8TH
CANADIAN
MASONRY
SYMPOSIUM

Jasper, Alberta
May 31 - June 3, 1998

FIELD MEASUREMENTS OF MASONRY VENEER EXPOSURE CONDITIONS

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ABSTRACT

Masonry, particularly single-wythe brick veneers are a very common cladding for buildings. Brick veneers over insulated structures are often exposed to much more severe conditions than masonry in traditional uninsulated solid walls or in uninsulated cavity walls. Quantitative measures of brickwork exposure would be useful to designers, writers of test standards, manufacturers, etc. Such information is however, difficult to obtain.

As part of a larger research project, the exposure conditions of several brick veneers exposed to the south-western Ontario environment have been continuously monitored for over two years. Measurements included the temperature conditions within, across, and behind the claddings, the relative humidity behind and sometimes within the claddings, and the relative wetness and dryness of the brickwork at four locations per panel. The exterior temperature, humidity, windspeed and direction, and driving rain deposition were also measured.

The results of the monitoring have provided valuable information regarding the number and nature of freeze-thaw cycles, the powerful influence of sun and orientation, the difference in behaviour between thermally heavy and thermally light cladding, and the effect of cladding absorptance. This research has implications for the interpretation and development of freeze-thaw tests, the energy use of masonry clad enclosures, and provides guidance for designing joints for moisture and thermal movements.

INTRODUCTION

Masonry, particularly single-wythe brick veneers, are a very common and durable cladding system for buildings. Brick veneers over insulated framing or masonry backups are often exposed to much more severe conditions than masonry in traditional uninsulated solid walls or in uninsulated cavity walls.

Knowledge of the diurnal, seasonal and annual temperature range, the number of freeze-thaw cycles, heating and cooling rates, temperature gradients, wetting and drying times, etc. would be useful to quantitatively assess exposure. Quantitative exposure data is useful for the interpretation of freeze-thaw test results, the prediction of cyclic movements (of joints and veneer connectors), and the likelihood of condensation.

Such information is sometimes difficult to obtain and few sources exist. Some excellent previous studies [Ritchie and Davidson 1968, Ylae-Mattila 1987, Maurenbrecher and Chidiac 1995] have shown that orientation and colour have an important effect on exposure conditions. Our study focused on the full range of behaviour, not just the extremes as is often the case with other results in the literature. The relationship between weather conditions and the measured conditions and comparisons to other cladding systems were also part of this study.

EXPERIMENTAL PROGRAM

As part of a much larger multi-year research project, the response of several claddings exposed to the south-western Ontario environment have been continuously monitored for over two years. Twenty-six test panels were installed in the University of Waterloo's natural exposure and test facility, the Beghut, in the summer of 1995.

Sixteen of the panels were clad with brick, two with vinyl, and four with EIFS. The lightweight claddings provided useful information for comparison purposes. The colour of the EIFS panel was changed after the first year of monitoring, from bright white to a brown, very similar in appearance to the brick veneers. Table 1 summarises the number and orientation of each of the cladding types. All of the panels were insulated to RSI 3.3 to 4.1.

The exterior temperature, humidity, windspeed and direction, and driving rain deposition were measured with meteorological-quality instruments at the standard height of 10 m above grade. Interior conditions were tightly controlled to 21 °C.

A total of approximately 30 sensors were distributed through each test panel. Measurements included the temperature conditions within, across, and behind the claddings, the relative humidity behind and sometimes within the claddings, and the relative wetness and dryness of the brickwork at four locations per panel. Readings were taken every five minutes for two years. The annual and daily temperature range and rate of heating and cooling and temperature gradient were calculated from the collected data using 15 minute or hourly average values.

Temperatures were measured in the veneer at 10 mm from the inner and outer faces with high-resolution thermistors. The sensors were epoxied into small vertical holes 3 mm diameter holes drilled into the bottom of the brick to a depth of 1/4 of the brick height. Sensors for the vinyl panel were attached with epoxy to the back of the vinyl, and for the EIFS panels they were embedded into the base coat.

Cladding	Total No.	Orientation N	S	E	W	Colour
Brick	16	3	4	5	4	dark red
EIFS	4	1	1	1	1	white/ dark brown
Vinyl	2	1	1	0	0	grey

Table 1: Cladding characteristics of test panels

Exposure and Basis for Assessment

The exposure conditions of a brick veneer cladding in a South-western Ontario environment were analysed with regard to:

- surface temperatures and gradients across the brickwork;
- freeze-thaw cycles;
- rates of heating and cooling; and
- moisture content and driving rain deposition.

Although the test house is a low-rise building, many of the conclusions reached from the measurements reported below can be applied, with few modifications, to high-rise buildings.

RESULTS

Thermal Exposure

To provide results in a more generally applicable format, many of the results were converted to cladding temperatures relative to the air temperature. In a previous study of brick drying [Straube and Burnett 1995], it was also shown that the most important variable influencing the drying of brick veneers is the difference between the ambient air and the veneer surface temperature. The difference in temperature between the exterior air and the cladding surface was therefore studied in more depth.

The average cladding temperatures for the brick, EIFS, and vinyl walls for the month of February in both 1996 and 1997 were calculated. The average outdoor air temperatures over these two periods were -5.2 °C and -2.6 °C respectively. The differences between the average cladding temperature and the average air temperature are tabulated in Table 2. February was chosen as a representative cold month with a moderate amount of solar radiation.

Note that the south-facing brick wall was, on average, 7.3 °C warmer than the air temperature for the entire month of February 1996, while there was practically no difference between the air temperature and the white-coloured EIFS temperature. Previous studies [e.g., Straube and Burnett 1995] have also shown that the average temperature of dark-coloured brickwork veneers tends to be significantly above the ambient air temperature.

Orientation	**Brick** (dark red) (1996/1997)	**EIFS** (brown, 1997)	**EIFS** (white, 1997)	**Vinyl** (grey) (1996/1997)
North	3.3 / 5.1	2.3	1.7	-- / -1.1
South	7.3 / 6.7	2.5	0.1	-- / 0.0
East	3.1 / 4.5	1.1	-0.8	--
West	2.1 / 1.7	1.5	-0.3	--

Table 2: Average difference between ambient air temperature and cladding temperatures for February 1996/1997

Figure 1 provides more information in the form of a plot of the cumulative frequency of the hourly average temperature over the entire cold weather period (e.g. the six coldest months of the year). The brick temperatures are believed to be influenced by their moisture content. The conductivity and heat capacity both increase with moisture content, and evaporative cooling will decrease the temperature of drying bricks. The low driving rain exposure of the North exposure (see later) is believed to be one reason for its relatively high temperature.

The elevated average wall temperatures have a profound effect on the number and type of freeze-thaw cycles, space-heating energy consumption, the potential for and severity of condensation, and the drying capacity of the cladding. Freeze-thaw cycles and condensation are considered later.

Figure 2 compares the cumulative probability distribution of the hourly average temperature difference between the exterior air and the cladding surface for four different claddings: a standard dark brick veneer, a similarly coloured EIFS, a bright white EIFS, and a grey vinyl. The temperatures are clearly very different. The temperature differences shown above (i.e., in the order of 3 to 7 °C) suggest that a significant amount of drying (tens of kg/m^2/month) of the brickwork would be possible by evaporation from the front face and ventilation drying from the back face.

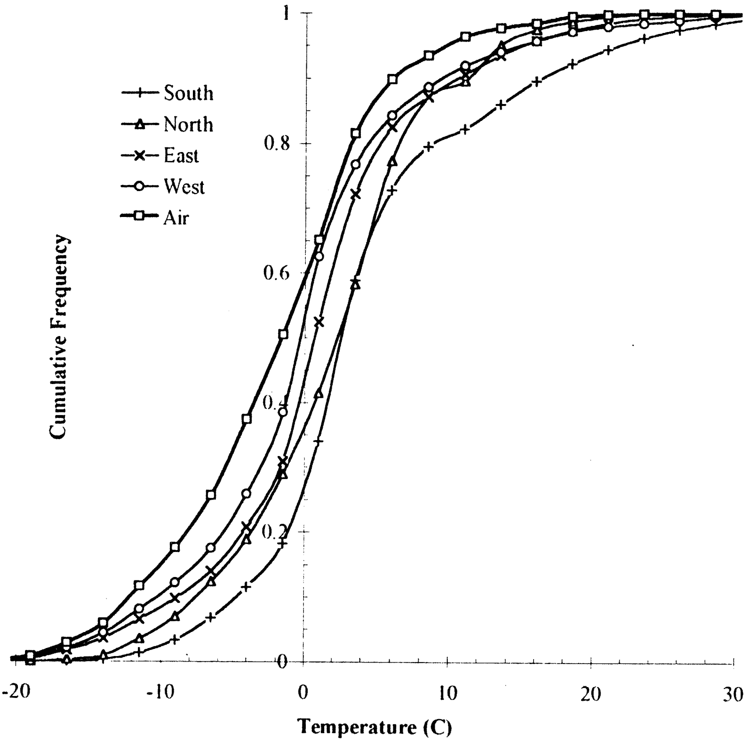

Figure 1: Cumulative Temperature Distribution of Brick Veneer over Winter Period (Hourly average values from October 31 to April 26, 1996)

The dark-coloured EIFS is an extreme example of a low mass system -- dark-coloured metal and vinyl claddings can be expected to behave in similar manner. Although the dark-coloured EIFS is cooler than the ambient for 75% of the time, it is more than 30 °C above ambient for 10% of the time. In fact, the temperature of the dark EIFS was more than 50°C above the air temperature during x% of the time! The sharp rise in distribution at -5 °C reflects the influence of solar radiation. Even a small amount of sun can drive the temperature significantly above ambient, while every night the temperature will drop below the air temperature because of night-sky radiation.

The brickwork was warmer on average than any of the lightweight claddings, but still was more than 15 °C above the air temperature 10% of the time. The white EIFS and vinyl cladding behaved in a similar manner, although the higher solar absorptance of the grey increased the solar-induced temperature rise.

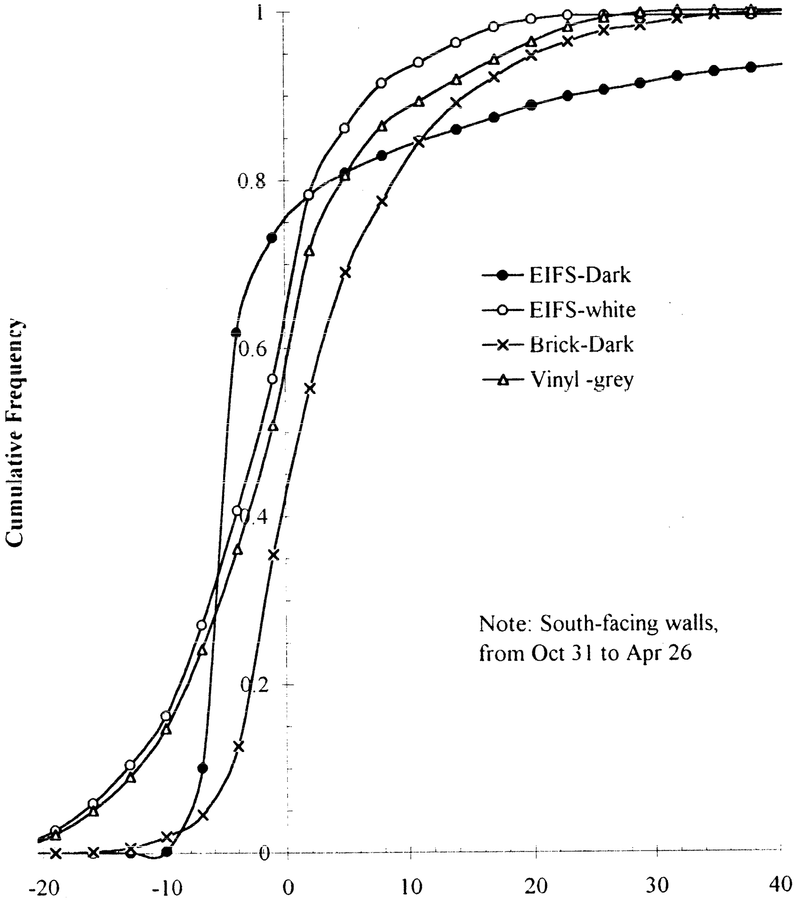

Figure 2: Cumulative Temperature Distribution of Different Claddings over Cold Weather Period

Daily Temperature Range. The daily range of temperatures provides a good indication of the magnitude of cyclic movements that joints and connectors should be designed for. During the winter the daily range of temperature experienced by the brickwork veneers is, on average, more than 10 °C and is often more than 20 °C. Each winter several days can be expected to have daily temperature ranges of more than 40 °C. The south-facing walls exhibit by far the highest temperature range and absolute temperature. The north-facing walls generally have only a few days with a temperature range of more than 10 °C. The east and west-facing walls fall mid-way between these extreme orientations.

The daily range of temperatures is almost as great during the summer. However, the west facing walls experience the highest temperature ranges, followed closely by the east walls. The south and north walls have much smaller daily ranges.

The temperature range experienced by the white-coloured EIFS was similar to that of the dark red brick, but colder during the winter. The lamina rarely exceeded 25 °C (whereas the brick occasionally exceeded 30 °C) but would drop below -20 °C occasionally. None of the brick veneers over an air space ever dropped below -20 °C although the exterior air temperature did. The daily range of the white-coloured EIFS was typically 15 °C, but the range occasionally exceeded 40 °C.

The dark coloured EIFS lamina behaved quite differently from the dark brick. Temperatures often reached 30 °C and occasionally exceeded 50 °C. On one cold February day, the dark-coloured finish exceeded 56 °C; the maximum temperature reached by the white finish the previous winter was just over 25°C. In both winters the coldest temperature was about -25 °C. The daily temperature range of the dark finish was often 30 °C and occasionally 60 °C.

These daily temperature ranges are what would be expected from calculations. Table 3 presents a summary of approximate expected radiation-induced wall surface temperatures. These values are intended for general design and assessment purposes. Perhaps the only surprise in Table 3 is that a thermally massive cladding like brick does not drop to, or below, the exterior air temperature because of heat storage from the previous day. Light-coloured or white-painted brick clearly will not absorb as much heat energy and will therefore approach the ambient temperature more closely. Maurenbrecher [Maurenbrecher 1995] found that the brick temperature occasionally fell below ambient air -- it is unclear if this was because of the more exposed location (on the 8th storey) or because of the lighter coloured brick (described as medium tan).

Table 3 also clearly shows the influence of solar absorptance. The darker the colour, the higher the temperature. Most red-brown brick veneers and dark brown or green EIFS and vinyl will have an absorptance of 0.75 to 0.85. Bright white would have an absorptance of about 0.20 and grey vinyl has an absorptance of about 0.40. Almost all building materials have an emmittance of about 0.90.

The values in Table 3 are valid for reasonably likely clear cold night minimums or clear sunny day maximums and apply to east/west orientations in the summer and south orientations in the winter. Thermally massive in the table refers to walls with a significant amount of thermal storage capacity (e.g., brick veneer or equivalent) outside of a low conductance material (e.g., insulation).

Walls with significantly more mass (e.g., multi-wythe brick, rubble) or less insulation ($U > 1\ W/m^2/°C$) will be less affected. Vinyl, metal, and EIFS are thermally lightweight claddings. The behaviour of wall types other than those in the table can be approximated by interpolating based on their heat capacity relative to brick veneer and vinyl.

Situation	**Thermally Massive Cladding (e.g., brick)**	**Thermally Lightweight Cladding (e.g., vinyl)**
Winter sun, south wall	$t_a + 35\alpha$	$t_a + 48\alpha$
Summer sun, east/west wall	$t_a + 28\alpha$	$t_a + 40\alpha$
Exposed to night sky, any orientation	$t_a - 3\varepsilon + 6\alpha$	$t_a - 3\varepsilon$

Table 3: Extreme daily radiation-induced wall surface temperatures (°C)

Notes: t_a refers to the ambient air temperature, ε is the surface emmittance, and α is the solar absorptance. All values are valid for approximately 45° North, i.e., most of Canada.

Heating and Cooling Rates. Another factor that affects the severity of exposure (e.g., freeze-thaw, expansion/contraction stresses) is the rate of heating and cooling. The rate of temperature change was calculated based on the difference between the temperature readings on either side of freezing, taken 60 minutes apart.

The cooling rates measured in the exposed brick-clad wall panels were, on average, about 0.5 to 1.5 °C/hour. However, cooling rates of 2 °C/hr and heating rates of 4 °C/hr were commonly experienced. The maximum hourly cooling rate measured while the brick was below 0°C was approximately 3 °C/hr, with a few walls recording maximums of almost 5 °C/hr. No pattern could be found to explain why some of the wall panels exhibited these high maximum cooling rates, although evaporative cooling of wet bricks likely played a role. It can be concluded that cooling rates of 5 °C/hr are extreme conditions for an insulated veneer wall while the brick is below 0°C. Cooling rates of 8 °C/hr might rarely be experienced by brickwork cooling down from warm (more than 20 °C) temperatures.

When the cooling rate was calculated on the basis of readings spaced only 15 minutes apart, the rates were higher, as expected. Peak cooling rates were in the range of 5 to 7 °C per hour (about 2°C more than when calculated based on one hour readings). Bear in mind that the 15 -minute temperature readings are the average of three temperatures taken

5 minutes apart. Therefore, the one-hour cooling rates are in fact based on two values, each the average of 3 readings taken at 5-minute intervals.

The south orientation exhibited the highest heating rates and cooling rates; heating rates of more than 10 °C/hr were often recorded. The east face had the next highest level of heating rates, and the west had the next highest cooling rates. The lowest heating and cooling rates were recorded by the north-facing veneer. The distribution of heating and cooling rates was affected little by whether the brick was above or below zero degrees. We expected that there would be a greater tendency for high rates of cooling when the brick temperatures were high because radiative and convective cooling mechanisms are much more effective with large temperature differentials. However, it appears that these effects, while important in assessing extreme rates, are not very significant for most of the time.

Implications for Standardised Freeze-thaw Testing. The CSA Brick Standard [CSA 1984] requires that the air temperature in the freezer reach -9°C within one hour of placing the brick samples into the freezer. The CBAC/IRC Industrial Research Fellowship studies [Arnott 1995] showed that it is unlikely that this requirement (a cooling rate of more than 29°C per hour) is met by commercial test labs. Also, the heat capacity of the bricks themselves is such that the cooling rate of the brick itself is less than 30 °C/hour even if the freezer air temperature is maintained at -20 °C. Nevertheless, the cooling rate as the bricks pass through 0°C is likely to be in the order of 20 °C/hr in a freezer test.

It is possible that the difference between the cooling rates applied in a lab test and the cooling rate actually experienced in the field would cause some durable bricks to fail the test. This is especially likely for bricks that have a low moisture diffusivity, because these bricks cannot redistribute moisture and freezing pressures as quickly as bricks with a high moisture diffusivity. This difference is moisture diffusivity might explain why highly absorbent bricks are sometimes found to be quite frost resistant.

The influence of each variable on brick damage needs to be explored in a controlled lab setting. The freezing rate, the freezing temperature, the temperature gradient, the moisture gradient, and, of course, the moisture content (degree of saturation) should be varied independently for similar bricks to assess the relative importance of each variable on freeze-thaw susceptibility.

Lightweight Claddings. The heating and cooling rates of the white-coloured EIFS lamina where practically the same as the red-brown brickwork veneers. However, the cooling rates were almost twice as high (often 5 °/hr and as high as 10 °C/hr) as the brickwork since the lamina has a very low heat capacity.

The dark-brown EIFS lamina experienced extreme heating and cooling rates. The rates were essentially four times the rates when the lamina was white. This result supports the estimation that the solar absorptance changed from 0.20 to about 0.80 when the EIFS surface was painted. Heating and cooling rates of 20 °C/hr occurred regularly, and rates of more than 30 °C/hr were observed over a dozen times during the winter of 1997. The cooling and heating rates were uniformly distributed, with a high cooling rate almost always following a high heating rate. Therefore, temperature cycles of 40 to 60 °C occurred over a short period of time (6-8 hours).

Freeze-thaw Cycles

Freeze-thaw cycles were counted for the period from October 1, 1995, to May 9, 1996. All of the winter freeze-thaw cycles occurred over this period. One freeze-thaw cycle was counted each time the exterior brickwork temperature dropped below 0 °C from some warmer temperature. This is the standard definition of freeze-thaw cycles. However, water in the pores of a brick is unlikely to freeze at 0 °C because of the reduced water pressure caused by surface tension attraction to the pore walls, the dissolved salts in the brick, and a number of other factors. Therefore, the number of cycles using, -4, -8 , -12, and -16 °C as the threshold were also counted. Table 4 summarises the number of freeze-thaw cycles as a function of orientation and temperature threshold for a brick veneer over a 30 mm wide airspace.

Orientation	**0°C**	**-4**	**-8**	**-12**	**-16**
South	70	37	21	6	3
East	71	47	26	11	2
West	71	59	36	18	6
North	46	34	19	9	0

Table 4: Freeze-thaw cycles over winter period as a function of orientation and temperature threshold

Note: Based on temperatures measured 10 mm from outer face of veneer.

The brickwork temperature of all orientations was primarily a function of the air temperature and solar radiation (the wall assembly behind the brick had little effect). The brickwork temperature was almost always above the air temperature. Therefore, while the air temperature dropped below -20 °C on several occasions, the brickwork never did. Some of the test panels were built with cavities fully-filled with insulation. Some of these walls did experience temperatures as low as -25 °C. It is believed that these lower temperatures are related to the occasionally higher moisture content of this brickwork.

The number of typical freeze-thaw cycles was 70 to 71 for the south, east and west-facing walls. The north wall experienced only 46 cycles. Others have also found the north face to have the least number of freeze-thaw cycles [Ritchie and Davidson 1968]. During periods of prolonged cold weather, the north wall—and to a lesser degree the east and west walls—experienced fewer cycles; the brick in these walls remained frozen. On the other hand, in warmer late fall and early spring weather, the north wall experienced more cycles.

Although the number of cycles was almost the same for both the interior and exterior temperature sensors in the brick, the interior was always less.

The number of cycles at lower temperatures was significantly lower, and the distribution of cycles with orientation was different. Even for the -4 °C threshold, the west face experienced significantly more freezing cycles than the east, and the east more than the south, which was similar to the north. The prevailing west winds and moisture content of the brickwork likely play a role.

Note that the standard CSA [CSA 1984] freeze-thaw durability test cools the brick to -20 °C for 50 cycles. None of the cycles approached this temperature, despite the frequently cold weather. Using the -16 °C threshold, one might suggest that the CSA test would be similar to 8 years of exposure on the west face of the Beghut and 25 years on the east face. However, the meaning of the -20 °C freezing temperature in the standard is apparently arbitrary, is climate independent, and should perhaps be re-examined in light of the different Canadian climate zones.

Temperature Gradients. All of the walls in this project were well insulated inside the cladding. Therefore it would be expected that heat flow through the conductive brick veneers would result in very small temperature gradients. However, because of dynamically varying exterior surface temperatures (solar heating) and the heat storage capacity of brick, the temperature gradient across the brickwork was found to be significant. Temperature sensors on the vinyl and EIFS cladding did not measure gradients across these thin materials.

The monitoring results suggest that very small gradients exist across the brick except during solar heating. Normally the temperature difference between the inner and outer sensors (located 65 mm apart, 10 mm inside of each face) was about 2-4°C, but under rapid solar heating the difference could be as much as 15 °C. The gradients were less when the brick was frozen; the maximum difference was then less than 10 °C for most of the time.

No systematic difference between the different orientations (except as noted above) or panel types was observed.

Moisture Content and Driving Rain Deposition

Some indication of the moisture content is of great interest because, when combined with temperature conditions, it allows the freeze-thaw susceptibility to be assessed. However, the in-situ moisture content of brickwork is difficult to measure accurately. Resistance-based moisture pins and gravimetric measurement of brick cores were employed to assess moisture content.

The moisture pins could only indicate relative moisture content. Exploratory lab tests found that the resistance dropped sharply (by two to three orders of magnitude) when an initially dry brick was wetted. Unfortunately, each individual brick gave unique readings and different readings on different days. Although strong patterns could be discerned (e.g., rain wetting and solar drying) the data is not presented here because of its qualitative nature.

The gravimetric measurements showed that the brick was usually significantly below the 24 hr cold water saturation moisture content and that the inside face was usually wetter than the exterior in cold weather. Values ranged from 3 to 40% of saturation. It is believed that freeze-thaw damage is unlikely below 90% saturation.

A total of 14 driving rain gauges are mounted on the four faces of BEG's test house. The east and west elevations of the building have six gauges each; the north and south have one each. The total driving rain captured by the rain gauges for the 245 day-long period from March 1 to October 31 was analysed. The actual amount of rain collected in the middle of each orientation is plotted as a function of season in Figure 3. These values do not include freezing rain or rain during the winter because such rain is difficult to measure.

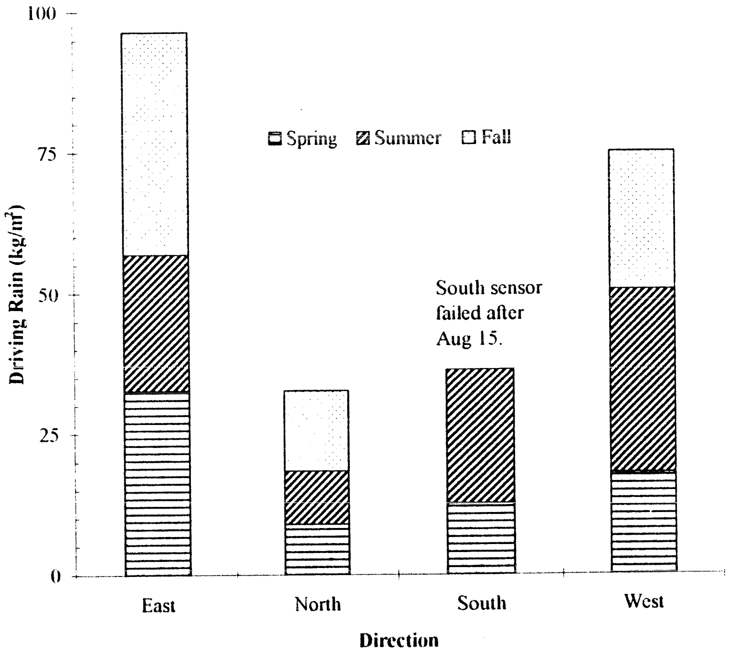

Figure 3: Driving Rain Deposition as a Function of Direction and season

The east face clearly receives the most driving rain, almost 100 kg/m^2/year, while the north face receives one-third as much (30 kg/m^2/year). The seasonal distribution is also interesting. The west face receives the most in the summer, while the south face receives almost as much as the east and west in the summer.

The data in Figure 3 is highly dependent on local climate and wall exposure. While the results are likely representative for low-rise buildings in areas with 900 mm of annual precipitation, wet and windy climates such as Halifax and Vancouver can expect 2 to 3 times this deposition, and tall buildings are expected to be exposed to 2 to 4 times as much driving rain. These much larger quantities of driving rain are expected to result in much higher brick moisture contents for longer periods of time than measured in this project.

IMPLICATIONS FOR DESIGN AND TESTING

Several important conclusions, valid for South-western Ontario and probably much of Canada, can be drawn from the information reported.

- On average, red or brown brick veneers will remain considerably (3 to 7 °C) above ambient temperatures in the winter time, depending on their orientation and solar shading. The lamina of dark-coloured EIFS will be warmer than the average ambient air, by perhaps 1 to 3 °C, and light-coloured vinyl and EIFS lamina will remain close to the air temperature.

- The number of freeze-thaw cycles varies significantly with orientation and with freezing temperature. None of the brick veneers over an air space experienced a single -20 °C freeze-thaw cycle (e.g., CSA brick standard) over two South-western Ontario winters.

- The heating and cooling rates for the brickwork were typically in the order of 5 and 3 °C/hr respectively, with maximum values of about 10 and 5 °C/hr. These rates are much less than those used in the CSA freeze-thaw durability test.

- Temperature gradients of as much as 15 °C can exist across a well-insulated brick veneer during solar heating. Below 0 °C gradients are more likely to be less than 5 °C.

- The daily temperature range experienced by the surface of a white-coloured EIFS will be almost the same as that of dark brick veneer. If the EIFS is also dark coloured, the temperature range will be much greater than the brickwork, with daily cycles of 40 to 60°C. Heating and cooling rates of 30 to 40 °C/hr will also be experienced. Seasonal extremes of -30 to +70 °C should be accepted as typical for dark-coloured, lightweight claddings in most of Canada. The lower figure is likely -50 °C for colder regions, e.g., the Prairies.

- The temperature of lightweight claddings will often drop about 3 °C below the temperature of the air at night because of night-sky radiation, while dark and heavyweight claddings will usually remain several degrees above the air temperature.

The results of the monitoring have provided valuable information regarding the number and nature of freeze-thaw cycles, the powerful influence of sun and orientation, the difference in behaviour between thermally heavy and thermally light cladding, and the influence of cladding type and colour on overall wall behaviour. It is hoped that this research will be useful for the interpretation and development of freeze-thaw tests, assessing the energy use of masonry clad enclosures, and for designing joints for thermal movements.

ACKNOWLEDGEMENTS

This research is part of the In-Service Performance of Enclosure Walls Project. The support, technical input and funding of the seven corporate partners (Brampton Brick, Canada Brick, Celfortec, Durisol Materials, Owens-Corning Canada, Roxul Insulations, and Sto Corporation) has been invaluable and is gratefully acknowledged. The Ontario Government also provided funding through the University Research Initiative Fund.

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