RESEARCH

POWER CONSUMPTION COMPARISON OF FIVE BUILDING ENVELOPES IN THE NORTHERN PRAIRIE CLIMATE OF MANITOBA

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ABSTRACT

The energy efficiency of a building depends on building envelope performance. The results presented in this paper are the first of a long-term building envelope research project at the Alternative Village at the University of Manitoba in Winnipeg, Manitoba, Canada. Five test buildings were constructed using the following systems: two wood frames with fiberglass batt insulation and dense pack cellulose, one polyurethane structural insulated panels (PUR SIP), and two with the Stay in place PVC concrete form building system using 102mm and 204mm of concrete externally insulated with 102mm of expanded polystyrene foam. All of the buildings had a common foundation and roof system with a footprint of 23.8 m^2. Blower door tests were conducted to determine air tightness. Each structure was heated with an electrical resistance heater and maintained at a constant internal temperature. The thermal gradient through the wall and power consumption were monitored. The study period discussed in this report represents the main heating season from October 2011 to April 2012 consisting of 209 days. Based on the power consumption, the PUR SIP consumed the least at 2498 kWh, while the 204 mm Stay in place PVC concrete form building used the most at 2898 kWh for the same time period. The thermal gradient through the cross section of the wood frame structures was compared through the cavity insulation and at the stud. It was found that the cellulose building provided better thermal resistance along the stud when compared to the fiberglass batt insulation.

KEYWORDS

fiberglass insulation, cellulose insulation, polyurethane structural insulated panels, power consumption, mass walls

1.0 INTRODUCTION

The city of Winnipeg in south central Manitoba, Canada experiences a wide annual range of climatic conditions. The design temperature has a range from a low -35°C in the winter to +30°C in the summer [1]. In reality this range is greater. Environment Canada reports recorded

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extremes ranging from -45°C to a high of +41°C without the effect of wind [2]. Within this context a building envelope faces a challenge to provide adequate thermal resistance.

The results presented in this paper are the first of a long-term building envelope research project at the Alternative Village (AV) at the University of Manitoba in Winnipeg. Data reported in this paper are for the period from October 2011 to April 2012. The AV is a 0.6 ha. site on the university campus. Figure 1 provides an aerial view of the village. The small square structures are the test buildings discussed in this paper.

FIGURE 1. Aerial view of alternative village.

The initial structure at the Alternative Village is a 390 m^2 Biosystems Strawbale Research Facility (BSRF) building. Research is done in and on this structure. During the summer of 2011 seven pad sites were constructed on the Alternative Village site to investigate building envelope performance. All of the structures are oriented the same with respect to the cardinal compass directions. The nature of the pad sites allows for buildings to be deconstructed allowing for other wall systems to be studied in the future. All buildings have been located such that their shadow does not influence adjacent buildings.

In-situ testing has been used to compare laboratory experiments with building performance in various studies [3-8]. As Straube points out, field measurements are complementary to laboratory experiments [8]. Some studies have looked at walls in existing buildings to determine U-values in selected locations [7].

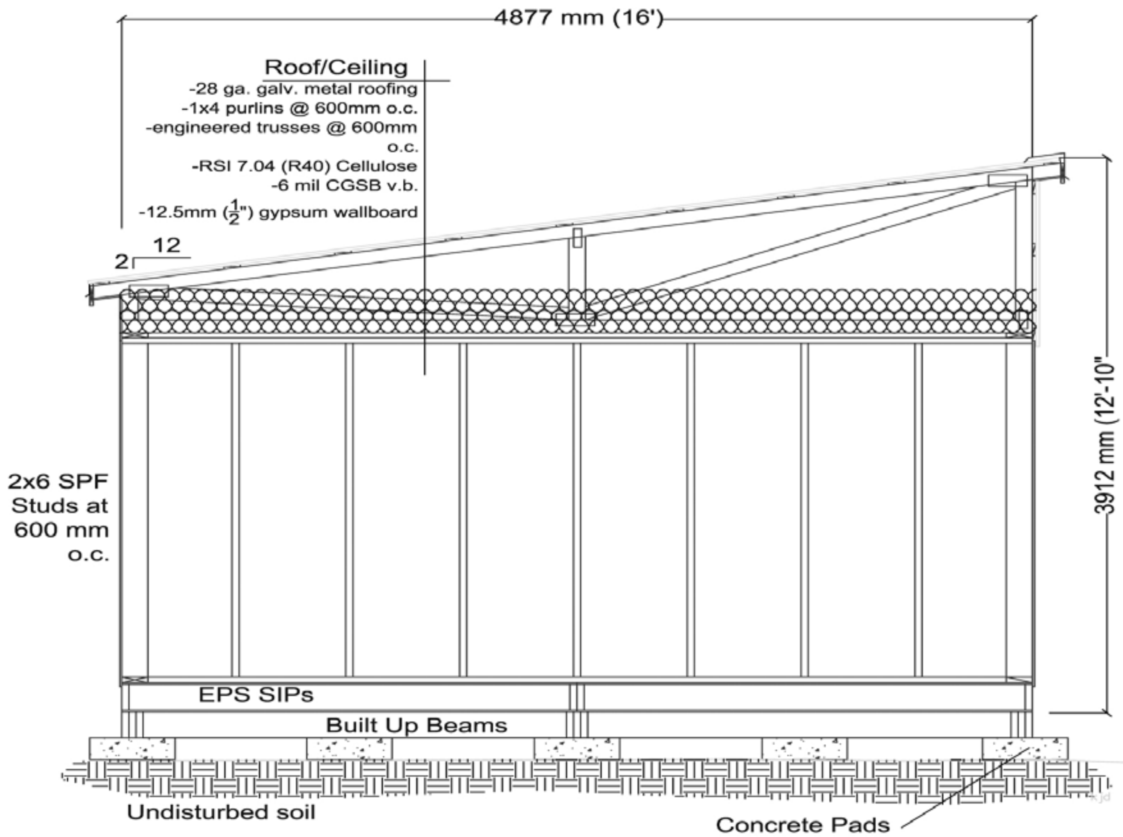
To minimize discontinuities in the envelope the structures have only one door opening. While these test structures are small and not subject to the vagaries of a normal occupied home, they provide a baseline for comparison and are the first phase of an ongoing research program. Of particular interest is the implication that building envelope type has on power consumption. Since thermal performance and heating /cooling costs are directly related, a reduction in power consumption will result in lower end-user cost. While not the only consideration in green building, understanding how various wall systems effect energy consumption is an important design consideration.

2.0 MATERIALS AND METHODS

2.1 Test Buildings

The test structures were all constructed with common roof and floor systems. Each pad is 4.87 m x 4.87m with a footprint 23.8m2. The construction of the foundation and roof are identical regardless of the wall system. By keeping these components the same, their relative effect on building performance will be consistent for all envelope types. Figure 2 illustrates a cross section through a typical wood-frame test structure. Each structure has only one 812mm x 2032mm door opening at the centre of the north wall. The following components are common to all test buildings.

FIGURE 2. Cross Section of Wood Frame Test Structure (Note: roof and floor are common to all test buildings).



Roof:

- 28 gauge galvanized metal roofing
- Nominal 1x4 Spruce-Pine-Fir (SPF) (19x89mm) purlins at 610mm on centre
- Engineered trusses at 610 mm on centre
- RSI 7.04 $m^2 \cdot K/W$ blown in cellulose insulation
- 6 mil (0.152 mm) polyethylene vapour barrier
- 12.5 mm gypsum wall board (GWB)

Floor:

Structural Insulated Panels (SIPs) made with:

- 11mm oriented strand board
- Nominal 2x8 SPF No.1/2 joists at 610 mm on centre
- 184 mm of Expanded polystyrene foam (EPS)
- 11mm oriented strand board

Foundation:

- Multi-ply dimensional lumber beams – 3-ply 2x10 SPF No.1/2
- 610mm x 610mm x150 mm concrete pads.
- 12.5 mm pressure treated plywood skirting.

Conduit for data cables and wiring were trenched underground and run to each structure from the BSRF. Each building has two power circuits, one 120V for lighting and another 220 V for a centrally located 2kW resistance baseboard heater.

2.2 Building Envelope Types

Figure 3 provides a plan-view cross section of the wall systems evaluated in the test program. The wall sections are discussed in detail in the following sections. Table 1 summarizes the thermal resistance and conductivity values for the wall sections based on theoretical values.

FIGURE 3. Plan View Cross Sections of Wall Systems.

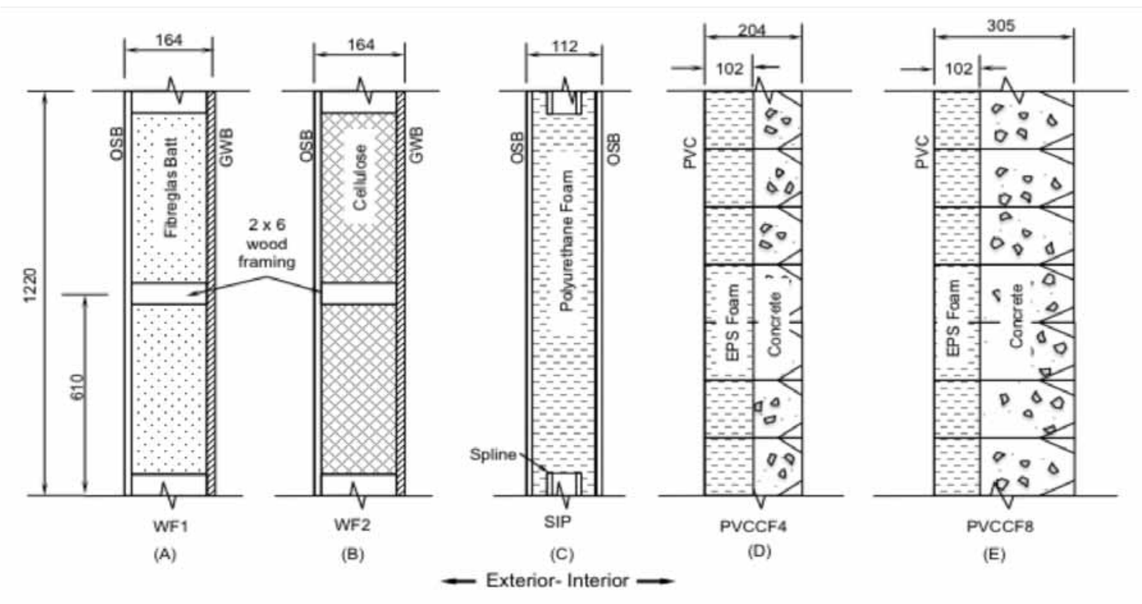


TABLE 1. Thermal Resistance and Heat Transfer Coefficient of Wall Sections.

Thermal Parameter	Wall System (1)(2)				
	WF1 Fibreglass	WF2 Cellulose	PVCCF4	PVCCF8	PUR SIP
Resistance – RSI ($m^2 K/W$)	3.95	3.69	3.03	3.09	4.16
Heat transfer coefficient U Value – ($W/m^2 K$)	0.253	0.271	0.330	0.324	0.240

NOTE: 1. Includes interior and exterior air film within total.
2. Whole wall values are used for fiberglass and cellulose assuming 10% framing.

The Alternative Village team constructed the wood frame systems for the fiberglass and cellulose insulation. A certified contractor installed the cellulose insulation. The PUR SIP and Stay in place PVC system suppliers constructed their own walls on site. This was done to ensure that the walls were built in accordance with product specifications. Alternative Village personnel completed the roof installation on all structures. The walls studied were selected based on common sizes for these systems typically used in the local construction industry and of interest to the local building community. While it is recognized that these systems represent different construction techniques, embodied energies, cost and durability, the focus of this study was to investigate thermal performance and power consumption.

2.2.1 Wood frame (WF1) – Fibreglass Batt Insulation (Baseline Building)

The predominant vernacular construction technique for residential buildings in Winnipeg is wood frame construction. The walls were framed with nominal 2x6 (38x140 mm) dimensional lumber studs at 610 mm on centre. Owens-Corning™fibreglass batt insulation was installed in the cavity between the studs. The exterior was sheathed with 11mm oriented strand board. A 6mil (0.152mm) vapour barrier was attached and sealed to the studs. The interior surface was finished with 12.5mm paper covered gypsum wallboard. The construction used was in accordance with standards at the time [9]. Fibreglass insulated structures are the vernacular for residential construction in Winnipeg. For this reason the fibreglass building was used as the benchmark for this research to which the other buildings were compared.

2.2.2 Wood Frame (WF2) – Dense Pack Cellulose

The cellulose building was constructed with the same framing system and exterior cladding as the fiberglass batt insulated structure described in 2.2.1. A fabric mesh was attached to the inside stud face to contain the dense packed cellulose. A certified contractor installed the cellulose insulation in accordance with the supplier's procedures.

2.2.3 Polyurethane Structural Insulated Panels (PUR SIP)

The third building was constructed using structural insulated panels (SIPs). The panels have 11mm OSB skins and a polyurethane foam (PUR) core with a total thickness of 112 mm. The standard size of the panels was 1220 mm x 2440 mm. They were joined with an insulated spline at 1200 mm intervals.

2.2.4 Stay in Place PVC Concrete Form (PVCCF)

Two structures were built using a Stay in place PVC concrete form system (PVCCF). It is comprised of a polyvinyl chloride form with 102 mm of expanded polystyrene (EPS) foam exterior insulation (Fig. 4). One wall had 102 mm

FIGURE 4. Pumping concrete into PVC stay in place Wall System.

of concrete and the other had 204 mm identified as PVCCF4 and PVCCF8 respectively in this paper. The premise behind this approach is to use the concrete as a thermal mass for heat storage, a well-known concept [10]. A total weight of approximately 11,000 and 22,000 kgs of concrete was in the PVCCF4 and 8 respectively.

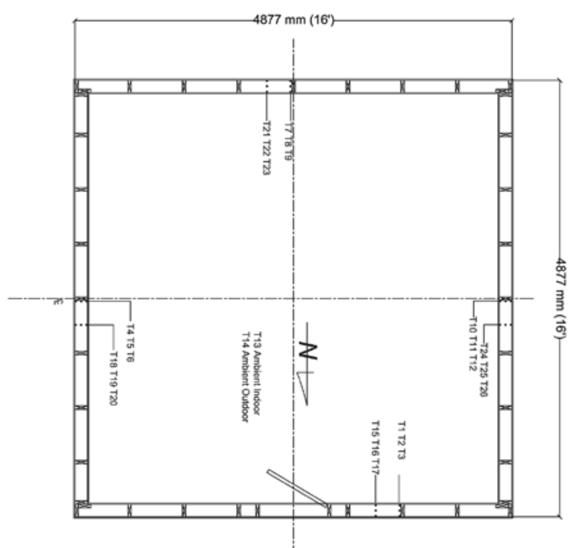
FIGURE 5. Data Acquisition System.

FIGURE 6. Thermocouples along stud.

2.3 DATA ACQUISITION

Each test structure was equipped with an Agilent 34972A-LXI data switch with u three 34901A multiplexers (Fig.5). This system was used to read and record thermocouple and heater run time used to determine energy consumption. An Onset U12-011 with an inductive coil on/off sensor was used to provide a backup reading for internal ambient temperature and relative humidity. Additional backup readings for heater run times were recorded using an Onset U9-004 motor on/off sensor.

FIGURE 7. Plan View Sensor Location Wood Frame.



Temperature was monitored with T-type thermocouples located within the wall system. The temperature was monitored at three locations through the cross section of each building envelope. In the wood frame structure 24 thermocouples were installed through the insulation and along the wall studs (Figs. 6, 7) to investigate thermal bridging at the framing members. A total of 17 locations were monitored in the Stay in place PVC concrete for buildings (Fig. 8) with 12 locations in the PUR SIP structure (Fig.9). The ambient indoor and outdoor temperatures were recorded at each building. Readings were recorded at 30-minute intervals over the study period.

Each structure had a 2kW baseboard heater installed on the floor along the north-south centreline of the building. The actual heater output wattage was determined by measuring the voltage and amperage at each heater. An optocoupler system was used in conjunction with a totalizer in the Agilent system to record the amount of time the heater was on for each 30-minute interval. Using the time data and heater output, the power consumption was determined in kWh.

FIGURE 8. Plan View Sensor Location Stay in place PVC concrete form.

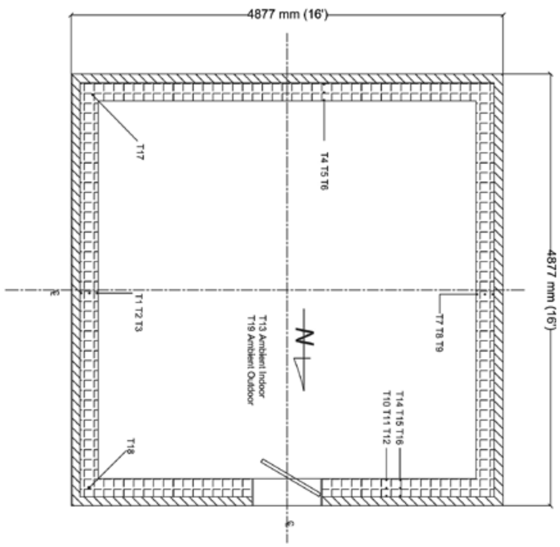
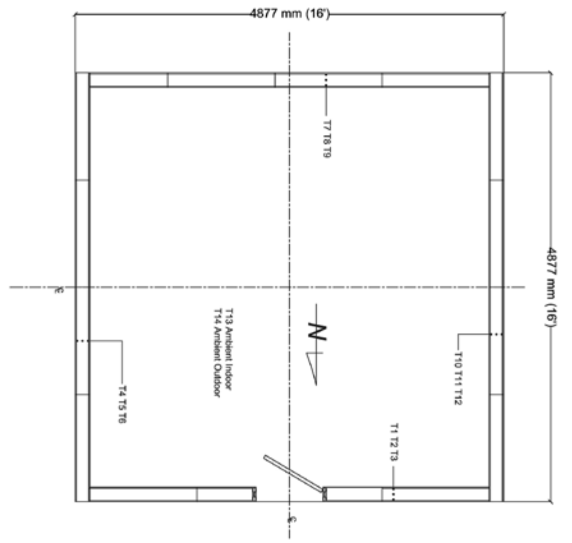


FIGURE 9. Plan View Sensor Location SIPs.



3.0 RESULTS AND DISCUSSION

3.1 Temperature Data

A total of 209 days of data were reduced to provide information on the thermal behaviour and power consumption for the five test buildings. In addition to the overall trends, two specific days were selected to provide a snapshot of performance, December 26, 2011, and January 19, 2012. The rationale was that December 26 had the greatest external temperature variance over a twenty-four period during the heating season, while January 19 had the lowest ambient external temperature. Based on a daily average, the external temperature over the study period ranged from -24.9°C to +22.3°C over the entire study period. The indoor temperature during the heating season was maintained at 21.6°C ± 0.8°C.

As described previously the fibreglass building was used as a benchmark to which the other buildings were compared. For the purpose of this paper only the north wall data is used for comparison to eliminate solar effects. The temperature gradient through the cross-section for all wall types based on sensor location is shown in Figs. 10 and 11. The temperatures shown represent the mid-cavity location for the fiberglass and cellulose wall systems. The inner and outer locations represent the interface between the sheathing material and the next layer for the fiberglass, cellulose, and PUR SIP buildings. For the PVCCF4 and PVCCF8 the outer layer represents the interface between the concrete and the EPS outer insulation. All wall sections were monitored at the mid-section of the wall.

FIGURE 10. Temperature Through Wall December 16, 2011.

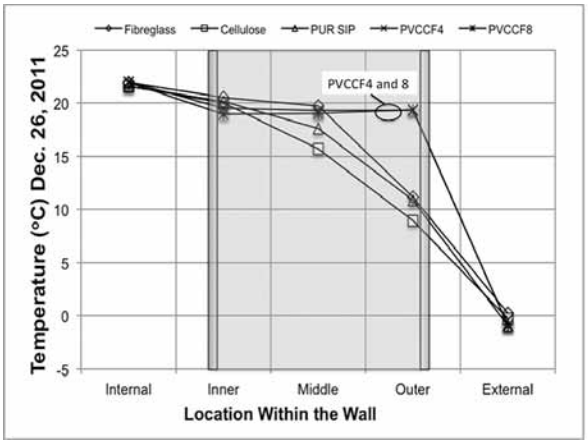
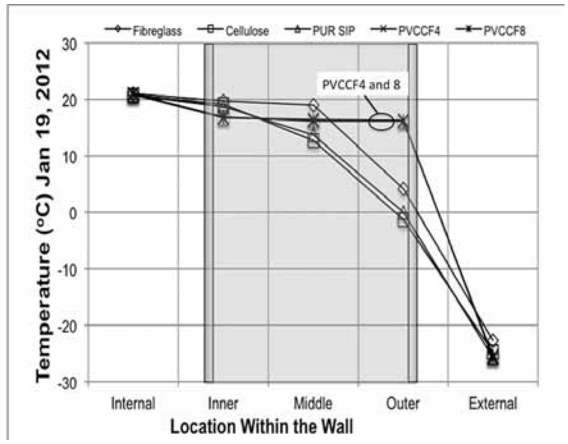


FIGURE 11. Temperature Through Wall January 19, 2012.



It can be seen that the frame and SIP wall exhibit a gradual decrease in temperature through the cross-section. The Stay in place PVC concrete form walls exhibit essentially a constant temperature through the concrete portion of the wall, with a final drop through the external foam insulation. The concrete temperature was relatively constant. For both December 26, 2011, and January 19, 2012, the temperature from the inside face to the outside interface at the foam layer varied by less than 0.5°C for both the PVCCF4 and PVCCF8.

The cross-section temperature in the fibreglass and cellulose buildings was monitored along the stud and at the midpoint of the insulated stud cavity. Figures 12 and 13 illustrate the variation through the wall at 3AM on January 19, 2012, to minimize the influence of other sources of heat energy such as solar.

FIGURE 12. Comparison of Temperature Gradient Fibreglass.

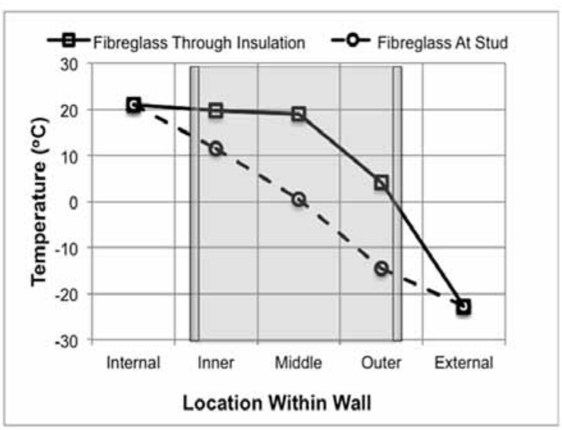
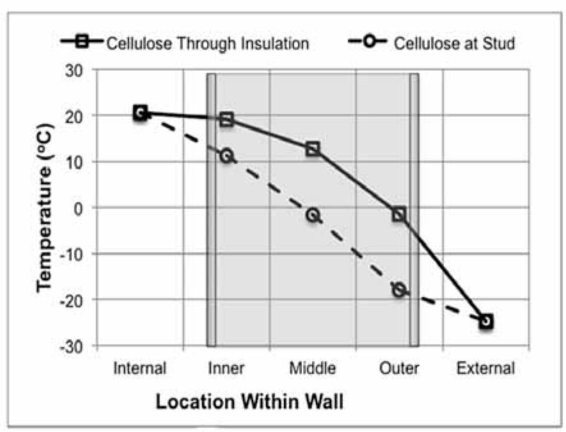


FIGURE 13. Comparison of Temperature Gradient Cellulose.



At this particular instant the fibreglass wall exhibited a 27.58°C difference at the midpoint of the stud cavity between the inside of interior and exterior sheathing. The cellulose wall exhibited a 31.3°C variation over the same zone. A claim sometimes made by proponents of dense pack cellulose is that it offers better sealing between the cavity insulation and the studs in a wood frame wall. Harley [11] discusses a process to evaluate insulation installation and indicates that cellulose can produce a better result than batt insulation. The installation of batt insulation takes time to do properly and may not always happen when installers are either inexperienced or rushed to complete a project. Figures 12 and 13 show the difference in the thermal gradient at the stud for these products. These figures represent not only a particular instant but also a general behaviour. In this case the gradient at the stud location for the fibreglass is less than that of the cellulose for this test structure. This would indicate a higher potential for reduced thermal resistance at the stud location. This difference in performance at the stud speaks to the reality that the whole wall insulation value will be less than that of the thermal resistance value for the cavity insulation.

The same comparison was done for the Stay in place PVC concrete form walls. The PVC forms create zones of concrete with 3 mm ties at 150 mm (Fig.3). Thermocouples were placed across the middle of the concrete zone and along frames. Unlike the wood frame structure, there was no significant difference between these locations. The maximum difference for the Stay in place PVCCF 4 wall was 0.3°C, while the Stay in place PVCCF8 measured a 0.1°C variation. Essentially, all of the thermal resistance provided by these systems occurs at the 102 mm EPS external foam layer.

3.2 Internal Humidity

The relative humidity was monitored using an Onset U12-011 data logger located at the centre of each structure. Table 2 provides a summary.

TABLE 2. Relative Humidity inside Test Buildings.

% RH	Fibreglass	Cellulose	PVCCF8	PVCCF4	PUR Sip
Minimum	17.65	20.29	20.67	25.37	11.63
Maximum	32.43	32.47	40.27	42.94	28.20
Average	23.44	25.85	30.93	33.92	19.51
Range	14.78	12.18	19.60	17.57	16.57

Since there was no occupancy in the structures, any humidity present was assumed to come from air infiltration and infrequent opening of the door. A review of the values in Table 2 indicates that the PVCCF wall systems maintained a higher average humidity with the PUR SIP being the lowest. It is postulated that the wall covering material influenced the relative humidity based on its potential to absorb moisture. By reckoning the sorption isotherm at approximately 50% relative humidity as a basis for comparison, then the PVC is negligible; gypsum wallboard is 0.4%; and the OSB is 4.7% [17]. Based on this comparison, it follows that OSB would have the lowest relative humidity. This analysis does not take into consideration the effect of air infiltration but does provide some rationale for the variability since all of the structures were subjected to the same external conditions. The average relative humidity in the framed buildings was comparable within 2.5%. Similarly, the Stay in place PVC concrete form systems were within 3% of each other. The relative humidity was 7.78% less in the framed buildings as compared to the concrete ones. The interior of the Stay in place PVC concrete form is sealed with PVC, while the framed structures have unpainted paper-covered gypsum wallboard that would provide some moisture storage and buffering. The PUR SIP building has unpainted OSB on the interior and exhibited the lowest relative humidity at 3.93% less than the fibreglass. Comparing research results for unpainted gypsum with OSB indicates that the OSB has slightly higher equilibrium moisture content for the same RH, which could also account for this difference [12,13].

3.3 Air Tightness of Test Structures

As mentioned previously, aside from a door on the north side of each building, there were no other openings or any means of forced ventilation. To establish the infiltration, a blower door test was conducted on all of the test buildings. All tests were conducted using a Minneapolis Blower Door [16] with a C ring and adjusted for natural infiltration [15]. Using these data Table 3 summarizes the test results.

TABLE 3. Test Structure Air Filtration.

Building Type	Parameter			
	CFM(50) (m^3/s) (1)	ACH_{50} (2)	ACH_{nat} (3)	Percent of Total Power Consumption (4)
Fibreglass	0.0090	0.640	0.0320	2.41
Cellulose	0.0116	0.831	0.0416	3.11
PVCCF4	0.0107	0.791	0.0396	2.52
PVCCF8	0.0112	0.907	0.0454	2.63
PUR SIP	0.0164	1.122	0.0561	4.38

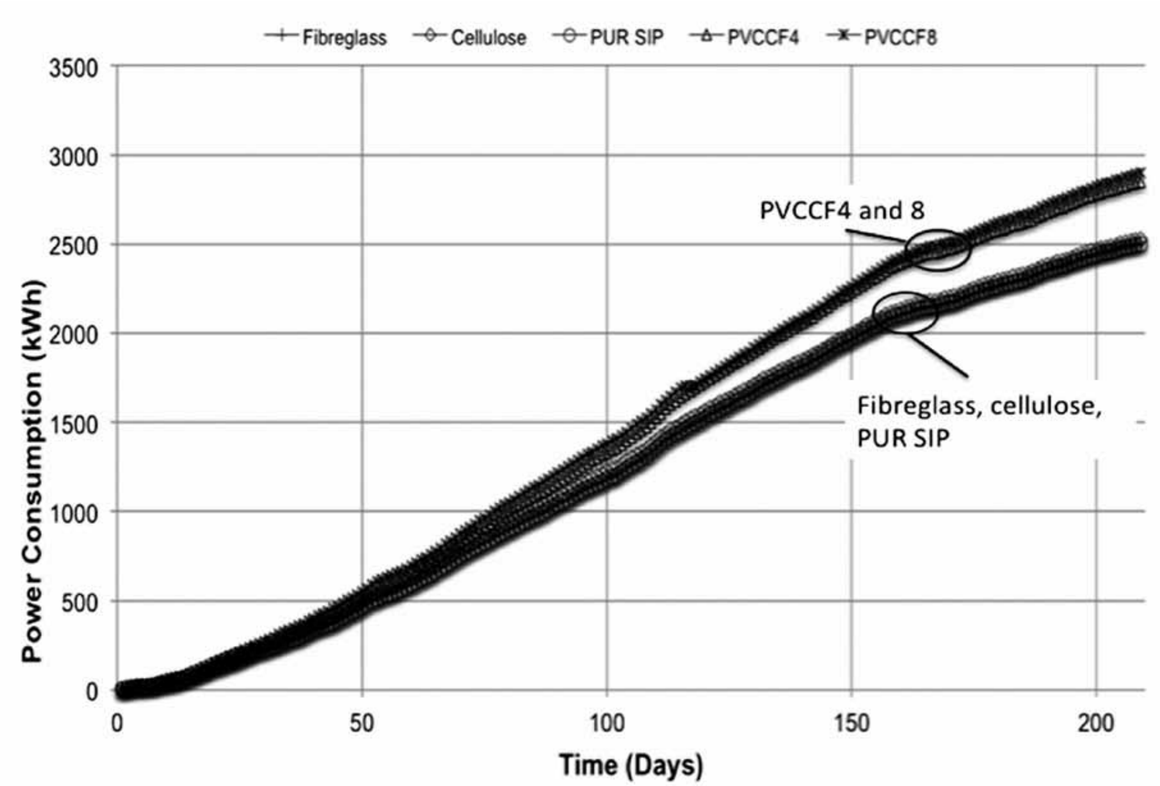
NOTE:
1. The CFM (50) determined from regression analysis of range of pressures. Values are air density corrected in accordance with Appendix H Minneapolis Blower Door manual. [16]
2. ACH_{50} – air changes per hour based on internal volume of structure at 50Pa.
3. ACH_{nat} –natural air changes per hour based on ACH50/LBL Factor. [15]
4. Air filtration as percentage of average daily power consumption over 209-day study period.

The air infiltration values determined from the blower door tests were used to adjust the power consumption data presented in the next section. It is noted that the SIP structure was the least air-tight. While this was unexpected, the SIP suppliers constructed their own walls on site as mentioned in Section 2.2. Another contributing factor to air leakage was the connection between the wall plate and the roof system. As a result of these data, the supplier has been able to revise this detail. Another important factor to consider is the small size of the test buildings and minor imperfections in sealing the building envelope had a significant impact. Even with the greatest air leakage, the SIP test structure exhibited the lowest power consumption.

3.4 POWER CONSUMPTION

Figure 14 contains a cumulative plot that compares the power consumption for the five buildings. It is clear that there are two distinct behaviours. The fibreglass, cellulose, and PUR SIP buildings had comparable performance while both of the Stay in place PVC concrete form buildings exhibited greater consumption.

FIGURE 14. Cumulative Power Consumption of Test Buildings.



A comparison of the power consumption for each of the test buildings is summarized in Table 4. The average daily rate was determined using the slope of the linear regression line of the cumulative plot for each test structure adjusted for the natural infiltration.

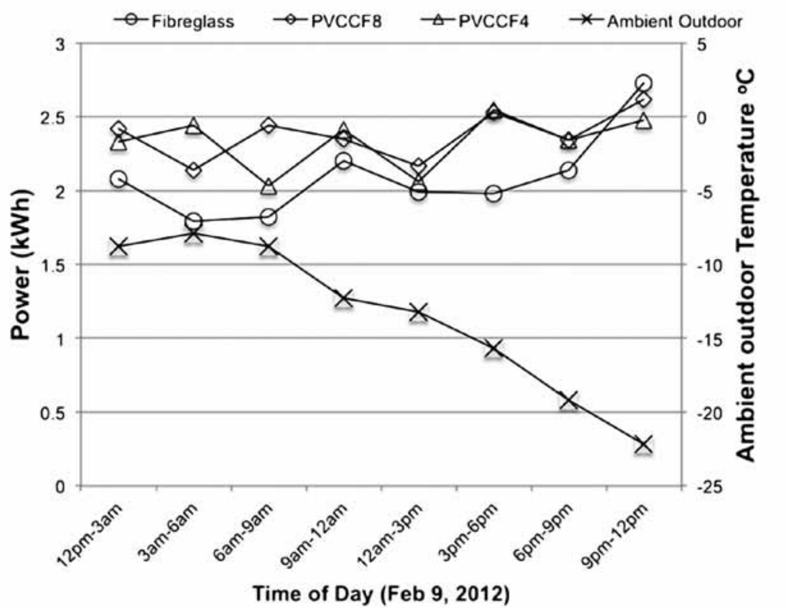
TABLE 4. Comparison of Power Consumption over Study Period.

Wall Type	Consumption Rate	Regression Coefficient	Total Power Consumption	Comparison to Fibreglass
	kWh/day	R2	kWh	
Fibreglass	12.41	0.985	2512	—
Cellulose	12.65	0.989	2530	1.01
PUR SIP	12.39	0.985	2498	0.99
PVCCF4	14.04	0.983	2848	1.13
PVCCF8	14.33	0.987	2898	1.15

The temperature gradient comparison in Figures 10 and 11 show the variation for the wall systems. It can be seen that the temperature in the Stay in place PVC concrete form walls is essentially consistent through the concrete until it reaches the external EPS foam where it drops to the external ambient temperature. A significant amount of power is used to maintain the concrete temperature, not unexpected given the difference in thermal conductivity of concrete when compared to the other insulating materials.

Based on values in Table 4 and in Figure 14 there is a clear difference in the performance of the concrete-based wall sections. The Stay in place PVC concrete form wall systems consumed on average 14% more power over the study period. As previously mentioned, a potential benefit of this system is to take advantage of the concrete thermal mass. Figure 15 compares power consumption with external ambient temperature at three-hour intervals on February 9, 2012. The ambient external temperature ranged from -7.9 to -22.2°C. The average indoor temperature for the fiberglass and the two PVCCF4 and 8 was 21.5°C. The maximum temperature differential between indoor and outdoor was 43.8°C. As the external temperature decreased at the end of the day, the compensating power consumption response of the fibreglass envelope was more rapid than the Stay in place PVC concrete form structures. This may be taken as an indicator of the effect of mass on performance, since the thermostat did not call for heat until the stored heat could not maintain the set point temperature. Over the next day the power consumption increased in the PVCCF structures to maintain the concrete temperature. While there is potential benefit from thermal mass, it can only be realized when the heat energy comes from a low cost source such as solar, animal husbandry, or from a manufacturing process, then the mass could be advantageous. In the case of commercial or large scale projects, the addition of thermal mass even when paying to heat or cool could allow for energy savings if the lag times created avoid energy consumption during "peak demand hours" when end user costs are higher. It is recognized that the Stay in place concrete form structures in this study had on average 22.5% less thermal resistance than the fiberglass building. If the thermal resistance were the same, it is postulated that the power consumption would be similar. If, for example, solar energy were available then the power consumption would be reduced and the true benefit of the mass wall would be more evident. In this case there was no other source of heat except the electric resistance heater. Given the thermal resistance of the assembly, it was anticipated that power consumption would be more. In the authors' opinion this behaviour does not, however, negate the impact of thermal mass, but highlights that conditions need to be such as to take advantage of thermal mass.

FIGURE 15. Power Consumption Comparison February 9, 2012.



The end user cost for heating is a direct implication of thermal performance. The current residential electricity rate for Winnipeg in 2013 is 7.183 cents per kilowatt-hour [14]. Based on this rate the price range for the test structures varies from $179.43 for the PUR SIP structure to $208.16 for the Stay in place PVCCF8 building. While the $28.75

dollar range is small the implications would be greater for larger structures. It is apparent that to take advantage of the thermal mass in the concrete buildings a low or no-cost energy source would be required.

4.0 CONCLUSION

Five test structures were monitored to investigate their relative power consumption in the northern prairie climate of Winnipeg, Manitoba, Canada. The study period was 209 days from October 2011 to April 2012. Two wood frame structures insulated with fiberglass batt and dense pack cellulose cavity insulation, one PUR SIP, and two Stay in place PVC concrete form buildings were evaluated. All the buildings were compared to the wood-frame fiberglass batt-insulated structure. Based on power consumption, the PUR SIP used 1% less than the baseline building, while the Stay in place concrete form structures averaged 14% more. While there was an indication of heat storage of the concrete, to effectively take advantage of the thermal mass a low or no-cost energy source is needed. Comparison of the thermal gradient at the centre of the stud space insulation to the gradient at the stud indicates that there is less thermal resistance at this interface.

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