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Energy Efficiency 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 programs 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.

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ENERGY EFFICIENCY OF BUILDINGS WITH HEAVY WALLS

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KEYWORDS

Thermal mass; Energy conservation; Thermal comfort; Building simulation; Concrete walls; Residential buildings.

EXECUTIVE SUMMARY

This project follows an earlier study which found that wall thermal mass reduced annual heating energy use by approximately 7%, and reduced overheating by more than 70% (235 hours), based on measurements from the side-by-side test buildings at Lincoln University. It was hypothesised that the energy savings would have been much greater if the buildings had been maintained within the same comfort zones, and if the windows had been larger.

The main objective of the project was to use the test buildings to determine the potential energy savings from using high-mass concrete walls in New Zealand homes. The test buildings were modified in a number of ways. Larger north-facing windows were installed to achieve a better match between solar gain and thermal mass in the concrete test building. The internal window shutters were operated to mimic the action of internal solar shades which are used to try to eliminate overheating, and so maintain the two buildings within the same comfort zone. In addition to existing ventilation fans, fixed overhangs were placed above the windows to help reduce summer overheating.

Over the trial year (1 July 2001 – 30 June 2002) the concrete test building used 7.5 kWh.m^{-2}(floor), or 15.5%, less heating energy than the timber test building. These savings are probably near the upper end of what can be expected from wall thermal mass in Christchurch homes.

The concrete building did not overheat during the trial, and was on average approximately 1^{o}C warmer than the timber building during the night. Shutters and fans were unable to avoid overheating in the timber building. It reached a maximum of 30.9^{o}C at a time when the ambient air temperature was 30.0^{o}C and the temperature in the concrete building peaked at 25.8^{o}C. Air conditioning and/or the frequent use of shades can be avoided by using wall thermal mass. This will be especially beneficial in homes with large areas of glazing.

A secondary objective of the project was to evaluate the capability of selected building energy programs to accurately predict the benefits of wall thermal mass, using the experimental data collected from the test buildings. It appears that new programmes such as BSim2000, with advanced capability to model solar energy flows, can predict mass-related energy savings with acceptable accuracy, at least in buildings with simple geometry. The capability of programmes to predict overheating was less robust.

A question that has not been answered is: What wall R-value should the timber test building have to obtain the same annual heating energy as the concrete test building? Further, if the buildings were designed to have the same annual heating energy use, what comfort benefits would be derived from the high-mass concrete walls? A test building trial to address this issue is recommended.

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1 INTRODUCTION

The energy efficiency and thermal comfort of a house can be significantly improved by adding thermal mass, in the form of heavy walls, to the building envelope. In an earlier study, these benefits were measured for one building design, at one location, using the side-by-side test buildings at Lincoln University (Bellamy and Mackenzie, 2001). These buildings were near-identical, apart from the amount of thermal mass in the walls (Figure 2, page 3). So differences in the buildings' thermal performance were able to be attributed to thermal mass. It was found that thermal mass reduced the annual heating energy use by about 7% (4.3 $kWh.m^{-2}$(floor)), and reduced overheating by more than 70% (235 hours) over the same period. Similar or slightly greater energy savings, depending on climate and building design, have been reported from thermal mass research overseas (Kosny et al, 2001).

The benefits of thermal mass reported by Bellamy and Mackenzie (2001) were significant. However, it can be argued that the energy savings and comfort improvements were understated and overstated respectively, for the following reasons:

Energy savings were not based on buildings with equal comfort
Energy savings would have been greater if the daytime comfort of the test buildings had been equal. Consider, for example, the use of movable shades to reduce solar gains and limit overheating in the timber building. By lowering daytime temperatures this building would have cooled to the heating temperature earlier in the evening, thereby increasing heating energy use.

Shading was not used to reduce summer overheating
The reduction in overheating due to thermal mass would have been less significant if the windows of the test buildings had been shaded by fixed overhangs. The improved comfort provided by thermal mass – the results showed that thermal mass provided up to 3°C of cooling, in addition to cooling from ventilation – could have also been achieved, in part at least, by window shades and/or increased ventilation.

Solar gain was not well-matched to the level of thermal mass
The test buildings were originally designed to represent the thermal performance of homes with code compliance levels of insulation and medium solar gain. The results showed that the solar gain in the concrete test building was not well-matched to its thermal mass. From April-October 1999 this building overheated for only nine hours, indicating that the solar gain during this period could have been greater, which would have reduced its heating energy use.

1.1 Objectives and research approach

The main objective of this research was to determine, and demonstrate more clearly, the potential energy savings from using high mass walls in place of lightweight timber-framed walls in New Zealand homes. A secondary objective was to evaluate the capability of selected building energy programs to accurately predict the benefits of wall thermal mass, using the experimental data collected from the buildings.

The research was based on the test buildings at Lincoln University. The buildings were modified to address the equal comfort, shading and matching issues discussed above, and their energy performance was monitored over one year.

The buildings were modified by adding fixed overhangs above the north windows to reduce summer overheating. Larger windows were used to achieve a better match, in the concrete building, between solar gain during the heating season and thermal mass. In addition, the internal shutters were operated to mimic the action of internal solar shades, to try to eliminate overheating, and so maintain the two buildings within the same comfort zone.

2 TEST BUILDINGS

The buildings' floor, roof and wall constructions, as described by Bellamy and Mackenzie (2001), were not altered. The windows, doors and shutters were modified as follows:

- The 3.36 m^2 single-glazed window on the north wall was replaced by a 4.88 m^2 double-glazed, PVC-framed window[1].
- The double-glazed door on the south wall was insulated with a 40 mm thick polystyrene panel, plus an air gap between the internal surface of the door and the panel.
- A fixed overhang was placed over the north window. The overhang was located 325 mm above the glass and projected 550 mm horizontally from the exterior face of the glass.
- Thermostatic control was added to the internal roller shutter on the north window. In addition to closing and opening at set times to mimic the action of curtains, the shutter was used to limit overheating – the shutter closed at 28°C and opened when the temperature dropped to 24°C. The shade provided by the shutter supplemented the cooling provided by the fans, which ventilated the building at approximately five air changes per hour when the temperature exceeded 27°C.

The modifications changed the heat loss and solar gain characteristics of the buildings. The heat loss factor was reduced by about 19% (see Appendix A, page 11). Solar gain from the north window was increased by about 30% during mid-winter – the glazed area was increased from 2.7 to 4.1 m^2 but this was partly offset by the lower solar transmittance of double-glazing compared with single-glazing.

The modified buildings were designed to represent a carpeted house with insulation in excess of code requirements and a high level of solar gain – operated to maintain, as far as possible, continuously comfortable conditions. The key parameters of the modified test buildings are shown in Table 1 below.

The new windows and the door insulation panels were installed in the test buildings during May 2001. The other modifications were completed by the end of June 2001.

Table 1. Key characteristics of the test buildings

Parameter	Test building		Comments
	Concrete	Timber	
Floor area (m^2)	20.25	20.23	Measured to the perimeter insulation. Visible floor area about 18.4 m^2.
North glazing: floor area ratio	0.20		Double-glazed PVC window orientated -8°.
Background air exchange rate ($l.s^{-1}$)	5.5		Varied slightly with temperature and wind. Equal to about 0.5 (air changes).h^{-1}.
Internal heat gain (W): 6pm-10pm 10pm-6pm	155 95		From internal equipment and lights. One light operated continuously and one from 6pm-10pm.
Heat loss factor ($W.m^{-2}$(floor). $^oC^{-1}$)	2.32	2.31	Includes carpet but not shutters.
Heating temperature (^oC): 7am-10pm 10pm-7am	20 16		Heaters, fans and shutters were controlled by the temperature at the centre of a 100 mm blackened globe near the centre of the room and 1.3 m above the floor (dry resultant temperature). The heating period was April to October inclusive. Daylight saving time (clocks forward one hour) applied from 7/10/01 to 17/3/02. The shutter colour was white on both sides.
Heater capacity (kW)	2.2		
Ventilation temperature (^oC)	27		
Ventilation capacity ((air changes).h^{-1})	4.6	4.7	
Shutter close temperature (^oC) Shutter open temperature (^oC)	28 24		
Shutter time: 1/7-7/10/01 & 1/4-30/6/02 7/10/01-1/11/01 1/11/01-1/4/02	6pm-7am 7pm-7am 9pm-7am		

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[1] NK Windows Ltd donated the PVC window frames.

Figure 1. North wall window

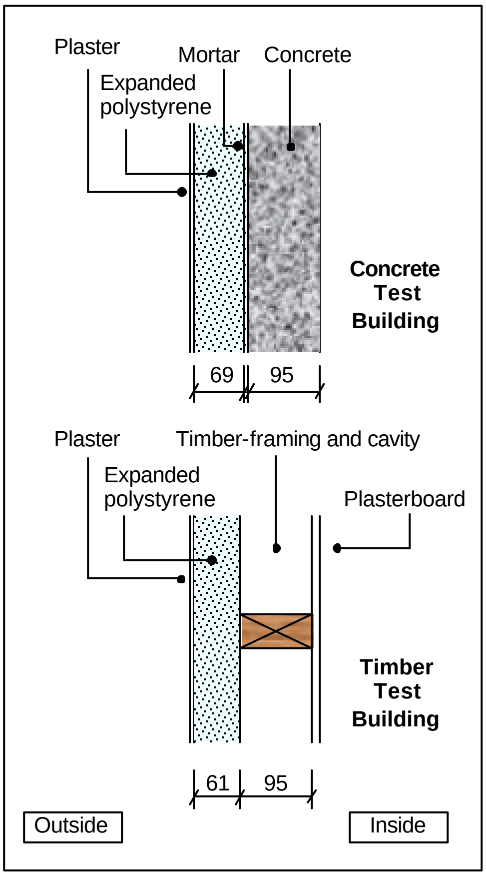


Figure 2. Wall cross-sections

Figure 3. Side-by-side test buildings (before window overhangs were erected)

3 EXPERIMENTAL EVALUATION OF ENERGY SAVINGS FROM WALL THERMAL MASS

3.1 Method

The trial was carried out from 1 July 2001 to 30 June 2002. The buildings were not modified during the trial, apart from changes to the closing time of the shutters and adjustments to clocks to account for daylight saving. The buildings were heated and ventilated for one month (June 2001) before the start of the trial. The length of this preheating period was considered adequate as the buildings had been heated and ventilated for most of the time from their construction, more than four years earlier.

The auxiliary heating energy used in the buildings during the heating period was found from:

$E_T = ME_T + \delta_{AER}$ (kWh) for the timber test building

$E_C = ME_C + \delta_{IG} - \delta_{TRES}$ (kWh) for the concrete test building

where ME_C = electrical energy used by the heater in the concrete building
ME_T = electrical energy used by the heater in the timber building
δ_{AER} = adjustment for differences in the background 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

Electrical energy use was found from digital Watt-hour meters, which were monitored by data loggers and read manually at the start of each month. The procedure for adjusting the Watt-hour meter readings to account for differences in the buildings' internal gains and background air exchange rates, and to account for temperature probe calibration errors, is outlined in Appendix B (page 14).

3.2 Results

The auxiliary heating energy used in the concrete building (Table 2, page 5) was 7.5 kWh.m^{-2}(floor), or 15.5%, less than the heating energy used in the timber building – virtually double the energy savings found from earlier research with the original test buildings (Bellamy and Mackenzie, 2001). Key climate statistics for the heating period of the trial were similar to long-term means (Table 2), so these energy savings can be treated as being typical of the long-term performance of the buildings.

The peak hourly heating loads were 1.85 kW and 1.65 kW in the concrete and timber building respectively.

From Table 2 it can be seen that the concrete building did not overheat during the trial, but the cooling provided by the shutter and the fan was insufficient to avoid overheating in the timber building. For the whole trial it overheated for 46 hours, but for only three hours during the heating period. So the energy savings were based on the two buildings having near-equal comfort zones.

The hourly mean dry resultant temperature in the timber building exceeded 30°C for 10 hours over the year and reached a maximum of 30.9°C on 11 February, at a time when the ambient air temperature was 30.0°C. At the same time the hourly mean temperature in the concrete building peaked at 25.8°C – more than 5°C cooler than the timber building and more than 4°C cooler than the ambient air. The maximum hourly mean dry resultant temperature in the concrete building was 27.8°C on 13 April, but this occurred when the internal shutter was open – the shutter close temperature had not been reached. The temperature would have been much lower if the shutter had been closed.

The internal shutter in the timber building was often closed to provide cooling, even during winter (Table 2). The shutter in the concrete building was used infrequently from April-September, and over the year it was closed for only 25% of the time that the shutter was closed in the timber building.

Table 2. Experimental results over the trial year 1 July 2001 – 30 June 2002

Month[1]	Mean ambient air temp [2] (°C)	Mean daily global solar radiation[3] (kWh.m^{-2})	Mean building air temp (°C)		Mean daily minimum – maximum building air temp (°C)		Overheating hours (dry resultant temp>28°C)		Window shading hours (shutter closed to provide cooling)		Ventilation hours (fan cooling)		Auxiliary heating energy use (kWh)		Energy saving due to wall thermal mass	
			Concrete	Timber	Concrete	Timber	Concrete	Timber	Concrete	Timber	Concrete	Timber	Concrete	Timber	(kWh)	(%)
<u>2001</u>																
July	4.6	1.64	19.4	19.3	16.2-22.7	16.1-23.0	0	0	0.0	12.3	8.2	37.8	225.7	258.8	33.1	13.0
Aug	8.1	2.17	19.7	19.5	16.8-23.0	16.0-23.6	0	0	2.5	53.1	24.6	25.3	150.8	175.4	24.6	14.0
Sept	10.5	3.58	20.2	19.9	17.6-23.4	16.0-24.2	0	0	1.0	56.6	16.2	40.6	69.8	93.5	23.7	25.3
Oct	12.7	3.95	20.4	20.2	18.5-22.7	16.5-24.1	0	7	14.3	58.6	6.5	26.4	51.5	59.0	7.5	12.7
Nov	13.7	5.14	19.9	19.8	18.3-22.0	16.5-23.9	0	0	0.0	12.8	0.0	17.0	-	-	-	-
Dec	16.0	5.20	21.9	21.6	20.3-23.7	18.3-25.2	0	8	11.8	72.1	3.7	42.1	-	-	-	-
<u>2002</u>																
Jan	16.3	4.80	22.0	21.8	20.5-23.7	18.8-25.0	0	11	37.4	91.1	6.1	47.4	-	-	-	-
Feb	15.2	4.56	21.7	21.1	19.9-23.8	17.8-24.8	0	7	17.1	44.5	5.8	38.0	-	-	-	-
Mar	15.4	4.28	22.6	21.7	20.6-25.3	17.5-26.3	0	10	79.2	189.1	35.3	70.2	-	-	-	-
Apr	11.9	2.29	20.4	20.0	18.6-23.0	16.6-23.7	0	0	7.8	73.1	32.0	17.6	43.7	64.1	20.4	31.8
May	9.6	1.67	20.0	19.7	17.4-23.0	16.1-23.8	0	3	8.6	49.2	15.6	25.8	109.6	133.2	23.6	17.7
June	7.5	1.23	19.7	19.4	16.8-22.7	16.1-22.9	0	0	0.0	17.7	7.7	32.1	181.6	201.4	19.8	9.8
Annual	11.8	3.37	20.66	20.33	18.5-23.3	16.9-24.2	0	46	179.7	730.2	161.7	420.3	832.7	985.4	152.7	15.5
Long-term mean[4]	*11.6*	*3.8*														

Note:

1. For the period from 9am on the first day of the month to 9am on the first day of the following month.
2. Mean ambient air temperature for the heating period (July-October 2001; April-June 2002) and the rest of the year (November 2001-March 2002) were 9.3 °C and 15.3°C respectively. The corresponding long-term values for Christchurch Airport were 8.6 °C and 15.7°C respectively.
3. Global solar radiation for the heating period (July-October 2001; April-June 2002) and the rest of the year (November 2001-March 2002) were 2.36 and 4.80 kWh.m^{-2}.day^{-1} respectively. The corresponding long-term values for Christchurch Airport were 2.56 and 5.55 kWh.m^{-2}.day^{-1} respectively.
4. For Christchurch Airport.

Looking at Table 2 the monthly mean air temperature in the concrete building was always greater than that in the timber building. Over the whole trial the mean night time (8pm-7am) air temperature in the concrete building was 19.6°C, which was 0.9°C warmer than in the timber building. Considering just the heating period, the concrete building was on average 1.0°C warmer than the timber building during the night.

The temperature smoothing effect of the high mass walls can also be seen from the daily minimum and maximum building air temperatures in Table 2. Over the length of the trial the diurnal variation in the air temperature averaged 4.8°C in the concrete building and 7.3°C in the timber building. The mean daily minimum was up to 3.1°C warmer in the concrete building than in the timber building (during March). The mean daily maximum was up to 1.9°C cooler in the concrete building than in the timber building (during November).

The minimum dry resultant temperatures were 15.6 °C and 12.8°C in the concrete and timber buildings respectively. This occurred on a cold November morning when the ambient air temperature was 2.3°C, and the buildings were not heated.

3.3 Discussion

The potential energy savings from wall thermal mass has been clearly demonstrated. The results dispel the notion that thermal mass has a negligible effect on the heating energy used in New Zealand homes.

The focus of this project has been the energy savings potential of wall thermal mass. But another important message is that heavy walls provide an effective solution to the overheating problem in lightweight homes. With high-mass buildings, designers have freedom to specify medium-large north-facing windows without sacrificing thermal comfort, or needing to resort to air conditioning and/or the frequent use of movable shades.

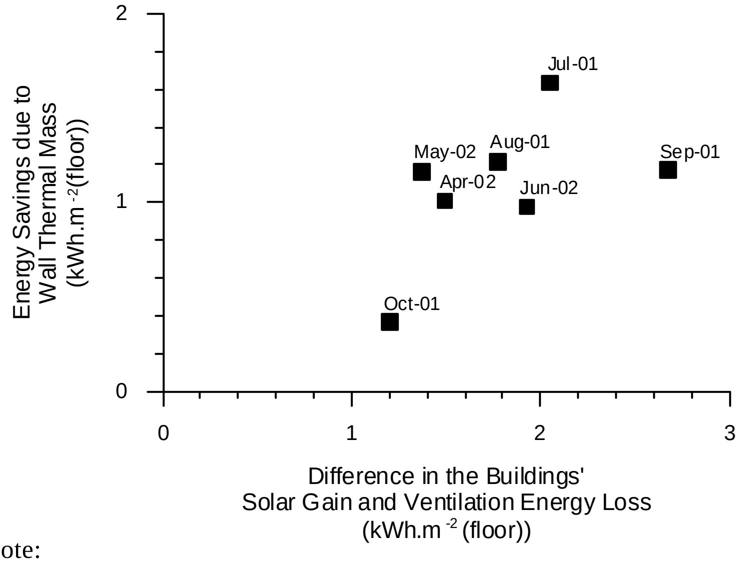
The energy savings and comfort improvements observed in this trial cannot be generalised to all house designs and locations. The benefits of thermal mass are related in a complex way to the climate, occupant behaviour, the building envelope and internal structure. Nevertheless, similar benefits can be expected in homes in similar climates, with building envelopes designed to exploit the thermal properties of heavy walls.

It can be shown that the energy savings were related to the amount of solar energy stored within the buildings, and the fraction of that energy subsequently utilised to offset the heating load. Figure 4 (page 7) shows that the energy savings were related to differences in the amount of solar energy stored in the buildings, which were found from differences in the buildings' solar gains (i.e. solar energy absorbed within the buildings) and ventilation energy losses. The data scatter in Figure 4 indicates that the fraction of the stored solar energy utilised to offset the heating load varied from month to month.

Maintaining near-equal daytime comfort conditions in the test buildings was a key part of this project. The rationale for this approach was that the heating energy used in a building depends on both heating and cooling temperatures, and the capability, through having adequate heating and cooling capacity, to maintain the building within the prescribed comfort zone. In this respect the reported energy savings were based on a fair comparison between high mass and lightweight walls.

The energy savings and comfort improvements observed in this project are probably near the upper end of the scale of what can be expected from wall thermal mass. The surface area and volume of concrete in the walls were relatively large for the given floor area. And the storage capacity of the thermal mass was largely exploited by using a large window that admitted large amounts of solar energy. Having said this, a concrete ceiling would be expected to provide additional comfort and energy saving benefits.

An obvious question arising from this research is how much additional insulation would need to be added to the walls of the timber building so that its heating energy use equalled that of the concrete building? This issue was outside the scope of this work and is being addressed in another project (Bellamy, 2003).



Note:

1. The difference in the buildings' solar gains and ventilation energy losses was found from $(SG - VEL)_{concrete} - (SG - VEL)_{timber}$ where SG and VEL are solar gain and ventilation energy loss respectively.
2. Solar gain was found from light sensors placed near the centre of the windows. Measurements were not adjusted to account for partial shading of the window.

Figure 4. Energy savings due to wall thermal mass versus the difference in the buildings' solar gains and ventilation energy losses.

4 BUILDING ENERGY PROGRAM TESTING

4.1 Method

Two building energy programs, Suncode[2] and BSim2000[3], were evaluated by simulating the thermal performance of the test buildings and comparing predicted energy savings and comfort improvements with the results from the experimental trial. The buildings were simulated from 1 June 2001 – 30 June 2002 using weather data from the test building site as input. The first month of simulation, June 2001, was not included in the evaluation. This month was used as a settling down period, so that the initial conditions used by the programs ceased to have a significant effect on the output.

The walls of the test buildings were modelled using the heat flow paths described in Appendix A. 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 A.

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[2] Version 6.0, supplied by Ecotope Inc., USA. Suncode has been superseded by SUNREL and is available from the National Renewable Energy Laboratory, Colorado, USA.

[3] Version 2,2,4,12, supplied by By og Byg (Danish Building and Urban Research). BSim2000 has been superseded by BSim2002 and is available from By og Byg. tsbi3, the predecessor of BSim2000, was tested by Bellamy and Mackenzie (2001).

The properties of the building materials were not measured. The values in Table 3, below, were best estimates based on values in literature and were not manipulated to fit the experimental data[4].

BSim2000 was unable to model the 24-28°C dead band in the internal shutter controller. The shutter was simulated as an internal solar shade that was fully closed or fully open during any given hour, in accordance with the need to keep the zone temperature from exceeding 28°C.

Suncode was unable to model temperature-controlled internal shutters, so the cooling provided by the shutters was modelled using the ‘air cooler’ option in Suncode. The ‘air cooler’ was operated to limit zone temperature to 28°C, so Suncode was unable to predict overheating in the test buildings.

Table 3. Key simulation parameters of the test buildings

Parameter	Value	Comments
Site:		
Latitude (°)	-43.7	Lincoln University, Canterbury, New Zealand
Longitude (° East)	172.5	
Ground reflectance (%)	20	
Deep ground temperature (°C)	12.0	
Window orientation (°)	-8	Window faces 8° west of true north
Infiltration rate ((air changes).h^{-1})	0.5	Treated as constant
Ventilation rate ((air changes).h^{-1})	4.7	Cooling temperature 27°C
Heater capacity (kW)	2.2	100% convection heat output Heating temperature 16/20°C from 10pm-7am/7am-10pm
Internal gain (W):		
6pm-10pm	155	100% convection heat output assumed
10pm-6pm	95	100% convection heat output assumed
R-value (m^2.°C.W^{-1}):		Mean for whole window (opening in wall insulation)
Window	0.36	
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	
Window solar transmittance (%)	74	For double-glazing for an angle of incidence of 0°
Solar absorptance (%):		
External surface of walls	30	
External surface of roof	90	Solar energy fractions lost from the building and converted directly to heat were 10% and 2% respectively
Inside building	92	
Thermal conductivity (W.m^{-1}.°C^{-1}):		
Expanded polystyrene	0.035	
Extruded polystyrene	0.028	
Macerated paper	0.045	
Plasterboard	0.17	Density 800 kg.m^{-3} and thermal capacity 1006 J.kg^{-1}.°C^{-1}
Concrete	1.4	Density 2200 kg.m^{-3} and thermal capacity 880 J.kg^{-1}.°C^{-1}
Timber	0.13	Density 500 kg.m^{-3} and thermal capacity 1400 J.kg^{-1}.°C^{-1}
Graded round stones	0.5	Density 1500 kg.m^{-3} and thermal capacity 900 J.kg^{-1}.°C^{-1}
Sand	1.8	Density 1800 kg.m^{-3} and thermal capacity 800 J.kg^{-1}.°C^{-1}
Underlying soil	1.5	Density 1900 kg.m^{-3} and thermal capacity 800 J.kg^{-1}.°C^{-1}

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[4] The one exception was the layers specified for the floor perimeter heat-flow path. The thicknesses of the sand and polystyrene layers were adjusted so that the overall R-value for the floor was essentially equal to the value assumed in Appendix A.

Table 4. Simulated thermal performance of the test buildings

Month[1]	Auxiliary heating energy use in the concrete building (kWh)			Auxiliary heating energy use in the timber building (kWh)			Absolute energy savings due to wall thermal mass[4] (kWh)			Overheating time in the concrete building (hours)			Overheating Time in the Timber Building (hours)		
	Exp't	BSim[2]	Suncode[3]	Exp't	BSim[2]	Suncode[3]	Exp't	BSim[2]	Suncode[3]	Exp't	BSim[2]	Suncode[3]	Exp't	BSim[2]	Suncode[3]
2001															
July	225.7	224.3	178.1	258.8	265.3	233.1	33.1	41.0	55.0	0	0	x	0	5	x
Aug	150.8	146.4	124.2	175.4	171.0	158.6	24.6	24.6	34.4	0	0	x	0	7	x
Sept	69.8	76.3	54.7	93.5	96.7	81.9	23.7	20.4	27.2	0	0	x	0	0	x
2002															
Jan	-	-	-	-	-	-	-	-	-	0	6	x	11	16	x
Feb	-	-	-	-	-	-	-	-	-	0	0	x	7	9	x
Mar	-	-	-	-	-	-	-	-	-	0	6	x	10	17	x
Apr	43.7	51.4	38.2	64.1	74.5	66.4	20.4	23.1	28.2	0	0	x	0	12	x
May	109.6	115.6	98.3	133.2	136.5	124.7	23.6	20.9	26.4	0	0	x	3	14	x
June	181.6	185.1	149.2	201.4	209.5	181.9	19.8	24.4	32.7	0	0	x	0	10	x
Total	781.2	799.1	642.7	926.4	953.5	836.8	145.2	154.4	203.9	0	12	x	31	90	x

Note:

1. October 2001 was excluded because of complications simulating the change to daylight saving time during the month.
2. The solar ray tracing option within BSim2000 was used. This feature enabled the solar gain, and its time-varying distribution on internal building surfaces, to be determined on an hourly basis, taking into account building geometry, rather than using a fixed distribution as used by Suncode. The shade cast by the fixed window overhangs was determined using this feature.
3. The cooling provided by the internal shutters was modelled using the ‘air cooler option’, so Suncode was unable to predict overheating.
4. Percentage savings in total heating energy use due to wall thermal mass were 15.7%, 16.2% and 23.2%, for the experiment, BSim2000 and Suncode respectively.

4.2 Results

Table 4 (page 9) shows that BSim2000 predicted the total heating energy use in both buildings with less than 5% error. The errors in monthly predictions were slightly larger. BSim2000 predicted the absolute and percentage energy savings with errors of 6.3% and 3.2% respectively.

Suncode consistently under-predicted the heating energy use in both buildings and over-predicted the absolute energy savings. The error in the total absolute energy savings was about 40%.

Only BSim2000 was tested for accuracy in predicting overheating because Suncode was unable to model the temperature-controlled internal shutters used in the test buildings. Table 4 shows that BSim2000 consistently over-predicted overheating hours.

4.3 Discussion

The large difference in the models' predicted energy savings indicates that models are not all the same in terms of their capability to simulate thermal mass.

Some of the difference in the predicted energy savings was due to the different way the programs modelled the cooling provided by the internal shutters. And the accuracy of a simulation was subject to human error, including selecting appropriate values for material properties and other program parameters. Much effort was made to minimise the effect of user errors, so the results appear to indicate that the accuracy of BSim2000 is slightly superior to Suncode, at least for simulating the performance of wall thermal mass in simple buildings. BSim2000's advanced capability for modelling solar gain (see note 2, Table 4) may have contributed to its superior accuracy.

5 CONCLUSIONS

Insulated heavy walls have the potential to provide significant energy savings and comfort improvements in New Zealand homes. Both provide economic and lifestyle benefits to homeowners. In the case of energy savings in Christchurch homes, a reduction in heating costs of 15% or more is probably near the upper end of the scale. In the case of comfort and overheating, air conditioning and/or the frequent use of shades can be largely avoided by using wall thermal mass. This will be especially beneficial in homes with large areas of glazing.

The benefits of thermal mass increase with increasing solar gain (i.e. larger north-facing windows). The capability of a building energy programme to accurately predict the benefits of thermal mass depend on its capability to model solar gain. It appears that new programmes such as BSim2000, with advanced capability to model solar energy flows, can predict mass-related energy savings with acceptable accuracy. The capability of programs to predict overheating was less robust.

6 REFERENCES

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APPENDIX A: HEAT LOSS FACTOR CALCULATIONS

The heat loss factor accounts for conduction heat flows through a building element (HL) and is 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 $m^2.^{o}C.W^{-1}$, including the surface resistance.

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 were 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 were taken as 0.06, 1.07, 0.32, 0.11 and 0.03 $m^2.^{o}C.W^{-1}$ respectively, so:

$$\begin{aligned} R_R &= \left[\frac{0.755}{1.59 + \frac{0.13}{0.045}} + \frac{0.035}{1.59 + \frac{0.035}{0.045} + \frac{0.095}{0.13}} + \frac{0.121}{1.59 + \frac{0.035}{0.13} + \frac{0.095}{0.045}} + \frac{0.005}{1.57 + \frac{0.13}{0.13}} + \frac{0.065}{0.46 + \frac{0.080}{0.13} + \frac{0.095}{0.045}} + \frac{0.019}{0.46 + \frac{0.175}{0.13}} \right]^{-1} \\ &= 4.25 \end{aligned}$$

For the timber test building:

$$\begin{aligned} HL_R &= 20.23/4.25 \\ &= 4.76\ \text{W.}^{\circ}\text{C}^{-1} \end{aligned}$$

For the concrete test building:

$$\begin{aligned} HL_R &= 20.25/4.25 \\ &= 4.76\ \text{W.}^{\circ}\text{C}^{-1} \end{aligned}$$

Window

The window glazing and PVC frame, and part of the surrounding wall, were within the area defined for the window (opening in the insulation of the north wall). The overall thermal resistance, not including the shutter, was taken as 0.36 $m^2.^{o}C.W^{-1}$.

For the timber and concrete test buildings:

$$\begin{aligned} HL_W &= 4.88/0.36 \\ &= 13.56\ \text{W.}^{\circ}\text{C}^{-1} \end{aligned}$$

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). The overall thermal resistance of the door, air gap and insulation sheet were taken as 0.33, 0.15 and 1.14 $m^2.^{o}C.W^{-1}$ respectively.

For the timber and concrete test buildings:

$$\begin{aligned} HL_D &= 2.03/(0.33+0.15+1.14) \\ &= 1.25\ \text{W.}^{\circ}\text{C}^{-1} \end{aligned}$$

Opaque wall

The thermal resistance of the opaque wall was found from:

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

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	(95.6%)
Concrete panel ? 250mm Insulfluf ? Plaster	(1.0%)
Plasterboard ? 95mm framing timber ? 69mm EPS ? Plaster	(1.0%)
Plasterboard ? 95mm framing timber ? 34mm EPS ? Plaster	(0.2%)
Plasterboard ? Cavity ? 69mm EPS ? Plaster	(2.2%)

The thermal conductivity of concrete was taken as 1.4 $W.m^{-1}.^{o}C^{-1}$ 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:

$$R_O = \left[\frac{0.956}{0.20+\frac{0.095}{1.4}+\frac{0.069}{0.035}} + \frac{0.01}{0.19+\frac{0.095}{1.4}+\frac{0.25}{0.045}} + \frac{0.01}{0.25+\frac{0.095}{0.13}+\frac{0.069}{0.035}} + \frac{0.002}{0.25+\frac{0.095}{0.13}+\frac{0.034}{0.035}} + \frac{0.022}{0.43+\frac{0.069}{0.035}} \right]^{-1}$$

$$= 2.26$$

For the timber test building:

$$\begin{aligned} HL_O &= (2.375x(5.299+3.812+5.307+3.816)-4.88-2.03)/2.28 \\ &= 36.40/2.28 \\ &= 15.96 \ W.^{o}C^{-1} \end{aligned}$$

For the concrete test building:

$$\begin{aligned} HL_O &= (2.375x(5.315+3.812+5.310+3.812)-4.88-2.03)/2.26 \\ &= 36.43/2.26 \\ &= 16.12 \ W.^{o}C^{-1} \end{aligned}$$

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:

$$\begin{aligned} HL &= 11.24+4.76+13.56+1.25+15.96 \\ &= 46.8 \ W.^{o}C^{-1} \\ &= 2.31 \ W.m^{2}(floor).^{o}C^{-1} \end{aligned}$$

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

$$\begin{aligned} HL &= 11.25+4.76+13.56+1.25+16.12 \\ &= 46.9 \ W.^{o}C^{-1} \\ &= 2.32 \ W.m^{2}(floor).^{o}C^{-1} \end{aligned}$$

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

Floor $\cong$ 24%
Roof $\cong$ 10%
Window $\cong$ 29%
Door $\cong$ 2 %
Opaque wall $\cong$ 35 %

Note that the heat loss factor for the original test buildings was 2.84 $W.m^{-2}(floor).^{o}C^{-1}$.

APPENDIX B: HEATING ENERGY USE ADJUSTMENT FACTORS

Air exchange rate adjustment factor (d_{AER})

The buildings were continuously pressurised to produce a relatively constant background air exchange rate of approximately 5.5 l/s. These airflows in the two buildings were equalised during a still day before the start of the trial. The leakage characteristics of the buildings were not identical, so the airflows in the buildings were not always equal. The following adjustment accounted for differences in the measured airflow rates through the orifice plates in the inlet ducts of the pressurisation fans:

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

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

The temperature sensors were calibrated, using a two-point calibration, at the start of the trial. A one-point calibration check at the end of the trial showed that the DRT sensor in the concrete building was reading approximately 0.3°C low, i.e. showing a value of 20°C when the 'correct' value was 20.3°C. The DRT sensor in the timber building was found to be reading correctly at the end of the trial.

The drift in the concrete building's DRT probe would have increased the auxiliary heating energy used in this building, so the following adjustment was made:

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

where M_{timber} = mass flow rate through the orifice plate in the timber building ($kg.s^{-1}$)
HL = heat loss factor of the concrete test building (approximately 0.042 $kW.^{o}C^{-1}$ with shutter closed over north window)
ΔT = the accumulated error in the DRT reading (^{o}C)

This adjustment was applied each hour when heating occurred in the concrete building.

Internal gain adjustment (d_{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:

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

where M_{IG} = the electricity used by all the internal heat-generating equipment (kWh)
FE = the electricity used by the cooling ventilation fans and internal heat-generating equipment while the fans were operating (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.