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Monitored Thermal Performance of ICF Walls in MURBs

INTRODUCTION

Insulating concrete forms (ICF) are generally stackable, hollow, polystyrene blocks into which concrete is poured to form walls in residential and commercial buildings.

ICF walls have many advantages, including ease of construction, high thermal resistance, thermal mass and airtight construction. These attributes should lead to lower heating and cooling energy consumption, increased comfort and reduced space-conditioning systems capacity requirements.

While ICF building systems have been available for many years, builders, owners and developers need quantitative performance monitoring data and analysis to better understand the energy-related performance of ICF. CMHC, in partnership with the Ready Mixed Concrete Association of Ontario (RMCAO) and the Jamesway Construction Group, initiated a research project to measure the thermal performance and air leakage characteristics of an apartment building constructed using an ICF system.

Figure 1 The building studied for the research project

Research Program

The objectives of this research project were to characterize:

- the thermal performance of an ICF wall,
- the airtightness of the building envelope, which included identifying areas of infiltration and the presence of thermal bridges in the ICF wall system, and,
- implications of the thermal performance on sizing of the space-conditioning system.

Jamesway Construction built the study building, shown in figure 1, in 2005 in Waterloo, Ont. The seven-storey building has 100 apartments and a floor area of 8,140 m^2 (26,705 sq. ft.).

The study analyzed temperature sensor results at nine locations on the ICF wall assembly. The sensors recorded the transient temperature behaviour of the opaque wall system. At each of the nine wall monitoring locations, sensors were installed:

1. On the exterior surface of the outer layer of insulation.
2. At the interface between the outer layer of insulation and the concrete.
3. At the interface between the inner layer of insulation and the concrete.
4. On the interior surface of the inner layer of insulation.

The wall monitoring locations included all elevations and every second floor level. Data loggers in eight apartments collected indoor air temperature information.

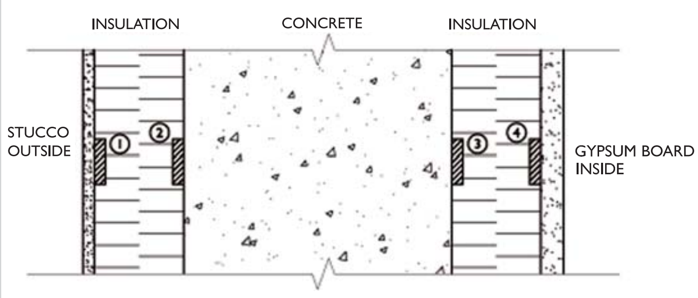

Figure 2 Wall cross-section schematic showing sensor locations

The 36 sensors collected data every 15 minutes from Dec. 1, 2005 to Feb. 28, 2006. Outdoor ambient air temperature data was retrieved from a University of Waterloo weather station. In addition to the temperature monitoring, the research project included an air leakage test of the entire building, thermographic scanning for thermal bridges and parametric energy modelling to attempt to identify the impact of thermal mass and air leakage on building energy consumption.

FINDINGS

Thermal Insulation Value

Three key layers made up the ICF wall system tested: an exterior expanded polystyrene insulation layer, a concrete layer and an interior expanded polystyrene insulation layer. Table 1 gives the properties of the insulation and concrete.

Table 1 shows that the insulation has a low volumetric heat capacity and a high thermal diffusivity. This means that the insulation has a low capacity for storing thermal energy and responds quickly to external temperature changes. The concrete, though, has a high volumetric heat capacity and a low thermal diffusivity, making it a good thermal storage medium that responds slowly to external temperature changes. Using conventional calculations, the thermal resistance of the ICF wall was determined to be RSI-3.7 (R-21), as Table 2 shows.

The thermal resistance of the overall wall assembly, including the stucco exterior, the gypsum board on the interior, and the exterior and interior film coefficients, was calculated to be 3.9 m^2K/W (R-22).

Temperature Gradient through the ICF Wall System

Over the course of the mid-winter monitoring, the following trends were noted:

- The indoor air temperature (IAT) was maintained at approximately 19.4°C (66.92°F), with very little variation between the suites.
- The temperatures on either side of the concrete (at locations 2 and 3 [*see* figure 2]) were relatively stable over the three months, varying only by approximately ±3.5°C from the average.
- The temperature at the interior surface of the concrete (location 3 [*see* figure 2]) was never higher than the temperature on the interior surface of the insulation (location 4 [*see* figure 2]). Hence, the heat flow never reversed direction such that the concrete transferred heat to the interior of the building even though the walls did appear to absorb some solar energy under certain conditions. While the presence of the absorbed solar energy would reduce heat loss, the overall impact would not be significant.

The temperature drop across the interior layer of insulation was found to be relatively constant over the course of the day. This means the heat loss from the building interior is also relatively constant. The

Table 1 Thermal properties of the study building's insulation and concrete

Property	Insulation	Concrete
Thickness (each layer)	66.675 mm	152.4 mm
Density	16.0 kg/m^3	2,350 kg/m^3
Thermal conductivity	0.037 W/mK	1.4 W/mK
Specific heat	1,210 J/m^3K	880 J/m^3K
Volumetric heat capacity	19,360 J/m^3K	2,068,000 J/m^3K
Thermal diffusivity	1.91e-6 m^2/s	6.77e-7 m^2/s
Thermal resistance	1.8 m^2K/W	0.1 m^2K/W

Table 2 Thermal resistance of the study building's ICF assembly

Wall component	Nominal thickness	Thermal conductivity	Thermal resistance
Outer insulation (expanded polystyrene)	66.7 mm	0.037 W/m K	1.8 m²K/W
Concrete (2350 kg/m³)	152.4 mm	1.4 W/m K	0.1 m²K/W
Inner insulation (expanded polystyrene)	66.7 mm	0.037 W/m K	1.8 m²K/W
Total assembly	**285.8 mm**	**—**	**3.7 m²K/W**

Thermal conductivity values are for a mean temperature of 24°C.
Reference: ASHRAE Fundamentals Handbook 2005.

temperature on the inside surface of the wall assembly and the indoor air temperature increased slightly over the course of the afternoon, but returned to the same temperatures exhibited in the morning hours. The elevated indoor air and wall surface temperatures are attributed to direct solar heat gain through the windows and the balcony door in the apartments.

Figure 3 shows the through-wall temperature conditions at the first storey location on the north wall (1N) on February 3, 2006, when the wall was observed to be at a quasi-steady-state condition. The temperature difference across the inner (1N-4 to 1N-3) and outer (1N-2 to 1N-1) layers of insulation was approximately 6.3°C. By comparison, there was only a difference of 0.4°C across the concrete (1N-3 to 1N-2). This indicates that the concrete does not contribute significantly to the overall thermal resistance of the wall under steady-state conditions.

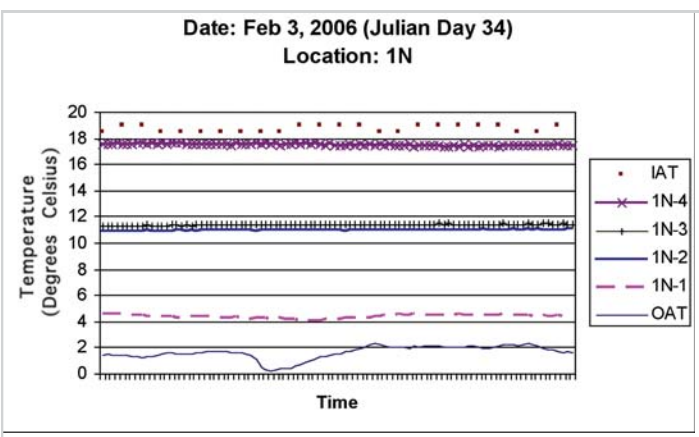

Figure 3 Quasi-steady-state wall performance

Figure 4 shows the wall conditions on the 7th floor, north wall location (7N) for a day with significant fluctuations in the outdoor air temperature (OAT). Not surprisingly, the temperature at 7N-1 (the exterior wall surface) closely follows the OAT; however, the temperature at the inner locations held constant throughout the day.

This indicates that the inner surface of the concrete (7N-3) is well isolated from outdoors temperature changes by both the insulation levels on the exterior of the wall and the capacitance of the concrete. The level of isolation is so large that what happens outdoors has almost no impact on the interior concrete temperature and therefore no significant impact on the heat flow through the wall from the interior in the short term (that is, daily or even weekly).

Wall temperature profiles were found to be relatively independent of building height, wall cladding (stucco vs. brick). Over periods of extended cold temperatures (lasting several days), the heat flow from the building interior to the concrete and from the concrete to the exterior was mostly balanced. During these conditions, the concrete added very little to the overall wall thermal resistance.

Air Leakage Testing

Airtightness testing was carried out to determine if the impact of the ICF wall assembly on the overall air leakage characteristics of the building. While it was expected that the opaque wall area would be relatively airtight, the conventional foundation, roof deck as well as the window, door, mechanical and electrical penetrations were expected to offset the airtightness of the walls.

At the time of the test, the building was in the final stages of construction and the caulking, weatherstripping, fire-stopping and mechanical penetrations were not yet complete and sealed. All intentional openings were sealed so that the leakage characteristics of the constructed building envelope with unintentional openings could be measured.

Three blower doors were used to conduct the test—two installed in ground floor exit doors and one in the service door leading to the roof. A multi-point test was conducted where the building was depressurized from 50 Pa to 20 Pa (below ambient outdoor pressure) with regular flow and pressure measurements taken.

During the test, an inspection of the building envelope was undertaken to identify air leakage areas. While many air leakage locations associated with mechanical and electrical penetrations were found, no leakage was detected in the ICF wall system itself.

The normalized air leakage index was calculated to be 1.25 L/s/m^2 @ 75 Pa. In comparison, a CMHC study (1) of 11 multi-unit residential buildings across Canada, found overall indexes in the range of 0.9 to 10.3 L/s/m^2 @ 75 Pa, with an average of 3.19 L/s/m^2 @ 75 Pa. Other references suggest that typical buildings have a normalized air leakage index in the range of 2 to 20 L/s/m^2@ 75 Pa.

The results show that the overall building is relatively airtight, due in large part to the continuity of the ICF wall assembly as no extraordinary air leakage control measures were undertaken at the roof and foundation levels and the building construction was not yet completely finished and all penetrations of the wall system were not sealed.

The results from this test suggest that the design heating and cooling loads and subsequent sizing of the building's heating and cooling system may be based upon an air infiltration rate that is up to 60 per cent lower than standard construction.

Thermal Bridges

An infrared thermographic survey of the building was also conducted to locate thermal bridges through the ICF wall assembly. The through-wall heating-cooling unit penetrations, window assemblies and balcony sliding doors exhibited expected thermal bridging. However, thermal bridging was also found at locations such as the wall–floor slab junction (see figure 5) where the temperature of the intersection was found to be 3°C less than the adjacent opaque wall temperature. However, this would not likely have a significant impact on the overall building heating load.

Thermal bridging was also detected where the balcony slabs intersect the ICF wall system. The temperature of the balcony near building (in front of the balcony door and at the intersection of the balcony and the exterior wall), was approximately five degrees warmer than the areas further away from the building even though there was a thermal break installed between the core slab and the balcony (see figure 6). No significant thermal bridging through the ICF wall itself was observed. This is due to the design of the ICF system, in which the plastic spanners within the ICF blocks do not fully penetrate either layer of insulation. In addition, the exterior layer of insulation is not totally breached at wall–floor intersections.

ENERGY MODELLING

The energy consumption of the apartment building was simulated using eQUEST® v.3.5 software. eQUEST was used to run parametric simulations in an effort to quantify the annual energy savings that might be attributed to the reduced infiltration and the increased thermal mass associated with the ICF wall construction. Three models were simulated:

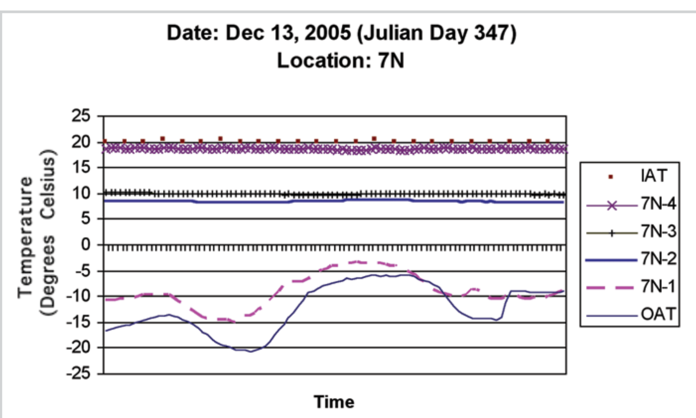

Figure 4 ICF wall isolating IAT from OAT

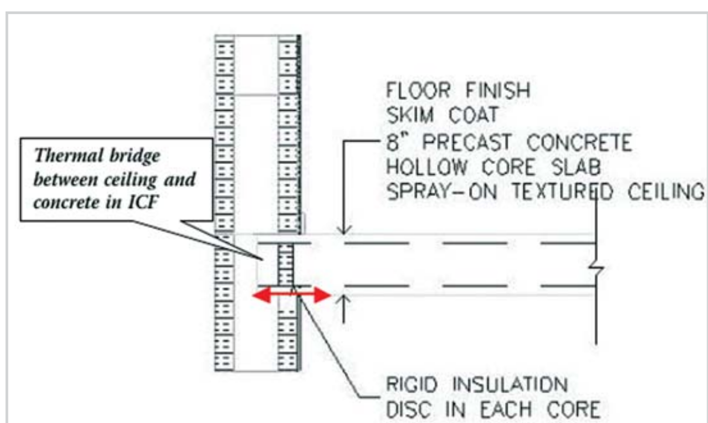

Figure 5 Thermal bridge at wall-floor slab intersection

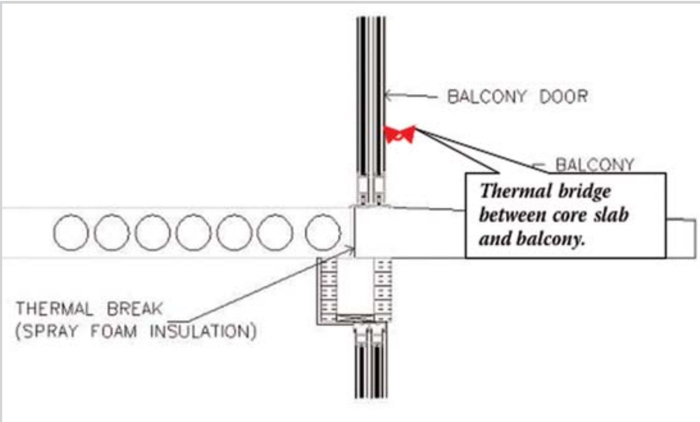

Figure 6 Construction detail showing thermal bridging at wall-balcony interesection

Model 1: Reference Case

This model simulates the performance of the apartment building as built. It is based upon the actual building construction and measured air infiltration.

Model 2: Typical Infiltration

This model is identical to Model 1, except the infiltration rate was increased to that of a typical MURB (0.691 ACH, with a 16 km/hr [10 mph] wind blowing on the building). This simulation was compared against the Model 1 simulation to investigate the impact of ICF wall enhanced air leakage characteristics on the building's energy performance.

Model 3: No Concrete

This model is identical to Model 1, except that the concrete layer of the ICF wall assembly was replaced by a 6.35 mm (0.25 in.) layer of expanded polystyrene. The thickness of this insulation was selected so that the total R-value of the wall assembly matched that of Model 1.

Table 3 shows the results of the three energy simulations

A comparison of the simulation results of Models 1 and 2 shows that the 60% reduction in air infiltration associated with the ICF wall construction lowered the building's peak heating and cooling loads by 57% and 16% respectively, giving rise to annual energy savings of 574,584 MJ and cost savings of $5,879.

Comparing the simulation results of Models 1 and 3 shows that the increased thermal mass offered by the ICF wall construction in this building showed an insignificant improvement when compared to a low-mass wall assembly having the same thermal resistance and infiltration. The annual energy savings and energy cost savings were estimated to be 6,436 MJ and $140.

The wall assembly used in Model 3 is a theoretical wall assembly, comprised only of polystyrene, having an extremely low thermal mass. Therefore, any other wall assemblies (such as stud infill) achieving the same level of infiltration and overall effective thermal resistance would be expected to yield similar results. However, in terms of peak building loads and total annual energy demand, the increased thermal mass provided by the ICF wall construction in this multi-unit residential type building yielded very minimal savings.

It is noted, however, that the ICF wall construction may have a greater impact upon the energy savings and the sizing of mechanical equipment for other building types, such as an office building, where energy saving control strategies may be implemented during unoccupied hours (for example, precooling the building using cooler night-time air).

Table 3 eQUEST® energy simulation results

	Model 1	**Model 2**	**Model 3**
Cooling load (kW)	197	234	202
Heating load (kW)	164	383	161
Annual electricity (MJ)	1,698,113	1,692,415	1,702,649
Annual natural gas (MJ)	5,466,351	6,046,631	5,468,250
Total annual (MJ)	7,164,463	7,739,047	7,170,899
Annual electricity cost	$44,114	$43,967	$44,233
Annual natural gas cost	$57,732	$63,758	$57,753
Total Cost	$101,846	$107,725	$101,986

CONCLUSIONS

The ICF wall assembly studied in this research project had an insulating value that was fairly close to the nominal insulation value of the polystyrene layers of insulation. While minor thermal bridges through the wall system were detected, the more severe bridges that were found were due to penetrations through the ICF system and did not represent a weakness in the ICF wall system.

No thermal mass impact or higher effective insulation value was observed. However, the air leakage testing found the building to be relatively airtight and this can, for the most part, be attributed to the ICF wall system. The energy savings associated with the reduced air leakage alone are significant and would continue to accrue over the life of the building as the amount of air leakage through the ICF wall section would not be expected to increase to any great extent over time.

Additionally, the ICF wall system provided a significant thermal buffer between indoor and outdoor conditions, which would provide for enhanced comfort conditions within the building.

Implications for the Housing Industry

The results of this research project indicate that insulated concrete forms can be used to build walls that offer good insulation values, significantly reduced air leakage and enhanced occupant comfort. ICF wall systems could be expected to reduce building energy consumption and related operating costs by reducing air leakage.

While this study could not attribute any effective insulation value that is higher than the nominal insulating value of the polystyrene layers, ICF wall systems would seem to deliver excellent thermal and air leakage performance. This study also indicates that the sizing of space conditioning systems for buildings constructed of ICF systems should take into account the relatively airtight wall system.

Acknowledgments

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