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Thermal Performance of Buildings with Heavy Walls

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Preface

The Cement and Concrete Association of New Zealand and the Building Research Association of New Zealand commissioned this research to investigate the effect of thermal mass in exterior walls on the comfort and heating energy use in New Zealand houses. The research was also commissioned to test the accuracy of selected building energy programmes for predicting the effect of wall thermal mass on building thermal performance. Both aspects of the project utilise a side-by-side test building facility built previously at Lincoln University.

Acknowledgements

The Building Research Levy and the Cement and Concrete Association of New Zealand jointly funded this work. This work was also supported by Lincoln University, which was contracted to perform this work.

Readership

This report is primarily intended for building designers, suppliers of heavy wall products and systems, and building energy researchers.

Note

The views expressed and conclusions drawn are those of the contractors and not necessarily those of the project sponsors.

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THERMAL PERFORMANCE OF BUILDINGS WITH HEAVY WALLS

BRANZ Study Report No.108 **L.A. Bellamy and D.W. Mackenzie**

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KEYWORDS

Thermal mass; Energy savings; Thermal comfort; Building simulation; Concrete walls.

ABSTRACT

Side-by-side test buildings were used to investigate the effect of wall thermal mass on thermal comfort and auxiliary heating energy use. The test buildings were nearly identical apart from the level of thermal mass in their walls. One had lightweight exterior-insulated timber-framed walls and the other had heavy exterior-insulated concrete walls. The test buildings were monitored over a period of 25 months with four different building configurations tested.

The results show that the heavy walls significantly improved comfort during the daytime and night-time through reducing the frequency of overheating and maintaining warmer temperatures respectively. The heavy walls provided up to 5°C cooling when the buildings were unventilated and up to 3°C cooling when the buildings were ventilated.

The energy savings from the heavy walls were strongly related to the solar gain and the reduction in ventilation energy losses. On sunny winter days, energy savings in excess of 50% were observed. Heavy walls typically reduced the monthly heating energy use. For some months, when both buildings were not ventilated much, the heavy walls increased the energy use.

Solar gain and insulation need to be matched to the level of thermal mass in order to exploit the energy savings potential of heavy walls.

The experimental data was used to assess the accuracy of two building energy programmes. The programmes accurately predicted the energy savings due to heavy walls, but were less accurate in predicting the effect of heavy walls on comfort.

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1. INTRODUCTION

Heavy wall products and systems are being used in the exterior walls of New Zealand houses. There is limited information on their thermal performance, in the New Zealand climate, compared with lightweight timber-framed systems. Information that is available has mostly been derived from computer modelling exercises and the reliability of this information is not known. The issue of thermal mass, and its effect on the thermal performance of buildings, remains a confusing issue for many house designers, builders and owners.

1.1 Aims and Research Approach

It was in the context of limited information on the thermal performance of heavy exterior walls that the following project aims were set:

- to investigate and demonstrate the effect of heavy exterior walls on the auxiliary heating energy use and thermal comfort in New Zealand houses
- to test the accuracy of selected building energy programmes for predicting the thermal performance of exterior wall thermal mass.

The research approach involved monitoring two existing side-by-side test buildings on the Lincoln University campus. These $20m^2$ single-room buildings were designed to be nearly identical apart from the amount of thermal mass in the exterior walls. The timber building was constructed with exterior-insulated timber-framed walls. The concrete building was constructed primarily with exterior-insulated concrete panels (Figure 1).

The effectiveness of heavy walls for saving energy and improving thermal comfort was assessed for the four building configurations shown in Table 1. Each configuration was tested for at least six months as this was considered the minimum period to evaluate wall thermal mass for a range of climatic conditions.

Data from the third trial was used to test the accuracy of Suncode[1] and tsbi3[2] for predicting the effect of heavy walls on thermal comfort and heating energy use.

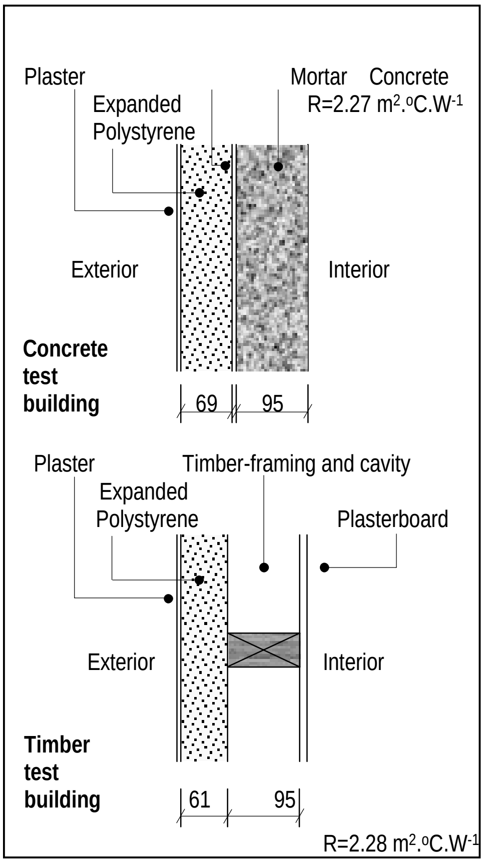

Figure 1. Wall cross-sections

Suncode was tested because it has underpinned the development of the Annual Loss Factor Method, which is recognised in the New Zealand Building Code (NZBC) as a suitable method for determining whether a building satisfies minimum energy efficiency performance requirements. Suncode was also used in the development of the Standard NZS 4218: 1996 Energy efficiency - housing and small building envelope.

[1] Version 6.0 supplied by Ecotope Inc., USA.
[2] Version B28 supplied by the Danish Building Research Institute.

The tsbi3 programme rated highly in a recent programme validation exercise carried out under the auspices of the International Energy Agency (Lomas et al. 1997). It was tested in this study to benchmark the performance of Suncode.

Table 1. Test building trials and configurations

Period	Trial	Configuration			
		Heating	Cooling Ventilation	Curtain	Carpet
1/6/98 – 31/12/98	Base Case	✓			✓
1/1/99 – 30/6/99	Ventilation	✓	✓		✓
1/7/99 – 31/12/99	Curtain	✓	✓	✓	✓
1/1/00 – 30/6/00	Bare Floor	✓	✓	✓	

1.2 Wall Thermal Mass

The R-value alone is not necessarily a good indicator of the thermal performance of heavy exterior walls. Due to the dynamic nature of the thermal energy flows in a building, the thermal performance of a heavy wall may be much better than a lightweight wall with the same R-value. Modelling-based studies by Kosny et al. (1998), Isaacs and Donn (1994) and Leslie (1976) indicate that the benefits from increasing the thermal mass in exterior walls are determined by the:

- climate
- heating and cooling regimes
- position of the thermal mass in relation to the wall insulation
- R-value of the wall
- design of other elements in the building, i.e. the windows, floor, roof and internal walls.

What emerges is a complex system, with many interactions influencing how heavy exterior walls perform compared with lightweight walls.

Kosny et al. have shown that, when both annual heating and annual cooling loads are considered, a heavy wall may perform better than a lightweight wall with more than double the heavy wall's R-value. The wall thermal mass benefit was greatest when all of the insulation was on the exterior side of the mass, but other heavy wall configurations (e.g. concrete in insulating concrete formwork) also performed better than a lightweight wall. Also, the wall thermal mass benefit is related to the wall R-value and that below an R-value of approximately 0.7 $m^2.^oC.W^{-1}$ a heavy wall may not perform as well as a lightweight wall.

In temperate climates cooling is by natural ventilation, which does not require purchased energy. Therefore the approach taken by Kosny et al. may overestimate the benefits of exterior wall thermal mass in New Zealand houses. Where air conditioning is not used a better approach is to consider the effect of wall thermal mass on the heating energy requirements and overheating. The problem with this approach is that while the value of energy savings is quantifiable, the value of improved comfort, due to a reduction in the incidence in overheating, is an intangible. Methodologies for combining both effects into one indicator, for building design comparison purposes, have not been developed as far as the authors are aware.

Isaacs and Donn, and Leslie, have investigated the benefits of wall thermal mass in New Zealand houses. Both simulation studies have shown that the energy savings, if any, are small when an intermittent heating regime is used. Savings were predicted to be slightly more significant for a continuous heating regime.

The energy performance of heavy and lightweight buildings cannot be easily compared if their comfort levels differ. This has been a complication of most thermal mass research, including the work by Isaacs and Donn, and Leslie. Had the simulated buildings in these studies been designed to have equal daytime comfort (e.g. by adjusting the window shading so that their overheating frequencies were equal), then the energy savings due to heavy walls would have been greater than reported.

Figure 2. Side-by-side test buildings at Lincoln University

2. TEST BUILDINGS

2.1 Thermal Characteristics

The thermal characteristics of the test buildings were designed to be similar to a house built to the minimum requirements of NZS4218: 1996. The interior dimensions were full-scale and the infiltration rate, internal heat gain, solar gain and heat loss factors, on a floor area basis, were similar to a new house. From Table 2 it can be seen that:

- the infiltration rate was slightly less than the minimum requirement specified in the NZBC (0.5 air changes per hour)
- the internal heat gain was approximately equal to 0.125 $kWh.m^{-2}$(floor).day^{-1}. This was slightly less than the values specified in NZS 4218: 1996 for an occupied house
- there was glazing on the north and south walls but none on the east and west. Solar gain during summer, on a floor area basis, was less than in a typical house. Solar gain during winter was not significantly affected by the lack of east and west windows
- the north glazing to floor area ratio was 13.3%. Ratios in passive solar houses are typically greater than 15%, while in new lightweight houses personal observations suggest that ratios less than 10% are not unusual
- the heat loss factor was approximately equal to 2.8 $W.m^{-2}$(floor).$^oC^{-1}$. This value is typical of a 140-180m^2 house constructed to the minimum requirements of NZS 4218: 1996.

Table 2. Selected physical and thermal parameters of the test buildings

Parameter	Test Building		Comments
	Concrete	Timber	
Floor area (m^2)	20.25	20.23	Floor area was measured to the floor's perimeter insulation. The visible floor area was approx. 18.4 m^2. See Appendix A.
Air volume (m^3)	43.9	43.6	
North glazing: floor area ratio	0.133	0.133	Single-glazed aluminium-framed window orientated 8^o west of true north. Negligible shading over the window.
South glazing: floor area ratio	0.05	0.05	Double-glazed aluminium-framed door.
Concrete wall: north glazing area ratio	12.4	0	3.3 m^3 (approx.) of concrete in heavy mass walls.
Infiltration rate at 15^{o}C ambient air temperature and no wind ((air changes).h^{-1})	0.42	0.42	The rate varied slightly with temperature and wind speed. Infiltration was from a continuously operating fan that pressurised the building. See Appendix D.
Internal heat gain (W): - 6pm to 10pm - 10pm to 6pm	 155 95	 155 95	From monitoring equipment, air pressurising fan and two 60W lights. One light operated continuously and the other operated from 6-10pm. Internal gain over 24 hours was approximately equal to 2.5 kWh.
Heat loss factor ($W.m^{-2}$(floor). $^oC^{-1}$)	2.84	2.84	For a carpeted building without curtains. See Appendix C.
Heating temperature (^{o}C): - 7am to 10pm - 10pm to 7am	 20 16	 20 16	The heater was operated by a datalogger to maintain a minimum dry resultant temperature (DRT) during the heating season (April-October). Compared with air temperature, DRT is a better indicator of comfort because it responds to radiation, air speed and air temperature. The heating temperatures followed NZS 4218: 1996 modelling method.
Heater capacity (kW)	2.2	2.2	
Fan ventilation temperature (^{o}C)	27	27	Fixed speed cooling fans were operated by a datalogger. When operating, ambient air entered the building through an axial flow fan in the north wall (below window) and building air exited through an axial flow fan mounted in the south wall (above door).
Ventilation rate ((air changes).h^{-1}): - Base case trial - Other trials	 0 4.6	 0 4.7	

It should be noted that while the test buildings had no internal walls, the amount of wall thermal mass in the concrete building was similar to a house with heavy internal and exterior walls. External walls are less efficient energy stores than internal walls[3]. Therefore the thermal performance of the concrete test building would have been somewhere between a house with heavy exterior walls and lightweight internal walls, and a house with heavy exterior and internal walls.

The test buildings were designed to have thermal characteristics similar to a new house with low to medium solar gain and relatively low insulation levels. They were designed to represent typical current building practice, not best practice.

Some aspects of the test buildings were not typical (e.g. little furniture; no windows on east and west walls; no latent heat gain; no occupants) and these should be considered when interpreting the results.

2.2 Steps Taken to Minimise Differences

The following steps were taken to minimise the differences, apart from wall thermal mass, between the two buildings:

- *Below-ground environment* **–** the two building sites were excavated to approximately 0.5m below existing ground level and backfilled with unwashed and compacted sand.
- *Above-ground external environment* **–** the two buildings were sited 5m apart, within a grassed area, with a 3m high E-W hedge (approximately 5m north of the buildings) sheltering both buildings from the prevailing wind. So the test buildings were exposed to essentially the same climate. Mutual shading would not have been significant because there were no east or west windows in the buildings. A shadow cast from a building to the west of the site would have enveloped the concrete building slightly before the timber building.
- *Window, floor and roof thermal characteristics* **–** the buildings had the same constructions.
- *Infiltration rates* **–** the airflow rates through the air pressurising fans were equalised on a calm day before the start of each trial. See Appendix D.
- *Wall R-values* **–** thicker expanded polystyrene sheets were used to insulate the concrete walls to account for differences in the R-values of timber-framing and concrete panels.
- *Datalogger control of heaters and fans* **–** dataloggers were used to control the action of this equipment in order to maintain accurate control of the building temperatures (see Appendix B for a description of the instrumentation).

A heat loss factor test was undertaken during November 1999 to assess whether the buildings were nearly identical apart from wall thermal mass. The results (Appendix G) indicate that the reported energy savings due to the heavy walls may have been slightly understated in this report, and the reduction in overheating problems may have been slightly overstated.

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[3] Energy released from an internal wall typically must pass through, and heat, a living space before being lost to the environment. Some energy stored in an external wall is released directly to the environment without heating a living space, and so an internal wall is a more efficient (and effective) energy store.

3. EXPERIMENTAL EVALUATION OF WALL THERMAL MASS

3.1 Method

The experimental evaluation of wall thermal mass was based on comparing the incidence of overheating[4], and the auxiliary heating energy use, of the two buildings. The primary data were hourly average measurements of dry resultant temperature (DRT) and, during the heating season, daily Watt-hour meter readings (read manually each day at 9 am). The heating season was April-October and during this period the buildings were heated to maintain a minimum DRT of 16°C from 10pm-7am and 20°C for the rest of the day.

The auxiliary heating energy used by the buildings (E) was calculated from:

$$E_T = ME_T + \delta_{AER} + \delta_{TRES} \qquad \text{(kWh)}$$

$$E_C = ME_C + \delta_{IG} \qquad \text{(kWh)}$$

where ME_C = electricity used by the heater in the concrete building
ME_T = electricity used by the heater in the timber building
δ_{AER} = adjustment for differences in the air exchange rate of the two buildings
δ_{TRES} = adjustment for errors in the temperature probe calibrations
δ_{IG} = adjustment for differences in the internal heat gain of the two buildings.

The procedure used for estimating these adjustments is outlined in Appendix E. The treatment of uncertainty in the auxiliary heating energy is described in Appendix F.

3.1.1 Base case trial (June-December 1998)

In this trial the buildings had carpets and were heated but did not have curtains and were not ventilated (apart from the airflow through the continuously operating fan in the attic), i.e. the buildings were free to overheat.

3.1.2 Ventilation trial (January-June 1999)

Ventilation increases the auxiliary heating energy requirements because the vented energy, which may otherwise be stored, is not available to help meet future heating requirements. The timber building was expected to need significantly more ventilation than the concrete building. So this trial was expected to show the energy saving benefits of wall thermal mass more clearly than the base case trial.

To mimic natural ventilation, two axial flow fans, with integral back draught shutters, were installed in each building and provided ventilation at approximately 5 air changes per hour whenever DRT exceeded 27°C. The fans operated together. The fan in the north wall discharged air into the building and the fan in the south wall extracted air from the building.

On sunny days the DRT was significantly greater than the building air temperature. Ventilation, and the resulting increase in air movement inside the building, reduced the difference between DRT and building air temperature. This cooling was in addition to any cooling of the globe due to a drop in the building air temperature.

[4] During the day a DRT in the range 20-27°C was considered comfortable, 28-30°C was considered warm and uncomfortable, greater than 30°C was considered to be hot and very uncomfortable.

3.1.3 Curtain trial (July-October and December 1999)

By reducing the heat loss, curtains were expected to increase the percentage energy savings due to wall thermal mass. The energy flowing from the heavy walls was expected to make a relatively larger contribution to the heating load when curtains were used.

A motorised roller shutter was installed on the inside of each window to mimic the action of curtains. The shutters were closed over the windows from 6pm-7am during 1 July-3 October, from 7pm-7am during 3-31 October, to match the start of daylight savings time, and from 9pm-7am during December. All other aspects of the buildings remained unchanged.

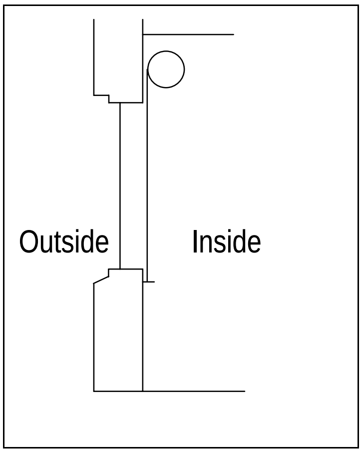

Figure 3. Window Shutter

The shutter slats were airtight when in place over the window. However the sides and bottom were not perfectly sealed and the top was unsealed. The thermal resistance of the shutter was expected to approximately equal 0.15 $m^2.^oC.W^{-1}$, similar to fabric curtains. The shutters were expected to reduce the heat loss factor of the buildings by approximately 8.5 $W.^oC^{-1}$ or 15%.

3.1.4 Bare floor trial (January-June 2000)

Removing the carpets was expected to reduce the effectiveness of the wall thermal mass. A bare concrete floor was expected to reduce the auxiliary heating energy requirements and overheating problems more significantly in the timber building than in the concrete building.

The carpets were removed and the concrete floors were painted a terracotta colour. The shutters were closed over the windows from 9pm-7am during 1 January-20 March, from 8pm-7am during 20-31 March, to match the end of daylight savings time, and from 6pm-7am for the rest of the trial. All other aspects of the buildings remained unchanged.

Removal of the carpets was expected to increase the heat loss factor of the buildings by approximately 3.2 W. $^oC^{-1}$, or almost 7% compared with the buildings in the curtain trial with the shutters closed over the windows.

3.2 Results

3.2.1 Base case trial

From Table 3 it can be seen that the most significant effect of heavy walls was a reduction in the incidence of overheating. The DRT in the concrete building seldom exceeded 28ºC while in the timber building DRT often exceeded 30ºC, even during winter.

During December 1998 the peak DRT in the concrete building was approximately 5ºC cooler than in the timber building (Figure 4). The hourly mean DRT during the afternoon was 2-3ºC cooler in the concrete building than in the timber building. The mean DRT just prior to sunrise was approximately 1.5ºC warmer in the concrete building than in the timber building.

The temperature smoothing effect of the heavy walls was also evident when the buildings were heated (Figure 6). During the day the concrete building was cooler and more comfortable than the timber building. After 10pm, when the heating temperature dropped from 20 to 16ºC, the concrete building was warmer than the timber building and often above the heating temperature.

The monthly auxiliary heating energy used by the two buildings was nearly equal (Table 3). On a daily basis the heavy walls tended to reduce energy use during periods of high solar gain, especially on cold days, and increase energy use during dull periods (Figure 5).

The scatter in Figure 5 would have been largely due to heat storage effects. The change in the amount of energy stored in the walls, from a change in the wall average temperature, would have significantly affected the daily heating energy requirements in the concrete building.

The peak heating loads of the two buildings were nearly equal but their hourly heating load profiles differed significantly. The results shown in Figure 6 were typical. Heavy walls, with on-demand air heating, increased the load during the day and decreased it during the night.

Table 3. Thermal performance during the base case trial (June-December 1998)

Month[3]	Ambient Air Temp.	Daily Global Solar Radiation	Overheating Hours				Auxiliary Heating Energy Use[1]		Energy Savings due to Heavy Walls[2]	
			DRT[4]>28°C		DRT>30°C		Concrete (kWh)	Timber (kWh)	Absolute (kWh)[5]	Percent (%)
	(°C)	(kWh.m^{-2})	Concrete	Timber	Concrete	Timber				
June	7.1	1.22	12	39	0	25	276.8	268.2	-8.6±16.3	-3.2
July	8.1	1.55	8	63	0	39	237.7	234.1	-3.6±14.3	-1.5
Aug	6.9	2.13	3	56	0	32	266.3	264.0	-2.3±15.9	-0.9
Sept	10.6	3.44	2	84	0	53	120.3	123.4	3.1±7.4	2.6
Oct	12.7	4.00	0	48	0	24	79.4	76.8	-2.6±5.0	-3.4
Nov	13.0	5.15	0	24	0	6	-	-	-	-
Dec	16.4	5.75	3	65	0	26	-	-	-	-
Total	-	-	28	379	0	205	980.5	966.5	-14.0±58.6	-1.4

Note:

1. *For the period from 9am on the 1st day of the month to 9am on the 1st day of the following month.*
2. *A negative value indicates the concrete building used more energy than the timber building.*
3. *Four days of missing data in September and five days of missing data in December.*
4. *Dry resultant temperature.*
5. *The uncertainties are conservative (Appendix F). The results from the heat loss factor test indicate that the energy savings were more likely to have been slightly greater rather than less than the values shown in the table.*

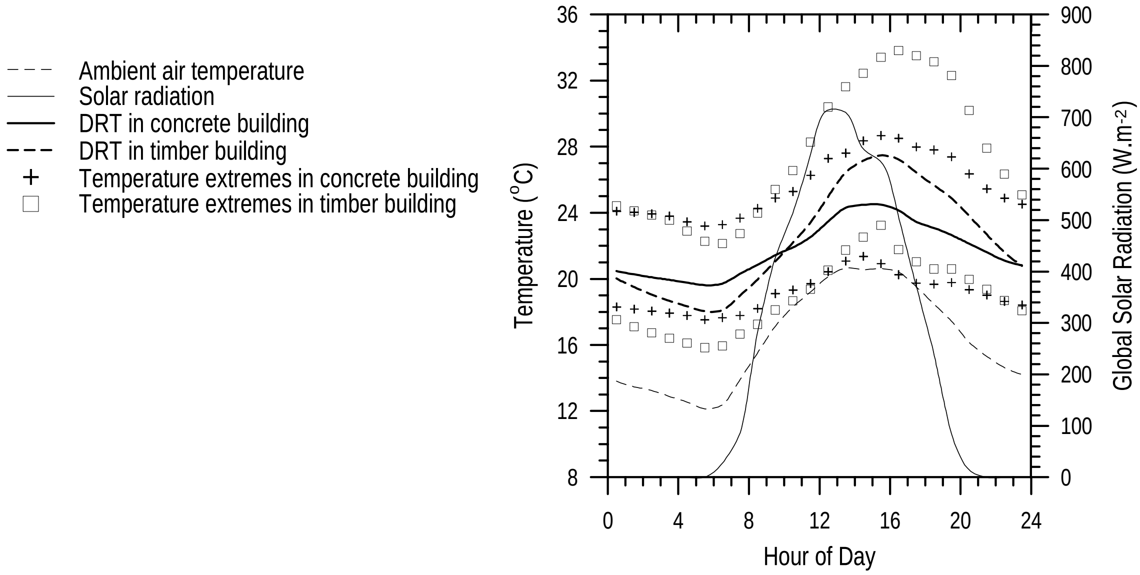

Figure 4. Mean and extreme dry resultant temperatures in the test buildings during December 1998 (base case trial)

Note: No heating or cooling during this month.

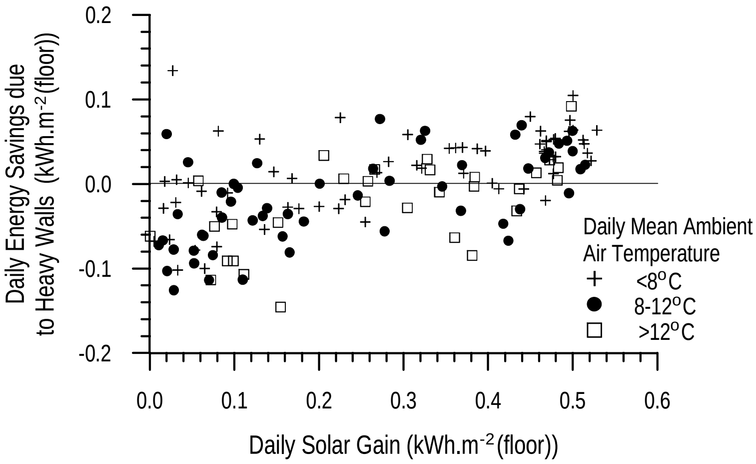

Figure 5. Daily savings in auxiliary heating energy use due to heavy walls versus daily solar gain through the window during the base case trial

Note: Energy and climate data for a given day was for the 24-hour period starting 9am on the previous day. Solar gain was the net solar gain through the window. Negative energy savings indicate that the concrete building used more energy than the timber building.

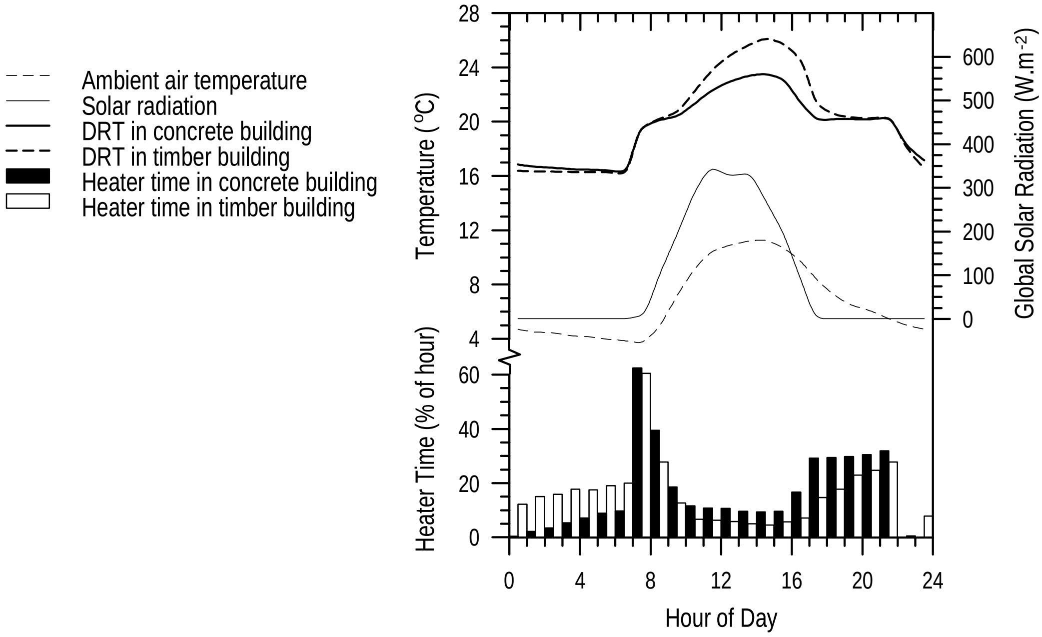

Figure 6. Hourly mean dry resultant temperature and heater operation time during August 1998 (base case trial)

Note: No cooling during this month.

3.2.2 Ventilation trial

Providing ventilation when the DRT exceeded 27°C did not eliminate overheating. Both buildings overheated, especially during March, but overheating was markedly less frequent in the concrete building compared with the timber building (Table 4). Reducing the solar gain or increasing the ventilation rate would typically have reduced the incidence of overheating in both buildings. An important result however is that the heavy walls provided up to 3-4°C cooling in addition to that provided by ventilation (Figure 7).

Depending on the time of the year, the monthly auxiliary heating energy used in the concrete building was 8-15% less than in the timber building (Table 4). The concrete building required less ventilation and stored solar energy more effectively than the timber building. Based on ventilation times, the difference in the ventilation energy losses was estimated to equal 19.4, 23.5 and 17.2 kWh for April, May and June respectively.

Comparing Figure 5 and Figure 8, the trend between daily heating energy savings and solar gain was more evident when the buildings were ventilated.

The temperature smoothing effect of the heavy mass walls is evident in Figure 7 and Figure 9. As for the base case trial, the concrete building was warmer during the night and cooler during the day. The shift in the heating load was also evident in this trial and as for the base case trial, the peak heating loads of the buildings were essentially equal.

Table 4. Thermal performance during the ventilation trial (January-June 1999)

Month[2]	Ambient Air Temp. (°C)	Daily Global Solar Radiation (kWh.m^{-2})	Overheating Hours DRT[3]>28°C Concrete	Overheating Hours DRT[3]>28°C Timber	Overheating Hours DRT>30°C Concrete	Overheating Hours DRT>30°C Timber	Auxiliary Heating Energy Use[1] Concrete (kWh)	Auxiliary Heating Energy Use[1] Timber (kWh)	Energy Savings due to Heavy Walls Absolute[4] (kWh)	Energy Savings due to Heavy Walls Percent (%)
Jan	17.7	5.51	10	67	0	21	-	-	-	-
Feb	17.7	5.36	34	89	7	39	-	-	-	-
Mar	17.0	3.82	36	82	16	46	-	-	-	-
Apr	12.4	2.45	7	29	0	11	67.3	78.6	11.3±4.6	14.3
May	11.9	1.75	2	15	0	5	113.0	128.8	15.7±7.3	12.2
June	7.3	1.43	0	4	0	1	235.6	256.9	21.4±14.6	8.3
Total	-	-	89	286	23	123	415.9	464.3	48.4±25.9	10.4

Note:

1. *For the period from 9am on the 1st day of the month to 9am on the 1st day of the following month.*
2. *Two days of missing data in January and one day of missing data in April.*
3. *Dry resultant temperature.*
4. *The uncertainties are conservative (Appendix F). The results from the heat loss factor test indicate that the energy savings were more likely to have been slightly greater rather than less than the values shown in the table.*

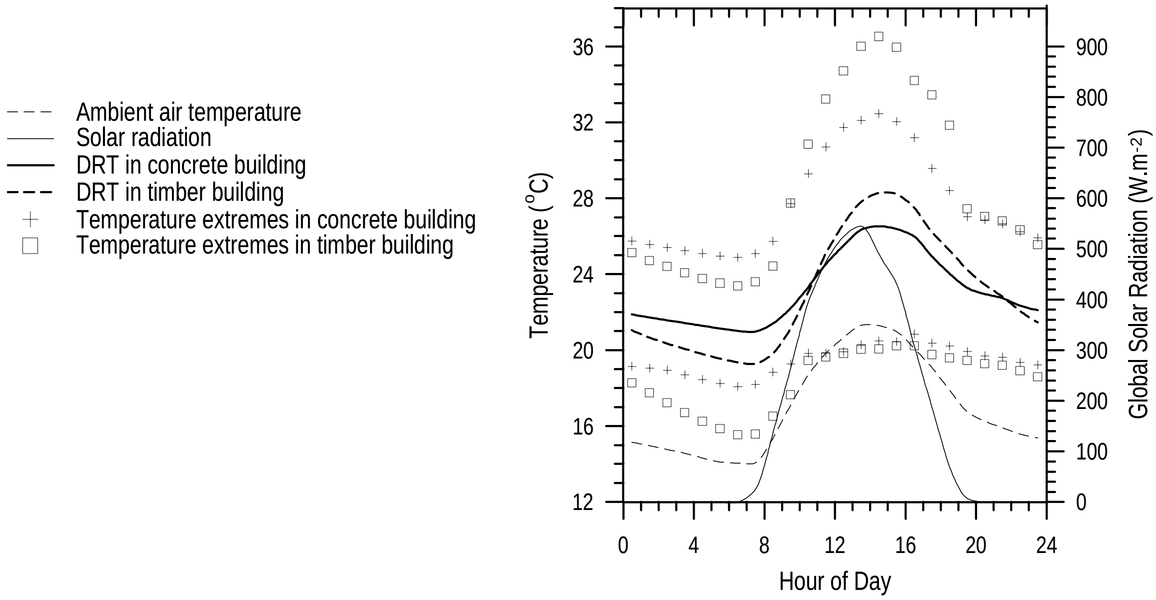

Figure 7. Mean and extreme dry resultant temperatures in the test buildings during March 1999 (ventilation trial)

Note: No heating during this month.

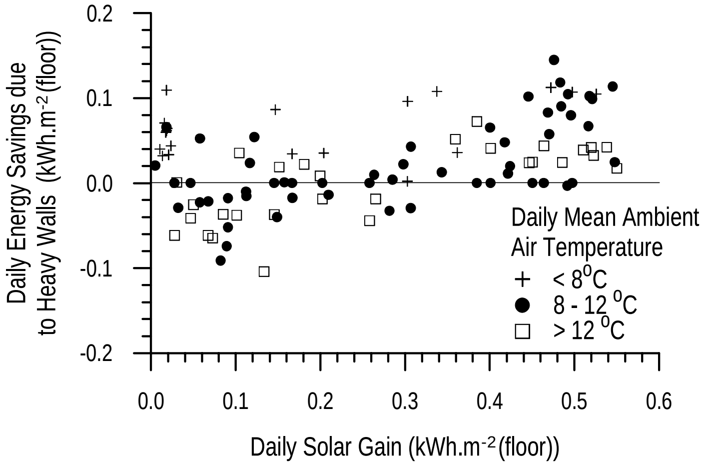

Figure 8. Daily savings in auxiliary heating energy use due to heavy walls versus daily solar gain through the window during the ventilation trial

Note: Energy and climate data for a given day was for the 24-hour period starting 9am on the previous day. Solar gain was the net solar gain through the window. Negative energy savings indicate that the concrete building used more energy than the timber building.

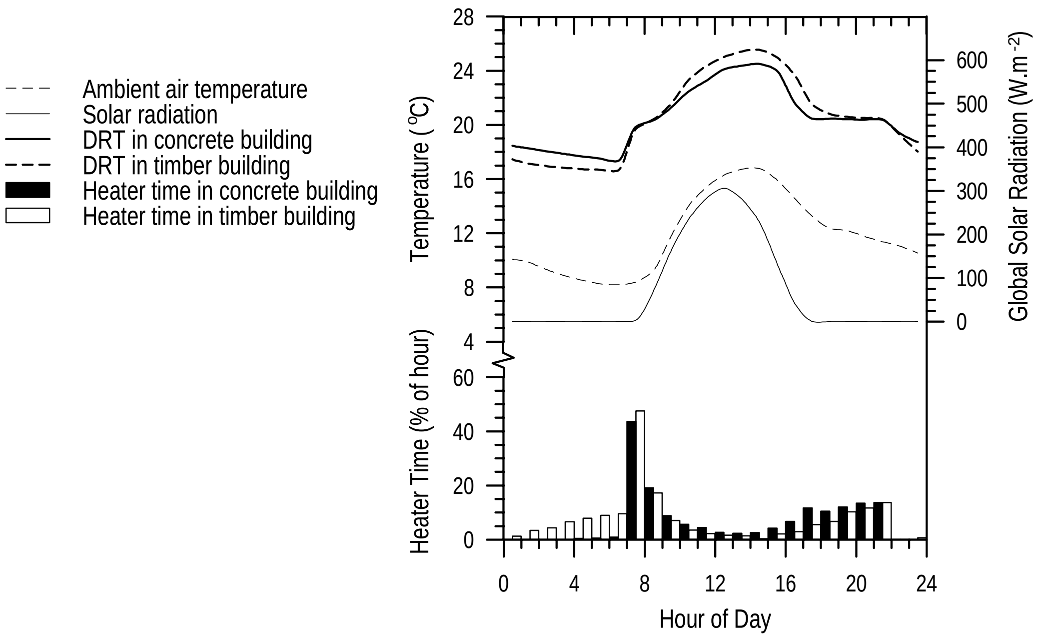

Figure 9. Hourly mean dry resultant temperature and heater operation time during May 1999 (ventilation trial)

3.2.3 Curtain trial

The concrete building did not overheat and overheating was infrequent in the timber building (Table 5). The reduction in overheating compared with the ventilation trial would have been due to the cooler ambient air and ground temperatures (Figure 10). This was a seasonal effect. The effect of the shutters, if any, would have been to slightly increase the risk of overheating (by keeping the buildings warmer at night and reducing their cooling capacity).

The 5.1% energy savings (Table 5) was less than the savings observed for the ventilation trial (10.4%). By plotting the monthly energy savings against monthly solar gain (Figure 11) the effect of season was largely removed enabling the results from the ventilation and curtain trials to be compared. If the June results are excluded, Figure 11 shows that there was a strong, and nearly linear, relationship between energy savings and solar gain. This indicates that the difference in the buildings, utilisation of window solar gain was essentially constant[5]. Figure 11 shows that the effectiveness of heavy walls was largely unaffected by the shutters.

The June result in Figure 11 appears to be an outlier. Both buildings were ventilated more frequently during June than during July (29/10.1 and 7.4/0.5 hours for June/July in the timber and concrete buildings respectively). The climates for these months were nearly the same, although the ground was warmer during June. This may have contributed to the higher ventilation rates during June, resulting in the observed energy savings due to the heavy walls.

Figure 12 shows that the monthly energy savings were strongly related to the reduction in the ventilation requirements due to the heavy walls. However, the scatter in Figure 12 also indicates that other mechanisms in addition to ventilation affected the energy savings.

As observed in the ventilation trial, the heavy walls shifted the heating load profile and the peak heating loads were nearly equal.

Table 5. Thermal performance during the curtain trial (July-October and December 1999)

Month	Ambient Air Temp.	Daily Global Solar Radiation	Overheating Hours				Auxiliary Heating Energy Use[1]		Energy Savings due to Heavy Walls	
			DRT[2]>28°C		DRT>30°C		Concrete (kWh)	Timber (kWh)	Absolute (kWh)[3]	Percent (%)
	(°C)	(kWh.m^{-2})	Concrete	Timber	Concrete	Timber				
July	7.3	1.30	0	0	0	0	293.1	293.0	-0.1±17.7	0.0
Aug	7.5	2.22	0	5	0	0	234.3	246.8	12.5±14.6	5.1
Sept	10.1	3.53	0	8	0	0	122.9	140.4	17.5±8.1	12.5
Oct	12.9	4.13	0	12	0	3	75.9	85.3	9.4±5.2	11.0
Dec	17.7	6.01	0	13	0	3	-	-	-	-
Total	-	-	0	38	0	6	726.2	765.5	39.3±45.4	5.1

Note:

1. *For the period from 9am on the 1st day of the month to 9am on the 1st day of the following month.*
2. *Dry resultant temperature.*
3. *The uncertainties are conservative (Appendix F). The results from the heat loss factor test indicate that the energy savings were more likely to have been slightly greater rather than less than the values shown in the table.*

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5 The window solar gain utilisation factor (U) can be defined by:

$U = (E^* - E)/S$

where E^* is the energy requirement if there was no solar gain through the window and S is the window solar gain. If E^* and S of the two buildings were equal then the slope of an energy savings (ΔE) versus window solar gain (S) curve equals ΔU, the difference between the buildings window solar gain utilisation factors, i.e. the energy effectiveness of heavy mass walls.

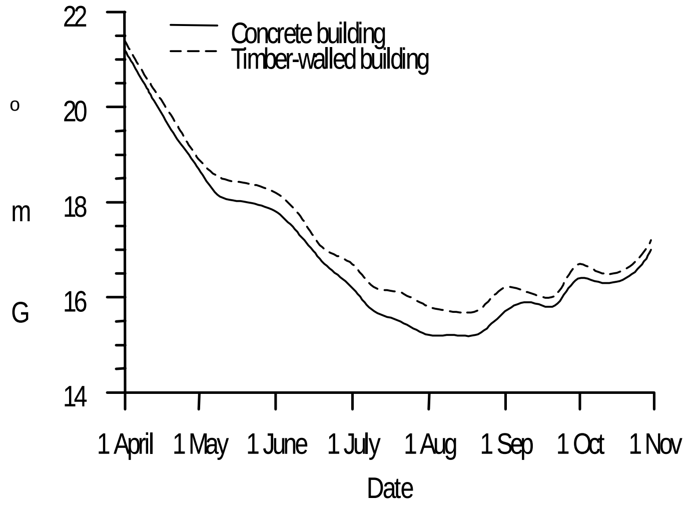

Figure 10. Ground temperature 0.65 m below floor level during the 1999 heating season (ventilation and curtain trials)

Note: The ground temperature measurements were taken near the centre of the floor.

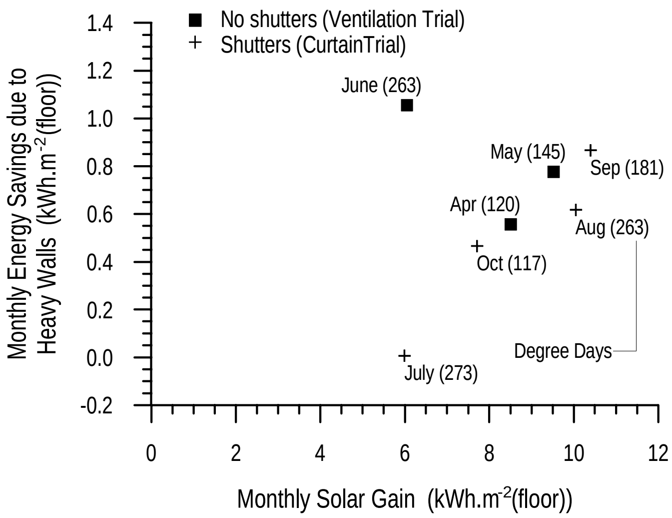

Figure 11. Monthly savings in auxiliary heating energy use due to heavy walls versus monthly solar gain through the window for the ventilation and curtain trials

Note: The degree days were for a base temperature of 16°C.

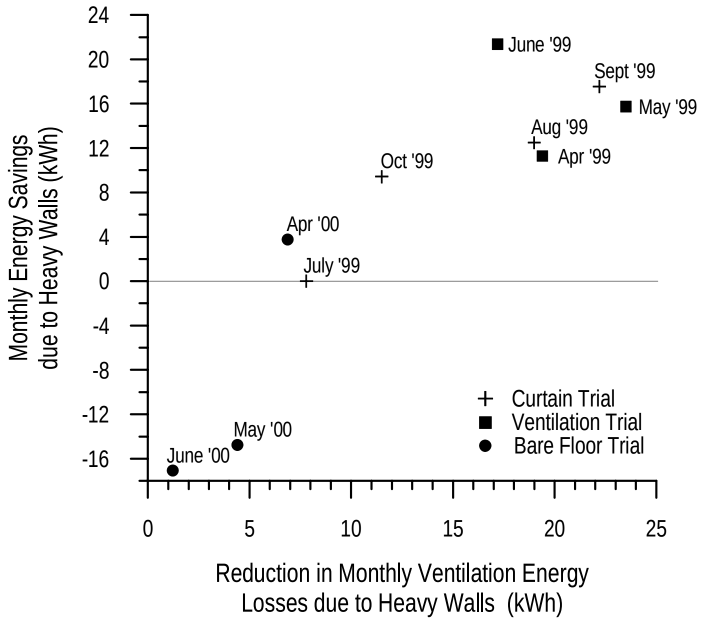

Figure 12. Monthly savings in auxiliary heating energy use due to heavy walls versus the reduction in monthly ventilation energy losses due to heavy walls (ventilation, curtain and bare floor trials)

Note: A negative energy savings indicates that the concrete building used more energy than the timber building.

3.2.4 Bare floor trial

Removing the carpets to expose the concrete floor reduced the incidence of overheating in both buildings. Table 6 shows that the DRT exceeded 30°C for only one and 23 hours in the concrete and timber buildings respectively. The corresponding values for the ventilation trial were 23 and 123 hours.

It can be seen from Figure 13 that during March 2000 the peak DRT in the concrete building was 2-3°C cooler than in the timber building (3-4°C in the ventilation trial (March 1999)). During the afternoon the hourly mean DRT in the concrete building was 0.3-0.9°C cooler than in the timber building (1-2°C for the ventilation trial). Just prior to sunrise the hourly mean DRT in the concrete building was approximately 1°C warmer than in the timber building (1.7°C in the ventilation trial). These results indicate that the concrete walls had a significant temperature smoothing effect even with an exposed concrete floor.

Table 6. Thermal performance during the bare floor trial (January-June 2000)

Month[3]	Ambient Air Temp. (°C)	Daily Global Solar Radiation ($kWh.m^{-2}$)	Overheating Hours DRT>28°C Concrete	DRT>28°C Timber	DRT>30°C Concrete	DRT>30°C Timber	Auxiliary Heating Energy Use[1] Concrete (kWh)	Timber (kWh)	Energy Savings due to Heavy Walls[2] Absolute[4] (kWh)	Percent (%)
Jan	15.5	5.14	2	11	0	3	-	-	-	-
Feb	16.5	4.42	5	27	0	10	-	-	-	-
Mar	14.6	4.14	11	18	1	9	-	-	-	-
Apr	12.4	2.38	0	4	0	1	58.3	62.0	3.7±4.1	6.0
May	10.2	1.59	0	0	0	0	160.9	146.2	-14.7±9.4	-10.1
June	8.6	1.33	0	0	0	0	226.4	209.3	-17.1±13.2	-8.2
Total	-	-	18	60	1	23	445.6	417.5	-28.1±26.5	-6.7

Note:
1. *For the period from 9am on the 1st day of the month to 9am on the 1st day of the following month.*
2. *A negative value indicates the concrete building used more energy than the timber building.*
3. *Three days of missing data in January.*
4. *The uncertainties are conservative (Appendix F). The results from the heat loss factor trial indicate that the energy savings were more likely to have been slightly greater rather than less than the values shown in the table.*

The temperature smoothing effect of the heavy walls was also evident when the buildings were heated. Figure 14 shows that the hourly mean DRT just before sunrise during May 2000 was 17.7^{o}C in the concrete building, and that this was approximately 1^{o}C greater than in the timber building (17.4 and 0.7^{o}C for the ventilation trial).

The ventilation heat losses from the timber building were estimated to be 6.9, 4.4 and 1.2 kWh greater than from the concrete building for April, May and June respectively. These differences were significantly less than the corresponding values during the ventilation trial. However, the reductions for May and June were not sufficient to produce a reduction in the monthly auxiliary heating energy requirements (Table 6).

Comparing Tables 4 and 6 it appears that the thermal performance of the concrete test building with carpets was very similar to the timber test building without carpets. Overheating hours and auxiliary heating energy use were remarkably similar for these two cases. The comparison is for the same season, but different years, and April-June 1999 was sunnier than the corresponding period in 2000. Further, the windows did not have shutters during the ventilation trial (but did during the bare floor trial).

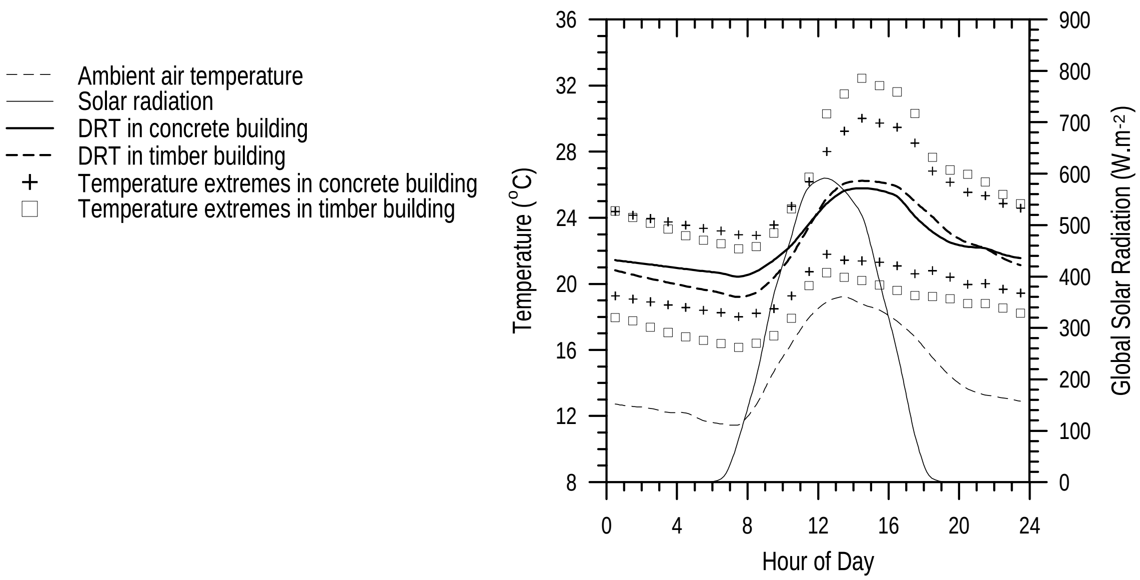

Figure 13. Mean and extreme dry resultant temperatures in the test buildings during March 2000 (bare floor trial)

Note: No heating during this month.

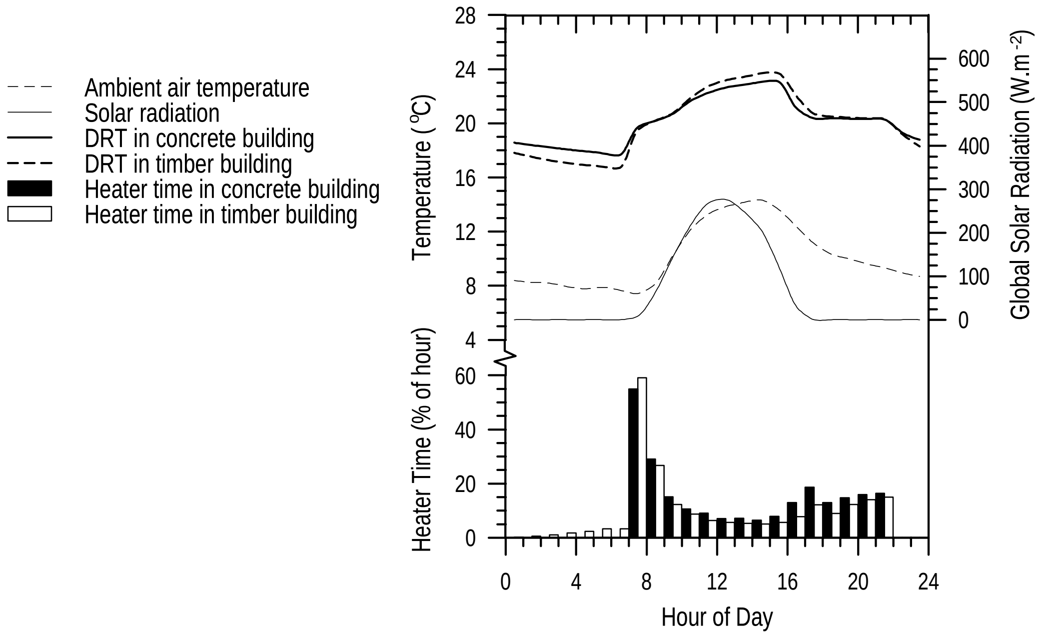

Figure 14. Hourly mean dry resultant temperature and heater operation time during May 2000 (bare floor trial)

3.3 Explanatory Model of Energy Savings

Bellamy and Mackenzie (1999) have shown that differences between the monthly auxiliary heating energy requirements of the test buildings were primarily related to:

- the ventilation energy losses
- the conduction heat flows at the exterior surfaces of the buildings.

For those parts of the buildings with the same construction (window, door, roof and floor), differences in conduction heat flows would have been closely related to differences in the buildings' air temperatures. Differences in conduction at exterior wall surfaces would have been closely related to differences in the bulk average temperatures of the buildings' walls.

The following would have increased the energy saving due to the heavy walls:

- the air temperature in the concrete building was cooler during the day
- the concrete building was ventilated less frequently than the timber building.

The following would have decreased the energy saving due to the heavy walls:

- the air temperature in the concrete building was warmer for most of the night (10pm-7am), providing excess comfort, i.e. temperatures in excess of the heating temperature
- the bulk average temperature of the concrete walls was typically greater than the timber walls.

The balance of these factors determined the energy savings from the heavy walls. During sunny and cool periods the first two factors dominated, resulting in energy savings. During overcast and milder periods the last two factors dominated, reducing the energy savings or resulting in increased auxiliary heating energy use in the concrete building.

3.4 Implications for House Design

This project tested various configurations of a single building design in only one location. The results have been interpreted, where possible, for different designs in different locations.

3.4.1 Comfort

Through reducing temperature swings, thermal comfort was always superior in the concrete test building. Adding thermal mass to walls can be expected to provide superior comfort for any design at any location provided the house is adequately heated.

The results support the view that overheating is a significant problem for many new lightweight houses in New Zealand. If the test buildings had larger windows the overheating problem observed in the timber building, especially during autumn, would have been exacerbated. The trend in housing design for expansive glazing areas and greater insulation levels means that overheating is an increasingly important issue.

Adding thermal mass to a building provides significant cooling without sacrificing the beneficial effects of solar energy inside the building. Thermal mass can be added to a lightweight house by having an exposed concrete floor (with lightweight walls) or by having heavy walls (with a carpeted concrete floor). These appear to provide similar results. In practice, exposing large proportions of a concrete floor is unlikely to find favour with most New Zealanders.

The results show that heavy walls provide significant cooling in addition to the cooling provided by an exposed concrete floor. And this additional cooling improves comfort. Further, a building with heavy walls and an exposed concrete floor is significantly warmer during the night than a building with lightweight walls and a bare concrete floor.

3.4.2 Auxiliary heating energy requirements

The effect of heavy walls on the auxiliary heating energy use is more complex than comfort. The results do not allow generalised statements to be made concerning energy savings due to heavy walls, as this will depend on the location and the building design. For the heating regime used in this project the following can be said:

- heavy walls appear to have a relatively minor effect on the auxiliary heating energy use when a house is closed during the day
- adding thermal mass to walls will provide energy savings if a house requires significant cooling during the heating season. Cooling loads in a lightweight house, and the energy savings from increasing wall thermal mass, are strongly related to solar gain. So the energy savings from heavy walls is greatest in sunny regions where solar access is not significantly restricted
- adding thermal mass to walls may increase the auxiliary heating energy requirements when a house, with lightweight walls, has a low requirement for cooling ventilation.

The last point warrants further discussion, as it seems to be the only negative outcome from using heavy walls. Adding thermal mass to the walls of a house increases the cooling capacity. The designer can exploit this additional cooling capacity by increasing solar gain (e.g. larger north windows) without compromising comfort. The increased solar gain would be expected to result in significant energy savings. Increasing the insulation levels can be expected to achieve a similar result, i.e. energy savings without sacrificing comfort.

3.4.3 Integrated design

The previous discussion highlights the importance of integrating window, insulation and thermal mass design in order to obtain the potential benefits from heavy walls.

Houses with heavy walls can accept higher levels of solar gain and insulation without sacrificing comfort. If solar gain and insulation are not matched to the level of thermal mass then the cooling capacity from heavy walls may not be fully exploited. This may result in limited improvements in thermal comfort and an increase in the auxiliary heating energy requirements.

4. BUILDING ENERGY PROGRAMME TESTING

4.1 Method

Simulations were carried out for August and September 1999. The programmes were evaluated according to their accuracy in predicting the difference in the buildings' auxiliary heating energy use and comfort during September 1999. August was used as a settling down period, so that the initial conditions used by the programme ceased to have a significant effect on the output.

4.1.1 Climate data

Hourly mean weather data from the test-building site were used as programme input data. Shadowband corrections to the diffuse solar radiation measurements were based on the procedure outlined by Batlles et al. (1995)[6]. Daytime cloud cover (for tsbi3) was estimated from the diffuse fraction based on the empirical equation from Kasten and Czeplak (1980)[7].

4.1.2 Model parameters

The walls were modelled using the heat flow paths described in Appendix C. The floor was modelled as two heat flow paths. The perimeter (0.75m strip) was modelled as losing heat to the ambient air and the centre of the floor was connected to the ground. The roof was modelled as single heat flow path with the same R-value as calculated in Appendix C.

The properties of the building materials were not measured. The values in Table 7 were best estimates based on values in literature and were not manipulated to fit the experimental data[8].

4.2 Results

The results in Table 8 show that the programmes predicted the energy savings within 5% of the experimental data. This is well within the uncertainty range of the experimental data, without considering the additional uncertainty arising from some of the estimated model parameters.

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6 Diffuse solar radiation (G_d) was found from global solar radiation (G) and unadjusted diffuse solar radiation (G_{du}) measurements as follows:

$G_d = C_t G_{du}$ $\quad\quad 1<C_t<1.2$

where $C_t = 1.245 C_i + 0.522 \log(\Delta) + 0.23 \log(\varepsilon) + 0.322 \exp(-1/\sin(\beta))$

C_i = isotropic correction factor

$\varepsilon = ((G_{du} + (G - G_{du})/\sin(\beta))/G_{du}$

$\Delta = G_{du}/G_{ext}$

β = solar altitude

G_{ext} = extraterrestial radiation on a horizontal surface.

7 The cloud cover (C/8) was found from diffuse solar radiation (G_d) and global solar radiation (G) data as follows:

$C = 8((k_d - 0.3)/0.7)^{0.5} \quad\quad k_d \geq 0.3$

$= 0 \quad\quad k_d < 0.3$

where k_d = G_d/G.

8 The one exception was the layers specified for the floor perimeter heat flow path. The thickness of the sand and polystyrene layers was adjusted so that the floor's R-value was similar to the value assumed in Appendix sC.

Table 7. Selected model parameters

Parameter	Value	Comments
Site:		
Latitude (^{o})	-43.7	Lincoln University, Canterbury, New Zealand
Longitude (^{o} east)	172.5	
Ground reflectance (%)	20	
Deep ground temperature (^{o}C)	12	
Window orientation (^{o})	-8	Window faces 8^o west of true north
Infiltration rate ((air changes).h^{-1})	0.42	Constant
Ventilation rate ((air changes).h^{-1})	4.7	Cooling temperature 27^{o}C
Heater capacity (kW)	2.2	100% convection heat output. Heating temperature 16/20^{o}C from 10pm-7am/7am-10pm
Internal gain (W):		
6pm-10pm	155	100% convection heat output
10pm-6pm	95	100% convection heat output
R-value (m^2.^{o}C.W^{-1}):		
Window	0.18	Mean for whole window (opening in wall insulation)
Door	0.33	Mean for whole window (opening in wall insulation)
Carpet	0.33	
Shutter	0.15	
Wall cavity	0.18	
Attic	0.32	
Internal wall surface	0.12	
External wall surface	0.06	
Floor surface	0.16	
Ceiling surface	0.11	
External roof surface	0.03	
Solar transmittance (%):		
Window (single glazed)	85	For glazing when angle of incidence equals 0^o
Door (double glazed)	74	For glazing when angle of incidence equals 0^o
Solar absorptance (%):		
External surface of walls	30	
External surface of roof	90	
Inside building	92	Solar gain was distributed to the floor, walls and ceiling at a 5:3:1 ratio
Thermal conductivity (W.m^{-1}.^{o}C^{-1}):	0.035	
Expanded polystyrene	0.028	
Extruded polystyrene	0.045	
Macerated paper	0.17	
Plasterboard	1.4	Density and thermal capacity 800 kg.m^{-3} and1006 J.kg^{-1}.^{o}C^{-1} respectively
Concrete	0.13	Density and thermal capacity 2200 kg.m^{-3} and 880 J.kg^{-1}.^{o}C^{-1} respectively
Timber	0.5	Density and thermal capacity 500 kg.m^{-3} and1400 J.kg^{-1}.^{o}C^{-1} respectively
Graded round stones	1.8	Density and thermal capacity 1500 kg.m^{-3} and 900 J.kg^{-1}.^{o}C^{-1} respectively
Sand	1.5	Density and thermal capacity 1800 kg.m^{-3} and 800 J.kg^{-1}.^{o}C^{-1} respectively
Underlying soil		Density and thermal capacity 1900 kg.m^{-3} and 800 J.kg^{-1}.^{o}C^{-1} respectively

Note: See Appendix C for heat transfer areas.

Table 8 shows that tsbi3 was slightly more accurate in predicting the percentage energy savings, and that both programme predictions were well within the uncertainty bands.

Both programmes, especially Suncode, underestimated the building temperatures during the daytime. They also underestimated the cooling requirements and energy losses due to ventilation. These poor predictions may have been due in part to differences in the way zone temperatures were measured in the trials and calculated by the programmes (see Table 8 footnote).

Table 8. Predicted and measured building thermal performance for September 1999

Performance Indicator	Experimental Data	Programme Prediction	
		Suncode	tsbi3
Auxiliary heating energy use (kWh)[1]: – Concrete building – Timber building	 122.9 140.4	 110.4 127.5	 127.5 145.8
Energy savings due to heavy walls: – Absolute (kWh) – Percent (%)	 17.5±8.1 12.5±5.8	 17.1 13.4	 18.3 12.6
Ventilation energy loss (kWh): – Concrete building – Timber building	 2.0 24.2	 0.0 8.5	 0.0 13.7
Reduction in ventilation energy losses due to heavy walls (kWh)	22.2	8.5	13.7
Hours when zone temperature[2]<18°C: – Concrete building – Timber building	 179 231	 119 237	 99 250
Hours when zone temperature>26°C: – Concrete building – Timber building	 39 89	 0 48	 0 68
Hours when zone temperature>28°C: – Concrete building – Timber building	 0 8	 0 0	 0 4

Note:

1. *The predictions were for September while the experimental data was for 9am on 1 September to 9am on 1 October.*
2. *Dry resultant temperature (measured inside the black globe) for the experimental data. Zone temperature in tsbi3 was the operative temperature and in Suncode it was some weighted combination of the air and mean radiant temperatures.*

Both programmes predicted temperatures in the timber building better than in the concrete building. Daytime temperatures in the concrete building were warmer than predicted and night-time temperatures were cooler than predicted. This suggests that the models were overestimating the rate of heat transfer to and from the concrete walls.

4.3 Discussion

Earlier in this report a strong relationship was shown between energy savings and ventilation energy losses (Figure 12). It was surprising therefore that the programmes were accurate in predicting the energy savings while inaccurate in predicting the difference in the ventilation energy losses. This suggests that the predicted energy savings were subject to compensating errors, i.e. the underestimation of daytime temperatures and ventilation energy losses was compensated for by the other factors determining energy savings (as outlined on page 17).

Situations may arise where errors in simulated daytime temperatures will have a significant effect on the predicted energy savings. For example, suppose a designer uses simulation to determine the level of shading that has to be applied to the test buildings' windows to avoid overheating during September 1999. Suncode predicts that no shading is required and that the energy savings are 17.1 kWh (13.4%). tsbi3 predicts that shading is required on the timber building's window, but not on the concrete building's window, and that the energy savings is 26.8 kWh (17.4%). This highlights the need to test programmes for a wide range of building designs, occupant behaviours and climatic conditions.

5. CONCLUSIONS

This project has shown that exterior-insulated heavy walls can improve the thermal performance of New Zealand houses through reducing the incidence of overheating, maintaining warmer night-time temperatures and reducing auxiliary heating energy requirements.

Both energy savings and improved comfort need to be considered in order to get a complete picture of the thermal mass benefit. It would be wrong to judge wall thermal mass just on the energy savings results as the comfort levels in the test buildings differed. Obviously the concrete test building could have had more solar gain than the timber test building if the overheating hours were targeted to be nearly equal. Had this been the case then the energy saving benefit from wall thermal mass would have been significantly greater than measured.

Overheating can be reduced in a number of ways. Both reducing solar gain and using air conditioning would increase energy use. Thermal mass in heavy exterior-insulated walls provides significant cooling in addition to any cooling provided from ventilation and a bare concrete floor. House designers can easily achieve improved daytime comfort by simply replacing lightweight with heavy walls.

Simply replacing lightweight walls with heavy walls of equivalent R-value may increase or decrease the auxiliary heating energy requirements depending on the house design, climate and occupant behaviour. So achieving energy savings from heavy walls is less straightforward than achieving cooling.

Energy savings in a continuously heated house appear to be strongly related to the reduction in ventilation requirements provided by the heavy walls. Predicting the energy savings from heavy walls is currently beyond most designers. Appropriate design guidelines and tools that enable designers to exploit the energy savings benefit of heavy walls are required. These should enable designers to design windows (solar gain) and select insulation (heat loss) to exploit the thermal properties of heavy walls.

Design guides are invariably based on hourly output from building energy programmes. If the programmes tested in this project were representative, then building energy programmes appear to predict the energy savings from heavy walls reasonably well.

Some uncertainty remains about the accuracy of daytime comfort predictions by building energy programmes. Errors in these predictions can create errors in the predicted energy savings due to heavy walls. If a model underestimates the overheating problems in a lightweight house, then the fact that heavy walls enable the use of larger windows and greater solar gain, without sacrificing comfort, is not properly recognised.

This project has provided a better understanding of the benefits of heavy walls in New Zealand houses. Further work is required to extend this understanding and to quantify the effect of heavy walls on the auxiliary heating energy requirements when buildings have the same daytime comfort.

APPENDIX A: PHYSICAL DESIGN AND KEY DIMENSIONS OF TEST BUILDINGS

Walls

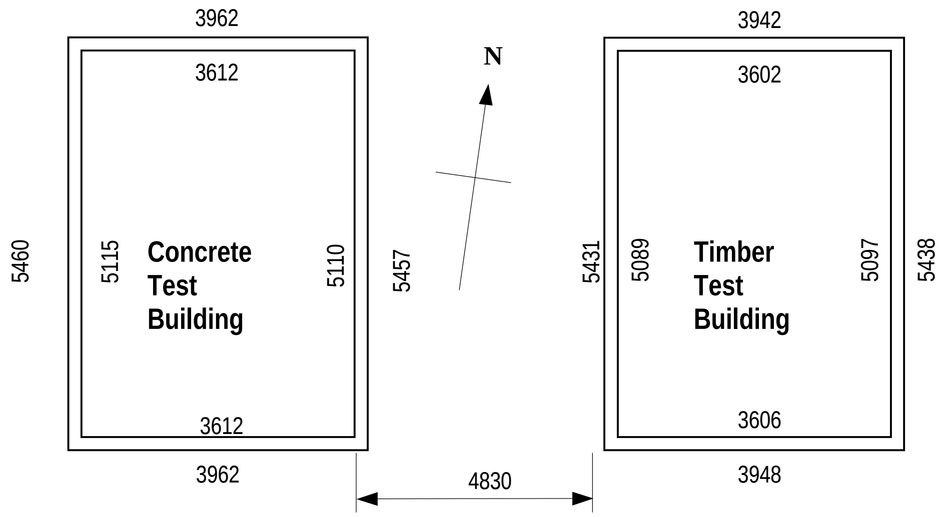


Figure A1. Wall lengths

Dimensions are averages from measurements at three heights.
Estimated accuracy ± 3mm.

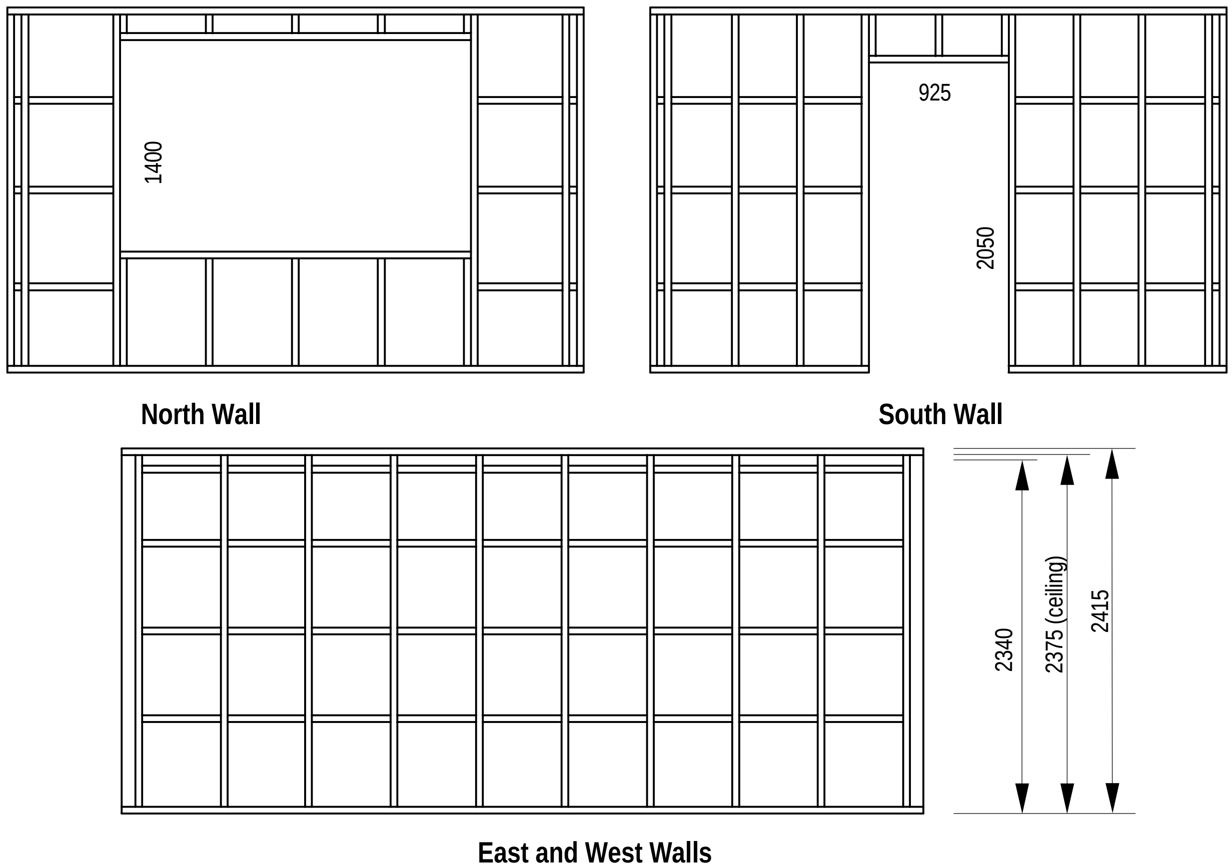


Figure A2. Timber framing in the walls of the timber test building

Timber framing 45mm wide Radiata Pine. Openings in the wall insulation for the window and door were 1425x2360 (3.36m^2) and 960x2110 (2.03m^2) respectively.

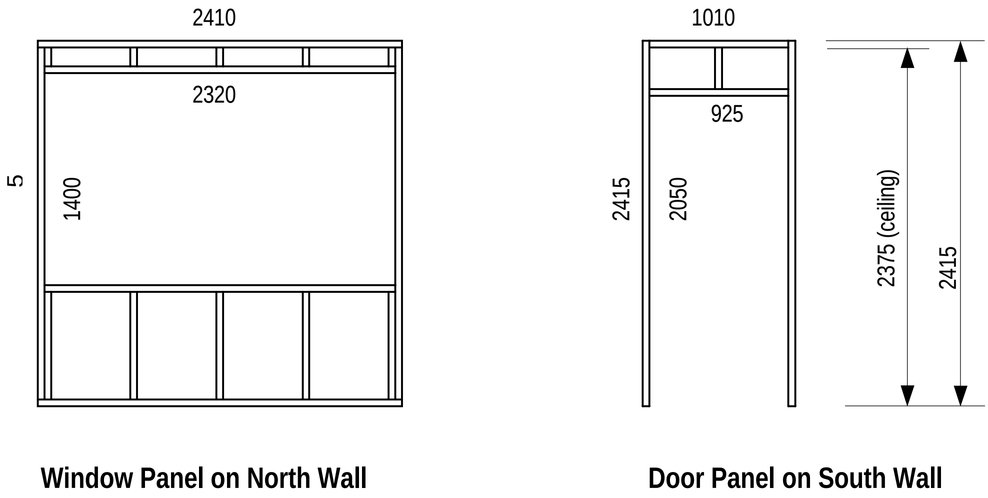


Figure A3. Timber framing in the walls of the concrete test building

Timber framing was 45mm wide Radiata Pine except for the door trimming studs (42mm). Insulation thickness on the timber frames same as for concrete panels. Openings in the wall insulation for the window and door were 1425x2360 ($3.36m^2$) and 960x2110 ($2.03m^2$) respectively.

Floor

The floor in each building was a nominal 100mm thick concrete slab-on-ground over a vapour barrier over 200mm of graded rounds over 350mm of unwashed compacted sand. The 200mm wide continuous concrete foundation was insulated with 80mm thick, vertical polystyrene sheets extending to approximately 850mm below the ground level. The floor was 150mm above the finished ground level. The floors were laid during 1997.

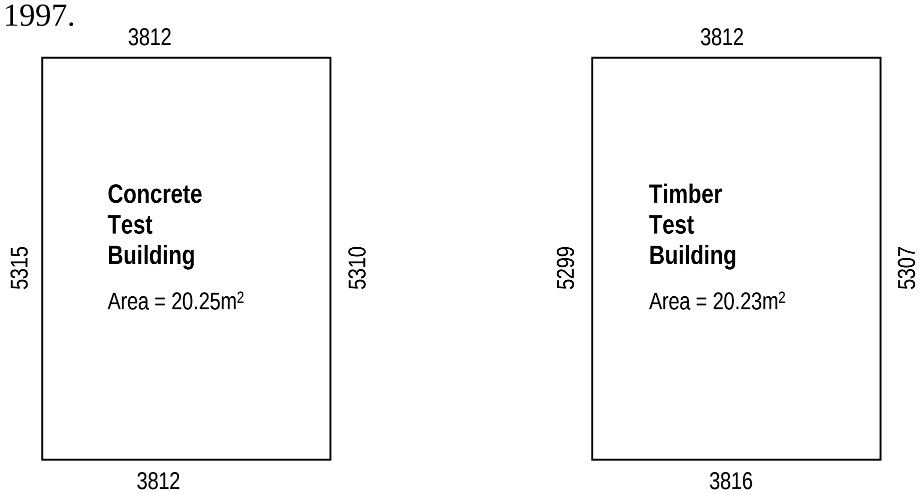


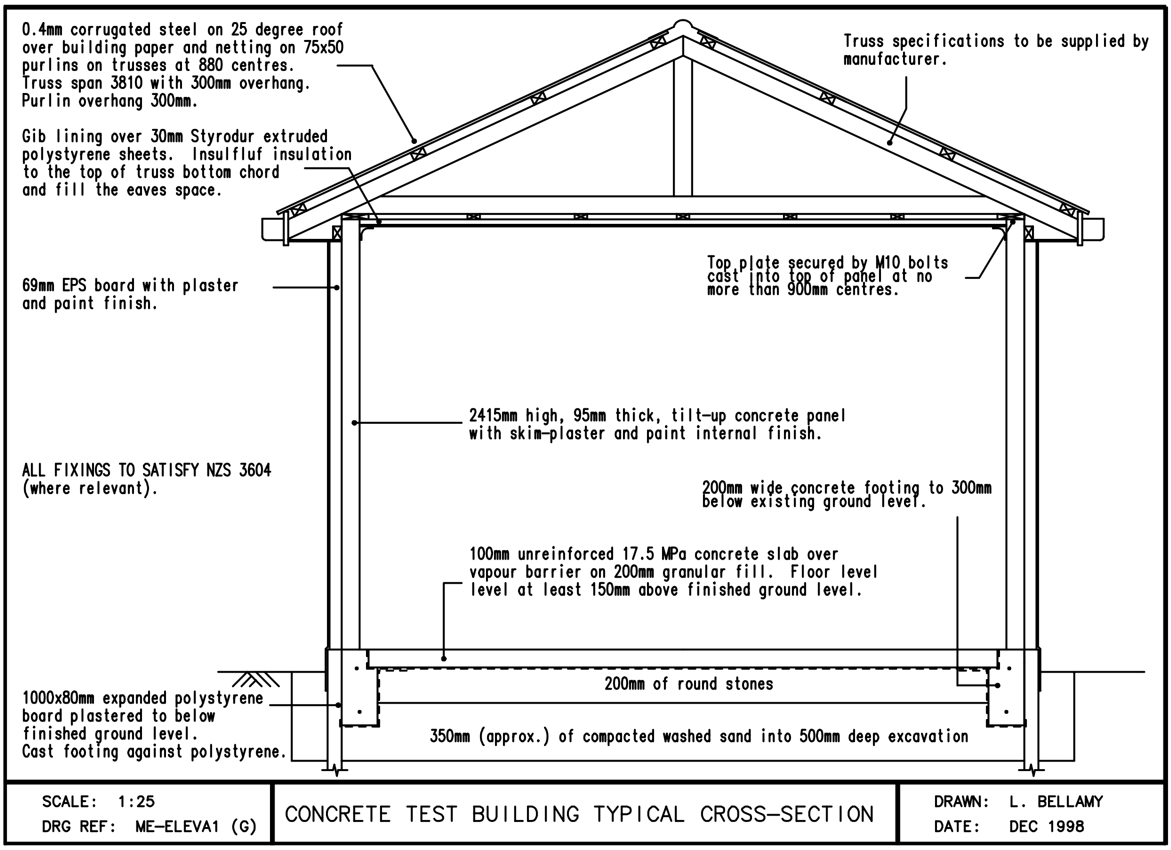
Figure A4. Floor dimensions

Dimensions are to the inside surface of the perimeter insulation, i.e. dimensions of the concrete slabs.

Roof

The roof was corrugated steel (charcoal colour) over building paper, over 70x35mm timber battens on timber trusses. The ceiling was 9.5mm plasterboard on 30mm thick extruded polystyrene (XPS) on 70x35mm timber battens on 95x45mm bottom chords of the timber trusses. Macerated paper insulation (Insulfluf) was blown into the roof space and levelled to the top edges of the bottom chords of the trusses. The insulation was placed in the eaves to insulate the tops of the walls.

Typical cross-sections



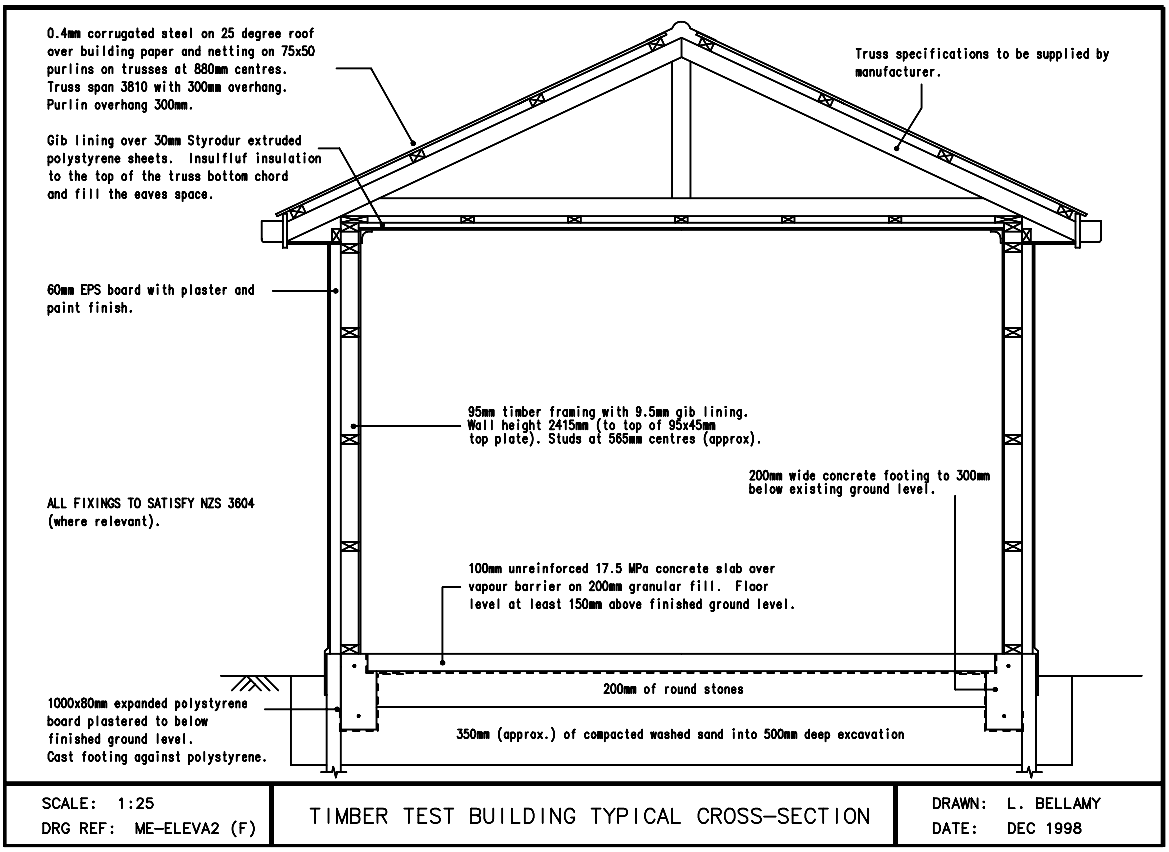


Figure A5. Typical building cross-sections

APPENDIX B: INSTRUMENTATION

A climate station was established on the site and the measurements shown in Table B1 were recorded by a Campbell Scientific CR10 datalogger.

Table B1. Climate station instrumentation

Measurement	Instrument
Wind speed at 5 and 10m above the ground.	Maximum M41 cup anemometers on a mast positioned midway between the buildings.
Wind direction	Maximum 200 series wind direction sensor at the top of the 10m mast.
Ambient air dry bulb temp.	AD590 temperature sensor in a Stevenson screen positioned between and north of the buildings.
Ambient air wet bulb temp.	AD590 temperature sensor in the Stevenson screen.
Global solar radiation	Kipp and Zonen CM11 pyranometer above the Stevenson Screen.
Diffuse solar radiation	Kipp and Zonen CM11 pyranometer with shade ring above the Stevenson Screen.
Light intensity	Li-Cor quantum sensor, 2m above the ground, positioned above the Stevenson Screen.

Note: A two-point calibration of the AD590 sensors was performed prior to the first trial. The pyranometers were calibrated against a Class 1 Eppley PSP pyranometer from 27 July-23 August 1999.

The buildings were instrumented as shown in Table B2. Apart from the mechanical Watt-hour meters, the measurements were made by a Campbell Scientific CR7 datalogger. The datalogger also controlled the operation of the heater and ventilation fans.

Table B2. Building instrumentation

Measurement	Instrument
Dry resultant temperature (DRT)	AD590 temperature sensor at the centre of 100mm diameter black globe (toilet ball-float) located 1.3m above the floor in the middle of the room.
Air temperature	AD590 temperature sensor within a radiation shield, located next to the globe.
Soil temperature	11 probes, each with an AD590 temperature sensor at the bottom (approximately 650mm below floor surface) and 2 type T differential thermocouples located 150 and 300mm above the bottom of the sensor.
Wall temperature	28 type T differential thermocouples measuring the temperature difference across of the wall insulation at 14 locations (measurements referenced to the temperature of a brass junction plate).
Ceiling temperature	12 type T thermocouples measuring the temperature difference across the extruded polystyrene insulation sheet in the ceiling, at 6 locations (measurements referenced to the temperature of a brass junction plate).
Attic fan airflow rate	Pressure drop across orifice plate by an AutoTran Model 750 pressure transducer.
Light gain through window	2 back-to-back Li-Cor quantum sensors mounted parallel to, and inside of, the window. Solar gain through the window was estimated from these and the climate station radiation measurements.
Heater operation	Datalogger recorded the length of time that the heater operated.
Ventilation fan operation	Datalogger recorded the length of time that the ventilation fans operated.
Heater electricity use	Class 2 mechanical Watt-hour meter and after 1 July 1999 by a Class 2 digital Watt-hour meter (pulse counting by datalogger from 1 November 1999).
Other electricity use	Class 2 mechanical Watt-hour meter and after 1 July 1999 by a Class 2 digital Watt-hour meter (pulse counting by datalogger from 1 November 1999).

Note: A two-point calibration of the AD590 sensors was performed prior to the first trial. The dry resultant and air temperature sensors were recalibrated one year later.

APPENDIX C: HEAT LOSS FACTOR CALCULATIONS

The heat loss factor for a building element (HL) was found from:

$$HL = A/R \quad (W.^{o}C^{-1})$$

where A (m^2) is the heat loss area of the building element and R ($m^2.^{o}C.W^{-1}$) is the thermal resistance of the building element, inclusive of surface resistances. NZS 4218: 1996 defines the heat transfer area as the area exposed to the inside air. This approach ignores corner effects, which may be significant in small buildings. To better account for corner effects, the heat loss areas in this calculation were defined as follows:

Floor:	Plane bounded by the inside surface of the floor perimeter insulation.
Ceiling/roof:	Plane bounded by the inside surface of the wall insulation.
Window:	Plane bounded by the opening in the wall insulation.
Door:	Plane bounded by the opening in the wall insulation.
Opaque walls:	Planes bounded by the ceiling and floor surface planes.

Floor

An estimated R-value based on values found in the literature was deemed acceptable for this calculation. R_F for the carpeted floor was taken as 1.8 $m^2.^{o}C.W^{-1}$.

For the timber test building:

$$\begin{aligned} HL_F &= 20.23/1.8 \\ &= 11.24 \ W.^{o}C^{-1} \end{aligned}$$

For the concrete test building:

$$\begin{aligned} HL_F &= 20.25/1.8 \\ &= 11.25 \ W.^{o}C^{-1} \end{aligned}$$

Roof

The thermal resistance of the roof was calculated from:

$$R_R = (\sum(A_i/A_r)/R_i)^{-1}$$

where (A_i/A_r) and R_i are the area fraction and thermal resistance of the *i*th heat transfer path respectively. Six different heat transfer paths through the roof were identified:

Plasterboard → 30mm XPS → 130mm Insulfluf → Attic	(75.5% of ceiling area)
Plasterboard → 30mm XPS → 35mm Insulfluf → 95mm truss chord → Attic	(3.5%)
Plasterboard → 30mm XPS → 35mm timber batten → 95mm Insulfluf → Attic	(12.1%)
Plasterboard → 30mm XPS → 35mm timber batten → 95mm truss chord → Attic	(0.5%)
Top plates → 95mm Insulfluf → Attic	(6.5%)
Top plates → 95mm truss chord → Attic	(1.9%)

The thermal conductivity of timber and Insulfluf was taken as 0.13 and 0.045 $W.m^{-1}.^{o}C^{-1}$ respectively. The R-value of plasterboard, 30mm XPS, the attic, and the inside and outside surface resistances was taken as 0.06, 1.07, 0.32, 0.11 and 0.03 $m^2.^{o}C.W^{-1}$ respectively, so:

$$R_R = \left[\frac{0.755}{1.59+\frac{0.13}{0.045}} + \frac{0.035}{1.59+\frac{0.035}{0.045}+\frac{0.095}{0.13}} + \frac{0.121}{1.59+\frac{0.035}{0.13}+\frac{0.095}{0.045}} + \frac{0.005}{1.57+\frac{0.13}{0.13}} + \frac{0.065}{0.46+\frac{0.080}{0.13}+\frac{0.095}{0.045}} + \frac{0.019}{0.46+\frac{0.175}{0.13}} \right]^{-1}$$

$$= 4.25$$

For the timber test building:

HL_R = 20.23/4.25
= 4.76 W.^{o}C^{-1}

For the concrete test building:

HL_R = 20.25/4.25
= 4.76 W.^{o}C^{-1}

Window

The window glazing and aluminium frame and part of the surrounding wall were within the area defined for the window (opening in the insulation of the north wall). From NZS 4214:1997 the overall thermal resistance was taken as 0.18 m^2.^{o}C.W^{-1}.

For the timber and concrete test buildings:

HL_W = 3.36/0.18
= 18.67 W.^{o}C^{-1}

Door

The glass door double-glazing and aluminium frame and part of the surrounding wall were within the area defined for the door (opening in the insulation of the south wall). From NZS 4214:1997 the overall thermal resistance was taken as 0.33 m^2.^{o}C.W^{-1}.

For the timber and concrete test buildings:

HL_D = 2.03/0.33
= 6.15 W.^{o}C^{-1}

Opaque wall

The thermal resistance of the opaque wall was found from:

$R_O = (\sum(A_i/A_{wall})/R_i)^{-1}$

where (A_i/A_{wall}) and R_i are the area fraction and thermal resistance of the *i*th heat transfer path respectively.

The principal heat transfer paths through the walls of the timber building were identified as:

Plasterboard → 95mm framing timber → 61mm EPS → Plaster	(19.3% of wall area)
Plasterboard → 95mm framing timber → 30mm EPS → Plaster	(0.2%)
Plasterboard → Cavity → 61mm EPS → Plaster	(79.5%)
Plasterboard → 95mm framing timber → 250mm Insulfluf → Plaster	(0.1%)
Plasterboard → Cavity → 250mm Insulfluf → Plaster	(0.9%)

The R-value of the internal and external surface resistances, cavity and exterior plaster was taken as 0.12, 0.06, 0.18 and 0.01 m^2.^{o}C.W^{-1} respectively.

R_O for the timber building was found from:

$$R_O = \left[\frac{0.002}{0.25+\frac{0.095}{0.13}+\frac{0.030}{0.035}}+\frac{0.193}{0.25+\frac{0.095}{0.13}+\frac{0.061}{0.035}}+\frac{0.795}{0.43+\frac{0.061}{0.035}}+\frac{0.001}{0.25+\frac{0.095}{0.13}+\frac{0.25}{0.045}}+\frac{0.009}{0.43+\frac{0.25}{0.045}}\right]^{-1} = 2.28$$

The principal heat transfer paths through the walls of the concrete building were identified as:

Concrete panel → 69mm EPS → Plaster	(91.8%)
Concrete panel → 250mm Insulfluf → Plaster	(1.0%)
Plasterboard → 95mm framing timber → 69mm EPS → Plaster	(2.2%)
Plasterboard → 95mm framing timber → 34mm EPS → Plaster	(0.2%)
Plasterboard → Cavity → 69mm EPS → Plaster	(4.8%)

The thermal conductivity of concrete was taken as 1.4 $W.m^{-1}.^oC^{-1}$ and the thermal resistance of the mortar between the insulation and the concrete panel was taken as 0.01. R_O for the opaque walls in the concrete building was found from:

$$R_O = \left[\frac{0.918}{0.20 + \frac{0.095}{1.4} + \frac{0.069}{0.035}} + \frac{0.01}{0.19 + \frac{0.095}{1.4} + \frac{0.25}{0.045}} + \frac{0.022}{0.25 + \frac{0.095}{0.13} + \frac{0.069}{0.035}} + \frac{0.002}{0.25 + \frac{0.095}{0.13} + \frac{0.034}{0.035}} + \frac{0.048}{0.43 + \frac{0.069}{0.035}} \right]^{-1}$$

$$= 2.27$$

For the timber test building:

HL_O = (2.375x(5.299+3.812+5.307+3.816)-3.36-2.03)/2.28
= 37.92/2.28
= 16.63 $W.^oC^{-1}$

For the concrete test building:

HL_O = (2.375x(5.315+3.812+5.310+3.812)-3.36-2.03)/2.27
= 37.95/2.27
= 16.71 $W.^oC^{-1}$

Total building

The total heat loss factor was found from:

$HL = HL_F + HL_R + HL_W + HL_D + HL_O$

The total heat loss factor for the timber test building was calculated as:

HL = 11.24+4.76+18.67+6.15+16.63
= 57.5 $W.^oC^{-1}$
= 2.84 $W.m^{-2}$(floor).$^oC^{-1}$

The total heat loss factor for the concrete test building was calculated as:

HL = 11.25+4.76+18.67+6.15+16.71
= 57.5 $W.^oC^{-1}$
= 2.84 $W.m^{-2}$(floor).$^oC^{-1}$

From these calculations the fraction of the total heat loss through the various surfaces of each building was as follows:

Floor ≅ 20%
Roof ≅ 8%
Window ≅ 32%
Door ≅ 11 %
Opaque wall ≅ 29 %

APPENDIX D: INFILTRATION IN THE TEST BUILDINGS

Calm conditions

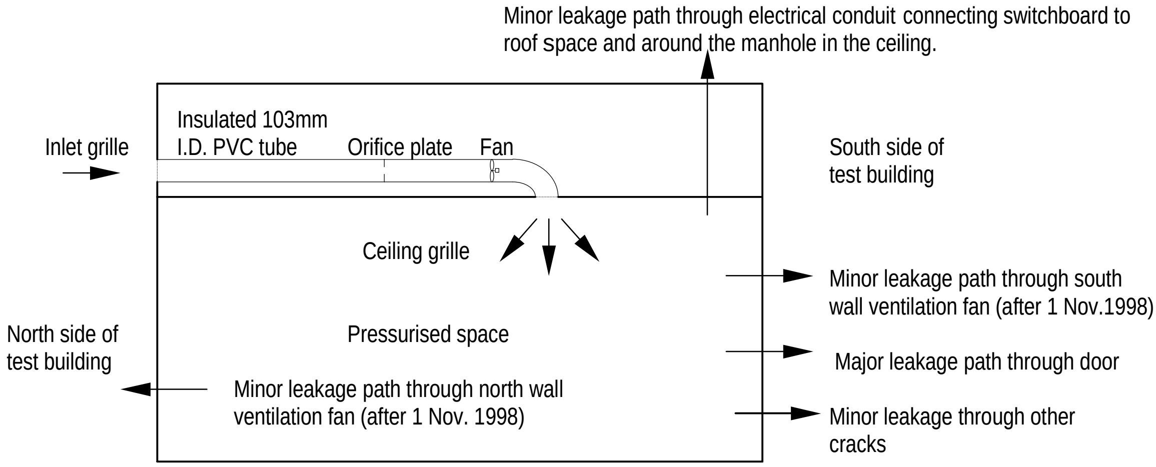


Figure D1. Infiltration airflow during calm conditions

During calm periods air entered the test building only via the fan in the attic since the internal pressure inside the building was greater than outside. The volumetric (V) and mass (M) flows rate through the fan were found from:

$$V = \frac{1000M}{\rho} \qquad \text{(litres.s}^{-1}\text{)}$$

$$M = \alpha A_2 \left(\frac{2\rho \Delta P}{1-\beta^2} \right)^{0.5} \qquad \text{(kg.s}^{-1}\text{)}$$

where α = discharge coefficient for the orifice plate in the fan inlet duct
$\cong$ 0.6
A_2 = orifice area of orifice plate
$\cong$ 0.00071 m^2
ρ = air density ($kg.m^{-3}$)
ΔP = pressure drop across the orifice plate (Pa)
β = A_2/A_1 where A_1 is the area of the 103mm diameter PVC duct upstream of the orifice plate
$\cong$ 0.085

The airflow rates in the two buildings were balanced during a calm period prior to the start of the trials by adjusting the flow area of the ceiling discharge grills. The airflow was approximately equal to 5.2 litres.s^{-1}. Airflows were balanced again after installation of the ventilation fans, however these had virtually no affect on the infiltration rate.

Windy conditions

During windy conditions, ambient air may have entered the buildings through cracks. An experimental investigation of the effect of wind on the infiltration rates was beyond the scope of this project. However a simple model was developed to provide a preliminary assessment.

The model predicted the internal pressure, the airflow through the orifice plate and the leakage through the windward and leeward walls for varying wind speeds and directions. Leakage through other surfaces was treated as zero. The model was:

$$P_{int} = P_{inlet} + \Delta P_{fan} - C_{fan} V_{fan}^2$$

$$= P_{ext,L} - C_{leak,L} \left| V_{leak,L} \right|^{1.5}$$

$$= P_{ext,W} - C_{leak,W} \left| V_{leak,W} \right|^{1.5} \qquad \text{(Pa)}$$

$$V_{leak,L} + V_{leak,W} + V_{fan} = 0 \qquad (\text{litres.s}^{-1})$$

where P_{inlet}, $P_{ext,L}$ and $P_{ext,W}$

= exterior wind pressure on the inlet grill, leeward wall and windward wall respectively

$C_{leak,L}$ = leakage coefficient for the leeward wall

$C_{leak,W}$ = leakage coefficient for the windward wall

$V_{leak,L}$ = leakage flow rate through the leeward wall

$V_{leak,W}$ = leakage flow rate through the windward wall

ΔP_{fan} = fan total pressure from the manufacturer's fan performance curve

C_{fan} = total pressure loss coefficient for the external grill, duct, orifice plate and ceiling grill attached to the ceiling fan.

The leakage coefficients were not explicitly measured. The values used in the model reflected the fact that the south walls were less airtight than the north walls and that the concrete building was slightly less air tight than the timber building. Also, the values were chosen so that during calm conditions the predicted airflow through the fan equalled the measured rate.

The model predicted that:

- the buildings infiltration rates (i.e. total air entering the building) were essentially equal for varying wind speeds and directions
- for wind speeds less than 5 m.s^{-1} (approximately 65% of time) the infiltration rate was essentially equal to the rate during calm conditions
- air started to enter the buildings through cracks in the windward wall when the wind exceeded 11-13 m.s^{-1}
- the orifice plate airflow measurements significantly underestimated the infiltration rate for southerly winds in excess of 13 m.s^{-1} (less than 2% of the time).

The main result is that the buildings' infiltration rates were essentially the same for varying wind conditions.

APPENDIX E: HEATING ENERGY USE ADJUSTMENT FACTORS

Air exchange rate adjustment factor (δ_{AER})

The following adjustment accounted for differences in the measured airflow rates through the orifice plates in the inlet ducts of the attic fans:

$$\delta_{AER} = \sum_{\substack{\text{Heating} \\ \text{Hours}}} (M_{concrete} - M_{timber})\, C_{p,ao}\, (T_{ai2} - T_{ao}) \qquad \text{(kWh)}$$

where M = mass flow rate of air through the orifice plate (kg.s^{-1})
$C_{p,ao}$ = specific heat capacity of the outside air (kJ.kg^{-1}.^{o}C^{-1})
T_{ai2} = air temperature inside the timber building (^{o}C)
T_{ao} = ambient air temperature (^{o}C)

This adjustment was applied for each hour when heating was required in the timber building.

Temperature probe calibration adjustment (δ_{TRES})

The air and DRT sensors were calibrated during February 1998. When recalibrated at the end of the ventilation trial both sensors in the timber building were reading approximately 0.3^{o}C high in the 16-20^{o}C range, i.e. showing a value of 16^{o}C when the 'real' value was 15.7^{o}C. The sensors in the concrete building were found to be accurate over the 16-20^{o}C range.

The error in the dry resultant temperature probe would have reduced the auxiliary heating energy use requirements of the timber building so the following adjustment was made:

$$\delta_{TRES} = \sum_{\substack{\text{Heating} \\ \text{Hours}}} \Delta T\, (HL + M_{timber} C_{p,ao}) \qquad \text{(kWh)}$$

where M_{timber} = mass flow rate through the orifice plate in the timber building (kg.s^{-1})
HL = heat loss factor of the timber-walled building (approx. 0.058 kW.^{o}C^{-1})
ΔT = the difference between the readings of the uncalibrated and calibrated DRT probe (^{o}C)

This adjustment was applied for each hour when heating was required in the timber building.

Internal gain adjustment (δ_{IG})

Heat from the ventilation fans was immediately lost to the outside air so it was not effective in reducing the auxiliary heating energy requirement. So the following adjustment was made to account for electricity used by the lights, ventilation fans and other heat producing equipment:

$$\delta_{IG} = (M_{IG} - FE)_{concrete} - (M_{IG} - FE)_{timber} \qquad \text{(kWh)}$$

where M_{IG} = the electricity used by all the internal heat generating equipment (kWh)
FE = the electricity used by the cooling ventilation fans (kWh)

The electricity used by the ventilation fans was not monitored so it was estimated from hourly records of venting time and measurements of fan power.

APPENDIX F: UNCERTAINTIES

Sources of uncertainties

The most significant uncertainties are shown in Table F1. Uncertainty in the temperature measurements includes uncertainties related to the temperature sensors and uncertainties related to the temperature distributions in the two buildings. These may have differed resulting in the two rooms having different mean temperatures while having the same measured temperature.

Table F1. Principal uncertainties affecting the differences in the thermal performance of the test buildings

Factor	Estimated Uncertainty	Affects Comfort?	Comparison of: Energy Use?	Comments
Differences in:				
Hourly mean T_{res} and T_{ai}	± 0.2°C	✓	✓	Temperature sensors were calibrated side-by-side with a precision (0.01°C resolution) thermometer
Watt-hour meter readings	± 2.5%	×	✓	Class 2 meters (better than ± 2% accuracy).
Wall insulation thickness	± 1mm	✓	✓	Variation in thickness of EPS sheet.
Ceiling insulation	± 5mm	✓	✓	Variation in thickness of loose fill insulation in ceiling.
Air exchange rates	± 0.05 ach	✓	✓	

Uncertainty in the differences of the auxiliary heating energy use

The total uncertainty in the difference in the auxiliary heating energy use, σ_E, was estimated from:

$$\sigma_E = (\sigma^2_{M,E} + \sigma^2_{IG,E} + \sigma^2_{T,E} + \sigma^2_{WI,E} + \sigma^2_{CI,E} + \sigma^2_{AER,E})^{0.5} \qquad \text{(kWh)}$$

where $\sigma_{M,E}$ = uncertainty arising from the Watt-hour meters monitoring the electricity consumption of the heaters

$$\cong 0.025\frac{(ME_C + ME_T)}{2} \qquad \text{(kWh)}$$

where ME_C and ME_T are the meter readings in the concrete and timber buildings respectively.

$\sigma_{IG,E}$ = uncertainty arising from the Watt-hour meters monitoring the electricity consumption of the equipment producing internal heat (at a rate of approximately 2.5 kWh per day)

$\cong$ 0.025 x 2.5 x d

$\cong$ 0.06d (kWh)

where d (days) is the period of the analysis.

$\sigma_{T,E}$ = uncertainty arising from the temperature sensors and the air temperature distributions. This was estimated by using tsbi3 to simulate the effect of a ±0.2°C variation of the heating temperature on the energy use during September 1999.

$$\cong \quad 0.045\frac{(ME_C + ME_T)}{2} \qquad \text{(kWh)}$$

$\sigma_{WI,E}$ = uncertainty arising from the wall insulation. This was found by simulation in the same way as described above.

$$\cong \quad 0.008\frac{(ME_C + ME_T)}{2} \qquad \text{(kWh)}$$

$\sigma_{CI,E}$ = uncertainty arising from the ceiling insulation. This was found by simulation in the same way as described above.

$$\cong \quad 0.004\frac{(ME_C + ME_T)}{2} \qquad \text{(kWh)}$$

$\sigma_{AER,E}$ =uncertainty arising from the air exchange rates. This was found by simulation in the same way as described above.

$$\cong \quad 0.029\frac{(ME_C + ME_T)}{2} \qquad \text{(kWh)}$$

Combining terms gives:

$$\sigma_E = ((0.03(ME_C + ME_T))^2 + (0.06d)^2)^{0.5} \qquad \text{(kWh)}$$

This equation predicts that the total uncertainty was approximately ±6% of the mean of the heater electricity use. The results from the heat loss factor test showed that the combined effects of the differences in construction, temperature sensors and Watt-hour meters resulted in a 3% difference in the heat loss factor. This is significantly less than the uncertainty in the difference in the buildings' auxiliary heating energy use, suggesting that this value is conservative.

Uncertainty in the differences of temperature

The total uncertainty in the temperature differences, σ_T, was estimated from:

$$\sigma_T = (\sigma_{T,T}^2 + \sigma_{IG,T}^2 + \sigma_{I,T}^2 + \sigma_{AER,T}^2)^{0.5} \qquad (^oC)$$

where $\sigma_{T,T}$ = uncertainty arising from the temperature sensors and air temperature distributions.

$= \quad 0.2 \qquad (^oC)$

$\sigma_{IG,T}$ = uncertainty arising from the buildings' internal heat gains which were taken as ± 5 W.

$\cong \quad 0.2 \qquad (^oC)$

$\sigma_{I,T}$ = uncertainty arising from the wall and ceiling insulation. This was estimated using a steady state heat loss analysis.

$\cong \quad 0.1 \qquad (^oC)$

$\sigma_{AER,T}$ = uncertainty arising from differences in the air exchange rates This was estimated using a steady state analysis with a temperature difference between the ambient and building air equal to 10^{o}C.

$\cong \quad 0.05 \qquad (^oC)$

The total uncertainty was estimated to equal ±0.3^{o}C.

APPENDIX G: HEAT LOSS FACTOR TEST

This test was conducted to assess whether the buildings differed significantly, apart from wall thermal mass, and to determine an experimental value for the heat loss factor. Differences in the following factors could have affected the results of the four trials:

- infiltration rate
- heat loss factor
- temperature sensor accuracy
- air temperature distributions
- external climates
- watt-hour meter accuracy.

Method

During this test each building was maintained, as close as possible, at a steady state condition. The DRT was kept relatively constant (25°C) and the shutter was closed during the daytime to block solar radiation that was transmitted through the window. From 1-15 November 1999 the shutter was closed over the window all the time. From 15-28 November it was closed from 6am-6pm and open for the rest of the day.

The normalised heat loss factor (HL^*) was used to test if the buildings differed. If the buildings were identical, apart from wall thermal mass, then:

$$HL^*_{concrete} = HL^*_{timber} \qquad (W.^oC^{-1})$$

HL^* can be derived from a simple building energy balance and was found from:

$$HL^* = \frac{1000}{h}\left(\frac{G + Q_H - Q_V}{\overline{T}_{res} - \overline{T}_{ao}}\right) \qquad (W.^oC^{-1})$$

where $\overline{T}_{res}$ and $\overline{T}_{ao}$ (°C) are the mean dry resultant and ambient air temperatures respectively, h (hours) is the length of the test period, G (kWh) is the electricity used by the heat generating equipment in the building, Q_H (kWh) is the electricity used by the heater and Q_V (kWh) is the energy lost due to ventilation. This test assumes the building solar gains were equal and that the change in energy stored in the building over the period was negligible compared with the other energy fluxes. This test accounts for the combined effect of the factors in the above list.

The steady state heat loss factor (HL) for night periods without ventilation was found from:

$$HL = \frac{1000}{h}\left(\frac{G + Q_H}{\overline{T}_{res} - \overline{T}_{ao}}\right) - \rho_{ao} C_{p,ao} \overline{V}_I \qquad (W.^oC^{-1})$$

where ρ_{ao} (kg.m^{-3}) is the ambient air density, $C_{p,ao}$ (kJ.kg^{-1}.°C^{-1}) is the specific heat and $\overline{V}_I$ (ℓ.s^{-1}) is the average infiltration rate. HL was determined only for the timber building, and only for periods when the ambient air temperature was relatively constant, in order to minimise the effect of energy storage fluxes on the results.

Results

The normalized heat loss factor for the concrete building was approximately 3% greater than for the timber building (Table G1). This indicates that the energy saving due to heavy walls may have been slightly understated in this report, and the comfort benefits slightly overstated.

The average heat loss factor for the timber building was 48.1 and 56.6 W.^{o}C^{-1} with and without shutters respectively (Table G2). These values compare well with the corresponding calculated values of 49.0 and 57.5 W.^{o}C^{-1} respectively. From these results the R-value of the shutter was found to approximately equal 0.15 m^2.^{o}C.W^{-1}.

Table G1. Normalised heat loss factor for two periods during the heat loss experiment

Period	Q_H Heating Energy (kWh)	G Internal Gains (kWh)	Q_V Vented Energy (kWh)	Dry Resultant Temp. (^{o}C)	Ambient Air Temp. (^{o}C)	Normalised Heat Loss Factor (W.^{o}C^{-1})
6-15 Nov. ′99 – concrete building	76.36	32.77	0	25.36	15.10	49.24
– timber building	78.14	31.68	2.46	25.51	15.10	47.75
15-27 Nov. ′99 – concrete building	145.05	26.51	0	25.23	13.49	50.74
– timber building	142.36	25.72	0	25.28	13.49	49.50

Note: The mean ambient air temperatures (^{o}C) for 5-6am, 6-7am, 7-8am and 8-9am were as follows:
6 Nov: 13.5, 13.6, 14.5 and 16.7
15 Nov: 12.0, 13.7, 16.0 and 16.9
27 Nov: 14.1, 15.2, 16.0 and 17.0

Table G2. Heat loss factor of the timber test building

	Period	Ambient Air Temp. at Start of Period (^{o}C)	Ambient Air Temp. at End of Period (^{o}C)	Mean Ambient Air Temp. (^{o}C)	Mean Wind Speed at 10m (m.s^{-1})	HL Heat Loss Factor (W.^{o}C^{-1})
SHUTTERS	10pm 4/11–5am 5/11 (7 hours)	12.34	12.43	12.40	0.43	47.3
	9pm 5/11–5am 6/11 (8 hours)	13.79	13.58	13.66	4.15	49.1
	0am 7/11–5am 7/11 (5 hours)	15.75	15.83	15.57	4.85	55.4
	1am 9/11–6am 9/11 (5hours)	13.19	13.20	12.99	3.52	48.4
	1am 12/11–5am 12/11 (4 hours)	9.82	9.57	9.71	10.26	47.3
	2am 13/11–6am 13/11 (4 hours)	4.76	4.41	4.46	3.63	43.4
	0am 14/11–3am 14/11 (3 hours)	5.93	6.49	6.16	2.29	43.5
	2am 15/11–5am 15/11 (3 hours)	11.36	11.51	11.28	3.41	46.9
	Average (39 hours)	10.87	10.88	11.48	3.86	48.1
NO SHUTTERS	11pm 15/11–4am 16/11 (5 hours)	17.50	17.60	17.37	8.35	78.5
	10pm 16/11–3am 17/11 (5 hours)	17.72	17.47	17.58	9.14	67.2
	11pm 18/11–4am 19/11 (5 hours)	9.89	9.92	9.92	3.58	49.4
	10pm 19/11–4am 20/11 (6 hours)	9.31	9.28	9.32	0.22	47.3
	0am 21/11–5am 21/11 (5 hours)	7.32	7.23	7.13	5.53	50.4
	1am 23/11-5am 23/11 (4 hours)	7.05	7.23	7.16	5.12	54.7
	10pm 25/11–5am 26/11 (7 hours)	10.18	10.40	10.04	6.09	54.2
	11pm 26/11–5am 27/11 (6 hours)	12.81	12.79	12.78	4.72	57.9
	10pm 27/11–6am 28/11 (8 hours)	8.86	8.82	8.31	6.40	53.5
	Average (51 hours)	11.18	11.19	10.94	5.43	56.6

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