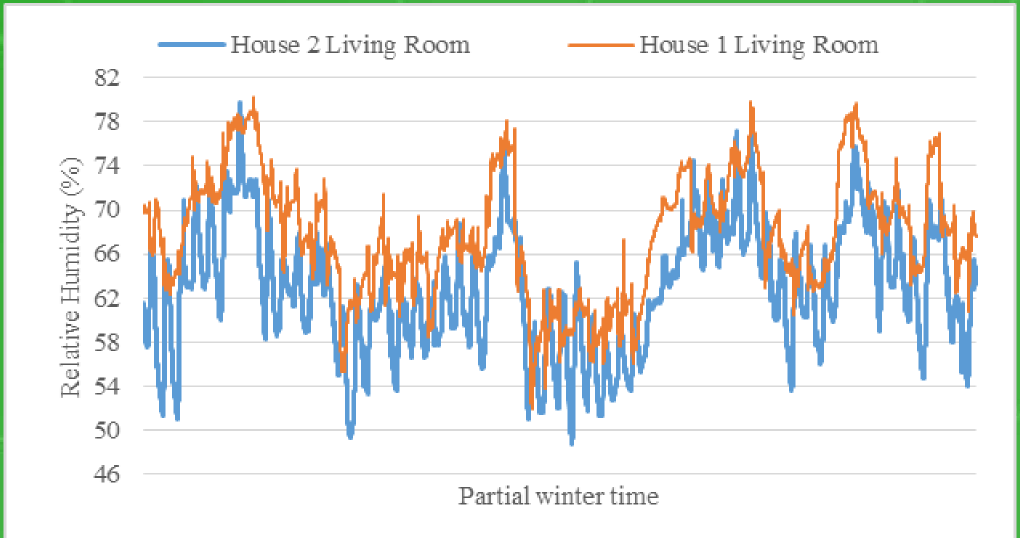


**Figure 8 Indoor relative humidity of living rooms of House 1 and House 2**

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# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Condition

## (Two Major Problems for Local House Thermal Design)

## 2. Large fluctuations of indoor air temperature

**Figure 9 shows winter indoor hourly mean air temperatures of House 1, House 2 and House 3. Indoor minimum air temperatures in winter of House 1 and House 2 occur during early morning. Minimum winter indoor hourly mean air temperatures of House 1 (14.1°C) and House 2 (14.8°C) occur at 6:45 to 8:30 for House 1 and at 7:45 to 8:05 for House 2. Large fluctuations in indoor air temperatures can result in very low indoor air temperatures during early morning and night time in winter, negatively impacting indoor thermal comfort and health conditions and costing more in energy for space heating to achieve the indoor thermal and health conditions. Reducing the fluctuation of winter indoor air temperature can improve indoor health conditions and housing energy efficiency.**

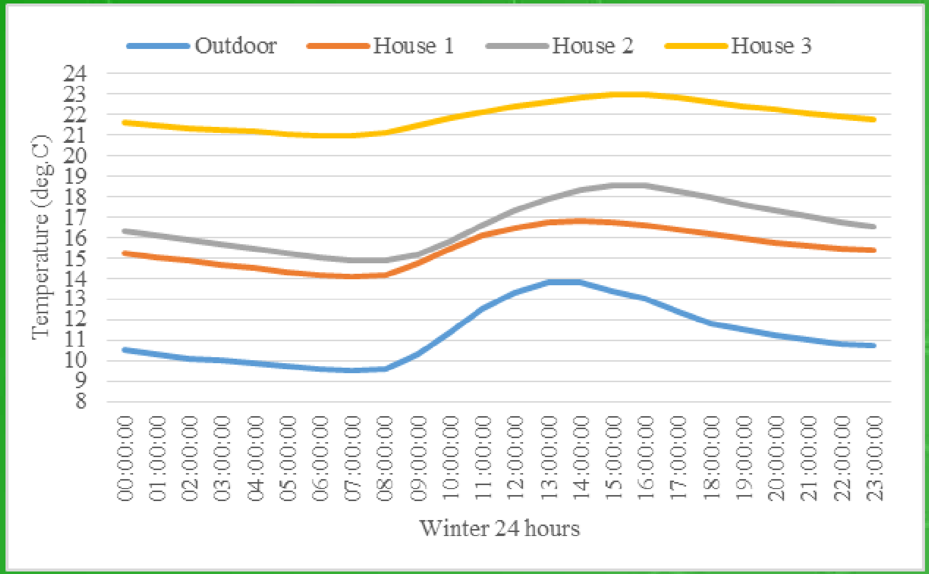


**Figure 9 Winter indoor hourly mean air temperature of the three houses**

## Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Conditio

**Conclusion:**

- **According the field study data of House 1 and House 2, increasing R-value of building envelope from 1.9 for roof, 1.5 for wall, 1.3 for floor and 0.13 for glazing, as required by the New Zealand building standards in 1996, to the 2009 requirements of 2.9 for roof, 1.9 for wall, 1.3 for floor and 0.26 for glazing can increase 17.6% of winter time, when indoor air temperatures are higher than or equate to 18°C (the minimum indoor air temperature required for health conditions) and 19.6% of winter time, when indoor relative humidity is between 40% and 60% (minimizing indirect health effects).**

- **Although upgrading insulation and using double glazing windows can significantly improve indoor health conditions, there is still 78.5% of winter time when indoor air temperatures are lower than 18°C and 71.6% of winter time when indoor relative humidity is higher than 60%. An Auckland house with sufficient insulation and double glazing windows needs space heating to achieve winter indoor health conditions. 0.0689 kWh/m$^3$day of daily mean space heating energy per cubic metre of indoor space is needed to achieve health conditions, when the indoor minimum air temperature is set at 20°C, for a local house with lightweight timber frame construction with sufficient insulation in its envelope according to the current building code. If the indoor air temperature of House 3 is set at 18°C the space heating energy can be lower than 0.0689 kWh/m$^3$day.**

# Case Study 2. Impact of Insulation and Space Heating on Winter Indoor Health Conditio

## Discussion and Further Studies:

- An Auckland house with sufficient insulation and double glazing windows needs space heating to achieve winter indoor health conditions. The question is what type of space heating method is suitable for Auckland houses with lightweight timber frame construction with internal insulation and external cladding to achieve the required indoor health conditions?

- Increasing R-value of building envelope and increasing space heating energy for achieving indoor health conditions without tackling inefficient hot water system is not good idea for local housing energy efficiency. A further study should focus on what type of hot water system is energy efficiency for the local houses.

- Increasing R-value of building envelope can significantly improve mean indoor thermal and health conditions but does not efficiently improve indoor thermal and health conditions of the southern downstairs bedroom (southern indoor space). A further study can focus on adding more insulation in the southern wall and limiting the ratio of window area to indoor space volume of the southern indoor space for improving indoor health of southern indoor spaces, which can impact the whole house indoor thermal and health conditions.

- Increasing R-value of building envelope can significantly improve mean indoor thermal and health conditions but does not reduce the fluctuations in indoor air temperatures, which can negatively impact indoor thermal and health conditions. A further study can focus on reducing fluctuations of indoor air temperature for improving indoor thermal and health conditions and housing energy efficiency.

# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

**There are about 425 schools in Auckland (New Zealand Ministry of Education). Most Auckland schools have a number of low-rise, isolated buildings (Figure 10) with lightweight structure and envelopes. In 90% of Auckland schools each isolated building has four or less classrooms, and in 50% of the city's schools each isolate building has only one or two classrooms (Figure 11). Generally, an Auckland school building is more like a 'big house' than a multi-storied building. Most classrooms have a large external surface area, including two or three sides of external walls and roof surface areas. For this type of school building, with a high ratio of building surface to volume, thermal performance of the building envelope is crucial to indoor thermal and health conditions. From 2010 to 2014 the redevelopment of Avondale College represented one of the biggest school rebuilding programs in New Zealand's history. The project provides the school's 2750 students with 92 new and refurbished teaching and resource spaces. It is the first time that Thermomass insulated precast panels (a sandwiched panel with 40mm of XPS rigid insulation and 70mm exterior and 150mm interior thickness of concrete) have been used as the main structure and building envelope of a new two-storey school building (New Maths Block) in New Zealand.**

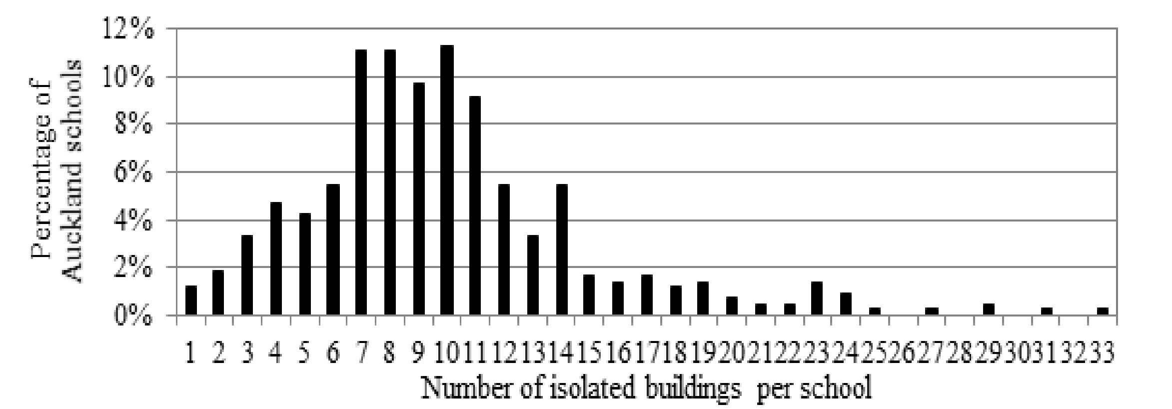


**Figure 10 Number of isolated buildings per school in Auckland**

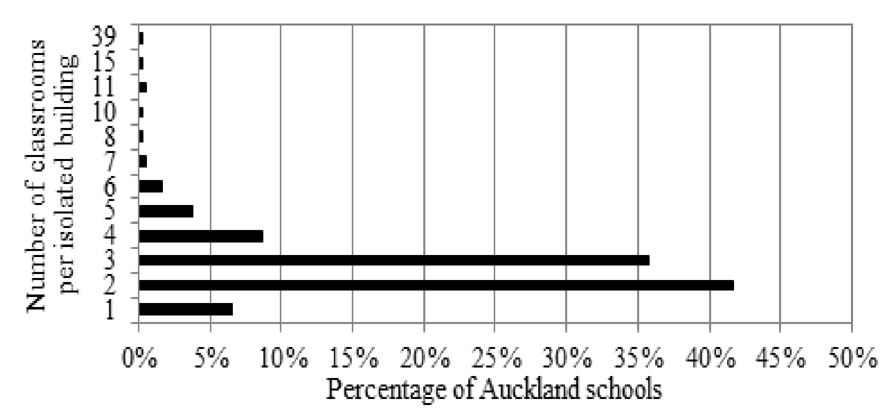


**Figure 11 Number of classrooms per isolated school building in Auckland**

# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

**Two classrooms with different building envelopes are selected for the field study. A heavyweight classroom in the middle and second floor of the New Maths Block with north orientation, which has roof, north wall and south wall as its external envelope, was used for the field study of indoor microclimatic conditions. The north wall with Thermomass insulated precast panels has partial internal surface area with thermal mass. The south wall, without Thermomass insulated precast panels and only an in-situ concrete frame, has limited internal surface area with thermal mass (Figure 12). Another lightweight classroom in the middle of the one-storey retrofitted school building with north orientation, which has roof, north wall and south wall as its external envelope, was used for the field study of indoor microclimatic conditions. The north and south walls are conventional lightweight, timber frame construction with internal insulation and external cladding and the internal surface of the wall does not have thermal mass (Figure 13). The two classrooms have sufficient insulation and double glazed windows and only use space heating during school hours.**

**Figure 12 Heavyweight classroom**


**Figure 13 Lightweight classroom**

# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

## Thermal mass in building envelopes and fluctuation of indoor air temperatures

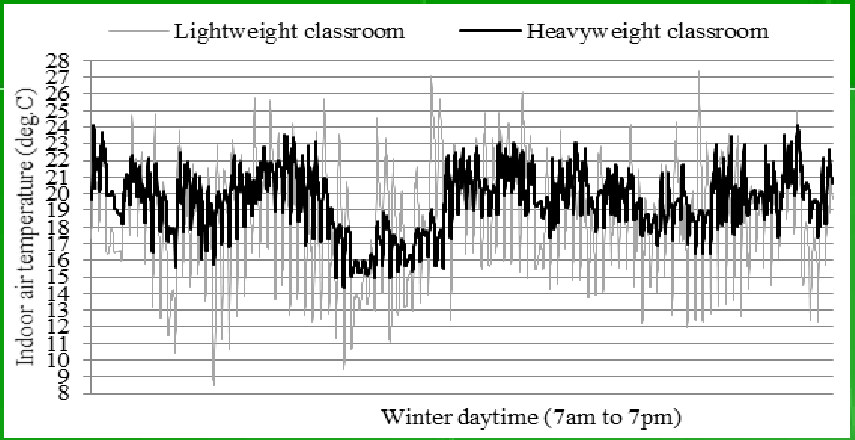


Figure 14 Indoor air temperatures during the winter daytime

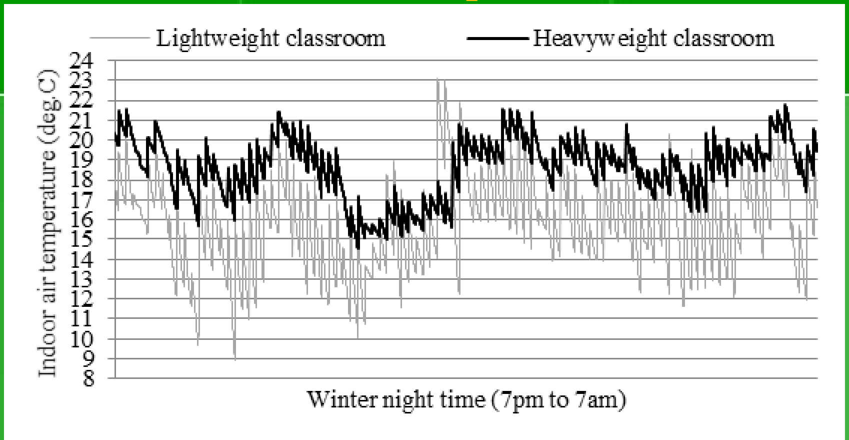


Figure 15 Indoor air temperatures during the winter night time

Table 11 Indoor air temperatures during winter daytime

| Daytime from 7am to 7pm | Lightweight | Heavyweight | Outdoor |
|---|---|---|---|
| Mean air temperature | 18.8°C | 19.5°C | 13.7°C |
| Difference of indoor / outdoor | 5.1°C | 5.8°C | |
| Maximum air temperature | 27.4°C | 24.2°C | 20.6°C |
| Minimum air temperature | 8.5°C | 14.3°C | 1.9°C |
| Air temperature fluctuation | 18.9°C | 9.9°C | 18.7°C |

Table 12 Indoor air temperatures during winter night time

| Night time from 7pm to 7am | Lightweight | Heavyweight | Outdoor |
|---|---|---|---|
| Mean air temperature | 15.8°C | 18.6°C | 10.7°C |
| Difference of indoor / outdoor | 5.1°C | 7.9°C | |
| Maximum air temperature | 23.1°C | 21.7°C | 17.7°C |
| Minimum air temperature | 9.0°C | 14.6°C | 2.0°C |
| Air temperature fluctuation | 14.1°C | 7.1 °C | 15.7°C |

As the internal surface of the wall of lightweight classroom does not have thermal mass, when indoor heat is lost through classroom walls during the daytime, there is not much heat left in the wall. The indoor temperature can quickly drop after the space heating stops. When indoor heat is lost through heavyweight classroom walls during daytime, some thermal mass in the internal surface of the heavyweight classroom has a delaying effect on the heat flow and a certain amount of heat would be stored in the wall. This stored heat would then be emitted into the indoor space with a considerable time delay after space heating ceased, which could positively impact indoor thermal conditions of a classroom during the evening and night time. During the winter night time, without impacts of space heating and sun, indoor mean air temperature of the heavyweight classroom (18.6°C) is 2.8°C higher than the lightweight classroom (15.8°C).

# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

## Thermal mass in building envelope and winter indoor air temperature

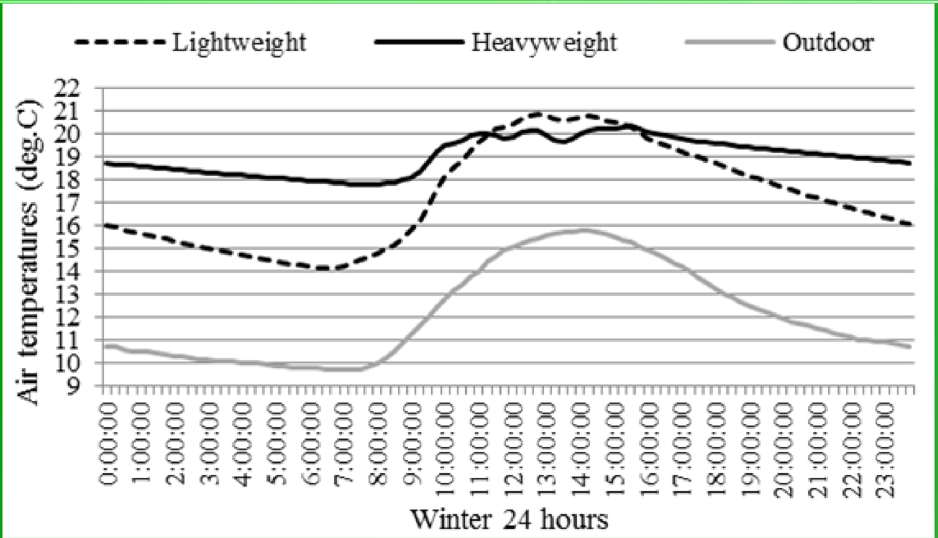


Figure 16 Winter indoor hourly air temperature

Table 13 Winter indoor and outdoor hourly mean air temperatures

| | Lightweight | Heavyweight | Difference | Outdoor |
|---|---|---|---|---|
| Minimum temperature | 14.1°C | 17.8°C | 3.7°C | 9.7°C |
| Time | 6:30am | 7:15am | 45min | 6:45am |
| Maximum temperature | 20.8°C | 20.0°C | 0.8C | 15.8°C |
| Time | 12:30pm | 3:15pm | 2h45min | 2pm |
| Fluctuation | 6.7°C | 2.2°C | 4.5°C | 6.1°C |

Table 14 Percentages of winter time related to indoor different air temperatures ranges

| Temperature ranges | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | Indoor Mean | Outdoor Mean |
|---|---|---|---|---|---|---|---|---|
| Lightweight classroom | 64.2% | 40.2% | 21.4% | 7.3% | 1.4% | 0.2% | 17.3°C | 12.2°C |
| Heavyweight classroom | 94.0% | 75.0% | 30.7% | 3.6% | 0% | 0% | 19.0°C | 12.2°C |

Table 15 Percentages of the winter school hours related to indoor different air temperatures ranges

| Temperature ranges | ≥16°C | ≥18°C | ≥20°C | ≥22°C | ≥24°C | ≥26°C | ≥27°C | Indoor Mean | Outdoor Mean |
|---|---|---|---|---|---|---|---|---|---|
| Lightweight classroom | 84.8% | 70.7% | 48.9% | 20.5% | 4.3% | 0.5% | 0.1% | 19.4°C | 14.3°C |
| Heavyweight classroom | 95.6% | 81.2% | 47.4% | 9.8% | 0% | 0% | 0% | 19.6°C | 14.3°C |

Some thermal mass in building envelope can positively impact indoor thermal comfort conditions.

# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

## Thermal mass in building envelope and winter indoor relative humidity

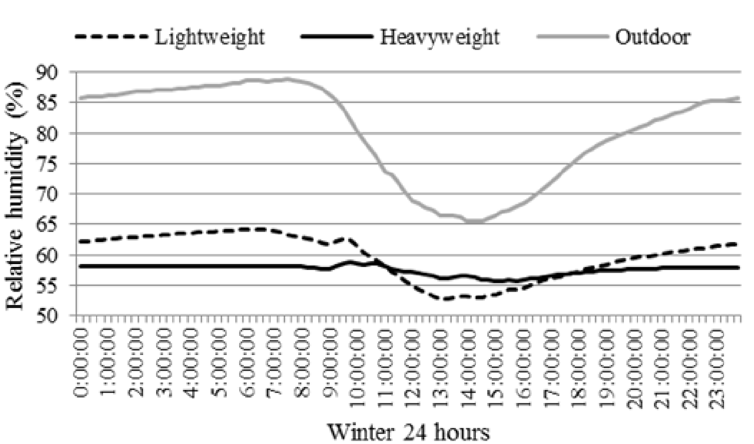


Figure 17 Winter indoor hourly mean relative humidity

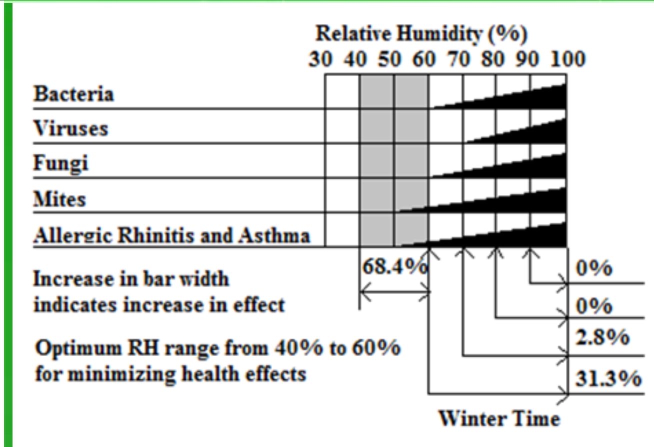


Figure 18 RH of the heavyweight classroom

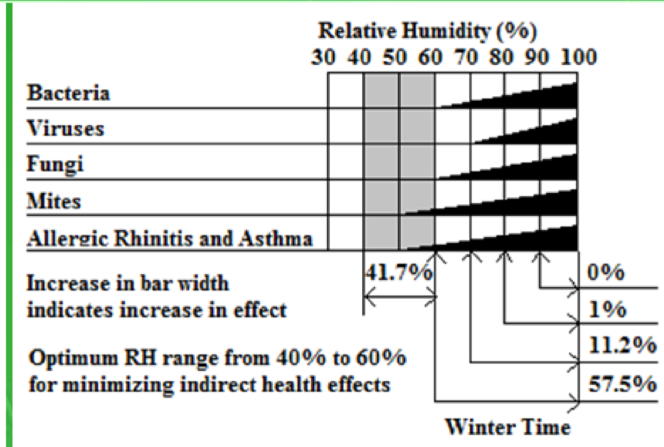


Figure 17 RH of the lightweight classroom

Table 16 Winter 24 hours RH near floor

| RH ranges | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | ≥90% | 40-60% | Indoor Mean | Outdoor Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| Retrofit | 99.2% | 91.2% | 57.5% | 11.2% | 2.5% | 1.0% | 0% | 41.7% | 60.7% | 80.2% |
| Mass | 99.7% | 89.2% | 31.3% | 2.8% | 0.2% | 0% | 0% | 68.4% | 57.3% | 80.2% |

Table 17 School hours RH near floor from 8:30am to 3:30pm

| RH ranges | ≥40% | ≥50% | ≥60% | ≥70% | ≥75% | ≥80% | ≥90% | 40-60% | Indoor Mean | Outdoor mean |
|---|---|---|---|---|---|---|---|---|---|---|
| Retrofit | 97.8% | 82.5% | 49.7% | 11.8% | 2.8% | 1.0% | 0% | 48.1% | 59.2% | 73.0% |
| Mass | 99.4% | 84.4% | 28.5% | 2.8% | 0.1% | 0% | 0% | 70.9% | 56.6% | 73.0% |

Some thermal mass in building envelope can positively impact indoor thermal and health conditions.

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# Case Study 3. Field Study to Compare and Evaluate Winter Indoor Thermal and Health Conditions of School Buildings with Different Building Envelopes

## Conclusions

- According to the field study data, a school building with some thermal mass in its envelope has significantly better winter indoor thermal and health conditions than a school building with a similar insulation level, but without thermal mass in its envelope. During the winter months and the winter school hours, the heavyweight classroom has significantly more winter time than the lightweight classroom when indoor air temperatures are higher than or equate to 18°C (the minimum indoor air temperature required for health conditions) and indoor relative humidity is between 40% and 60% (minimizing indirect health effects). During the winter night time, without impacts of space heating and sun, indoor mean air temperatures of the heavy weight classroom are higher the lightweight classroom especially for the early morning. Thermal mass effect of the heavyweight classroom can contribute 2.8°C to increasing indoor mean air temperature when the building envelope has a similar insulation level during the winter night time.

- During the winter indoor air temperature fluctuations of the lightweight classroom are much larger than the heavyweight classroom. Large fluctuations of winter indoor air temperatures in the lightweight classroom can negatively impact indoor thermal comfort conditions. A school building with thermal mass in its envelope can make winter indoor air temperatures more stable. Winter daily indoor minimum air temperatures occur during the early morning, just before school hours. The very low indoor air temperature of the lightweight classroom is a challenge for maintaining indoor thermal comfort in the morning of school hours, which not only uses more energy for space heating but also takes time to heat the space. Indoor hourly mean air temperatures of the heavyweight classroom are significantly higher than the lightweight classroom especially during early morning and night time. Adding thermal mass in a school building envelope with sufficient insulation can be an energy efficient solution to increasing indoor minimum air temperature during the winter time for thermal comfort.

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# Thank you