# PERFORMANCE ASSESSMENT OF TIM-ENVELOPES

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## ABSTRACT

During the past two decades, pressure on the building industry increased gradually. Energy efficiency, indoor air quality, comfort, durability, sustainability all became key issues within a framework of growing cost awareness. Hence, this multiplication of issues emphasized the need for a new methodology to assess building quality, called the performance concept. This paper uses performances to evaluate an advanced building envelope system: transparent insulation (TIM). But first, the performance concept itself is clarified and a performance array for hygro-thermal evaluation proposed, from the building down to the envelope. This array is then used to analyze the TIM-choice. The study shows that performances not only are a tool when evaluating an envelope solution but also help in improving it.

## KEY WORDS

Performance based design, transparent insulation, U-value, transient response, hygro-thermal stress and strain, moisture response

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## 1 INTRODUCTION

During the past two decades, energy efficiency, indoor air quality, comfort, durability, sustainability all became key issues for the construction industry. This multiplication of issues compelled the sector to consider a new approach towards integral quality assessment: the performance concept. “Performances” concern all physical qualities of a building construction, which can be expressed in a numerical or at least exact way and are predictable at the design stage and controllable during and after construction [1][2]. Performances figure as a translation of the interactions between user and society demands at one side and construction technology and building services at the other. In fact, buildings should be designed, constructed and equipped in a way user and society demands are fulfilled to an optimum degree. This interaction leads to a performance pyramid, from the performances at building level (level 1) down to the component (level 2), the layer (level 3) and the material (level 3). Most arrays go top down, a clear example being energy efficiency, see Table 1.

*Table 1 Energy efficiency*

| Level | Energy performances |
|---|---|
| 1 | the building should consume less than x kWh/(m².a) for HVAC, hot water production, lighting and appliances per gross floor area |
| 2 | translation of the level 1 performance into U-values for the envelope, heating efficiencies, window to opaque wall ratio’s, etc. |
| 3 | a U-value means an insulation layer with a thermal resistance y, a threshold for the heating efficiency dictates boiler performance, etc. |

## 2 EXAMPLE OF A PERFORMANCE ARRAY

In general, the reference array combines functionality, structural integrity, building physics, fire safety, service life, sustainability and economy. As an illustration, Table 2 gives the level 1 performances related to the heat and mass transfer part within building physics. Table 3 translates this set into level 2 hygro-thermal performances for TIM-envelopes. Although performance description may be the result of international cooperation, performance requirements differ substantially between countries as a consequence of climate, building tradition and politics.

*Table 2 Level 1 performances, building physics, heat and mass transfer*

| Field | Performances |
|---|---|
| Heat and Mass Transfer | Energy consumption for heating and cooling |
| | Winter thermal comfort and summer overheating |
| | Indoor air quality |
| | Humidity response |

*Table 3  Level 2 hygro-thermal performances of TIM envelope parts*

| Performance | Description and/or comments | Requirement |
|---|---|---|
| 1. air-tightness | Lack of air-tightness affects insulation quality, thermal comfort indoors, moisture response, acoustical insulation, etc. | 1. Air permeance<$10^{-6}$ s/m for $\Delta P_a$=10 Pa<br>1. $\Delta E$ by stack flow around the TIM-layer $\leq 0.1\|E\|$, $\|E\|$ being the average heat flow per unit surface, unit time and unit temperature difference and $\Delta E$ the stack flow induced increase |
| 2. U-value, Energy number E | For TIM, U is not a correct measure for energy efficiency. Use for that purpose E (definition above). | 2. E should tend to as much gain as possible |
| 3. Transient response | In climates with large diurnal temperature differences, the transient response fixes warm weather comfort and energy consumption for cooling. | 3. TIM may neither degrade summer comfort (more than 150 weighted temperature excess hours per year), nor increase the energy consumption for cooling |
| 4. Hygro-thermal stress and strain | Introduces durability and service life in a TIM-wall evaluation. | 4. Cracking risk in the load bearing construction behind TIM should be less than 5% within normal service life |
| 5. Moisture response | Relates to liquid and vapor transport. Moisture endangers thermal insulation quality, energy efficiency, durability and service life | 5. no rain penetration<br>6. risk on construction moisture drying longer than 1 year, less than 5%<br>7. risk on accumulation of concealed condensation less than 1%, risk on a yearly maximum above acceptable limits less than 5%<br>8. risk on a monthly average surface relative humidity (RH)>80% less than 1%, risk on surface condensation on a cold day with one per year frequency, less than 5% |
| 6. Thermal bridging (TB) | Thermal bridging degrades the insulation quality of an envelope. It promotes surface pollution, mold growth, surface condensation and local cracking. | 9. Thermal bridging should not increase the average U-value with 10% or more<br>10. temperature ratio>0.7 |

## 3 ASSESSING TIM-ENVELOPES

Application of TIM leads to various wall solutions. A simple choice consists of mounting TIM against a massive wall (Figure 1). Another possibility is to leave an air space between the TIM layer and the wall and to use this for pre-heating the incoming ventilation air or cooling the massive wall with outside air. Adding an opaque insulation layer at the cavity side of the massive wall makes preheating faster and more efficient. Some put the opaque insulation at the inside and insert a network of water pipes in the massive wall. Coupling these pipes to a cold water inlet and a sanitary hot water tank allows to use solar energy for preheating the sanitary hot water, while cooling the wall [3]. Here, the simplest solution, the TIM-massive wall combination, is discussed.

### Hygro-thermal properties of the TIM-insulation

The TIM material considered is a capillary PMMA type, with a mean radius of the capillaries of 3 mm. Density followed from weighting various samples with known dimensions. Thermal conductivity was measured as a function of mean temperature and thickness of the board. Also solar transmissivity underwent testing, as was vapor permeability and air permeability of the material wrapped in PMMA-foil. Results: see Table 4. Figure 2 illustrates the relation between thermal conductivity and thickness at 10°C. The sharp increase of $\lambda$ between 10 and 50 mm illustrates the important impact of infrared radiation on the heat transfer through the capillary TIM [4][5][6][7].

*Table 4 Hygro-thermal properties of capillary PMMA TIM*

| Property | Value | $s_d$ |
|---|---|---|
| Density ($kg/m^3$) | 30.5 (39 samples, minimum: 28.5, maximum 34.2) | 1.4 |
| Thermal conductivity (W/(m.K))<br>*parallel to the capillaries*<br>*orthogonal to the capillaries* | <br>$0.0956-0.0722\exp(-30d)+(0.00074-4.4\ 10^{-6}/d)\theta$<br>$0.0523+0.000328\theta$ (d thickness in m) | |
| Solar transmissivity | $0.954-1.71d$ (5 points, $d<0.12$ m, $r^2=1$) | |
| Vapor permeance (s/m)<br>(foils at both sides of the TIM) | $2.1\ 10^{-12}+2.7\ 10^{-14}\exp(4.65\phi)$ with $\phi$, relative humidity, a fraction of 1 | |
| Air permeance (s/m)<br>*with surface foil*<br>*without surface foil* | <br>$1.6\ 10^{-5}\Delta P_a^{-0.14}$<br>0.25 | |

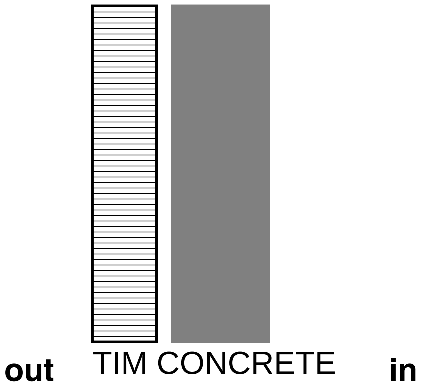

*Figure 1 TIM-massive wall combination*

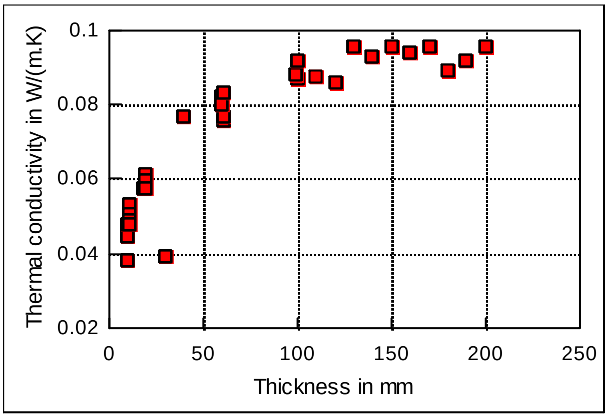

*Figure 2 TIM, $\lambda$ as function of thickness, $\theta_m=10$°C*

**Air-tightness**

TIM-elements need an exterior glass protection. Hence, as glass acts as a perfect air barrier, in- and exfiltration through the elements is of no concern. This however is not true for air rotation. If the TIM-layer is not pressed against the glazing and an air space is left between TIM and the massive wall, then the air permeable TIM and/or the joints between the individual boards allow buoyancy induced air flow around the TIM-layer. Following example underlines the importance of the phenomenon [8]. A 10 cm thick TIM-insulation without foiled surfaces is sandwiched between an 8 mm thick single glass panel and a 9 cm thick concrete block wall. Width of the cavity at both sides of the TIM: 20 mm. All joints between the TIM-boards and the boards and the frame are perfectly closed. Figure 3 gives the calculated 2D temperature profile in the wall for an outside temperature of 0°C, an inside temperature of 20°C and no solar gains. Average U-value: 1.85 W/(m².K) and not 0.51 W/(m².K) as could be expected without air rotation, i.e., an increase of 263% by buoyancy induced flow alone! The U-value of the wall without TIM is 2.4 W/(m².K), only 30% higher than with TIM. If instead, a 10 cm thick TIM-layer with foiled surfaces and taped joints was used, the temperature profile should look as depicted in figure 4. Temperature difference over the TIM 14.6° instead of 5°C and a U-value of 0.51 W/(m².K), i.e. no loss by air rotation.

The consequences of buoyancy were clearly seen in a SW-oriented test wall with identical construction as the wall above. Figure 5 compares the measured glass temperature at the top with the calculated value without air rotation, the last being systematically lower. This is only possible if at the top warmer air is projected through the TIM against the exterior glass panel.

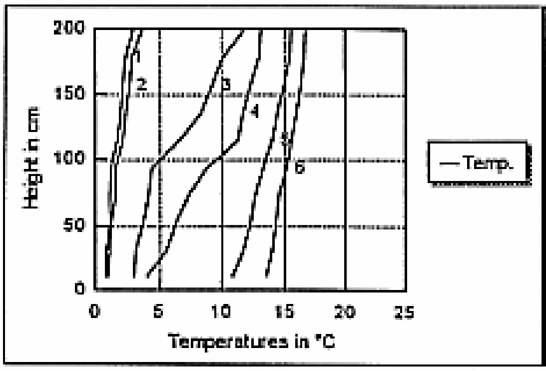

*Figure 3 TIM+massive wall, temperature profile with buoyancy induced air rotation*

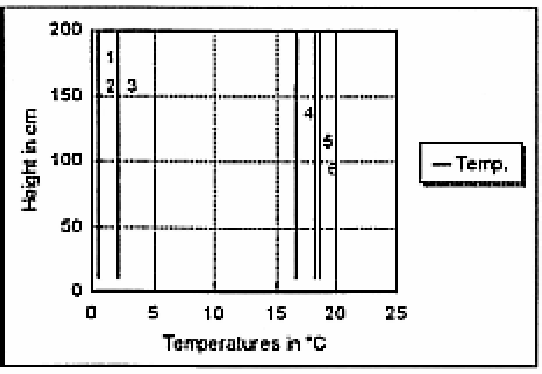

*Figure 4 TIM+massive wall, temperature profile without air rotation*

1:glass outside 2:glass inside 3: TIM outside 4: TIM inside 5:concrete outside 6:concrete inside

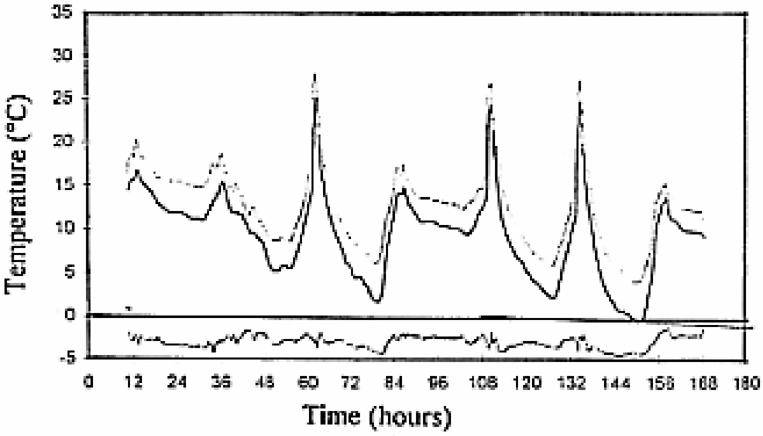

*Figure 5 TIM test wall, measured versus calculated outside surface temperature at the top of the exterior glazing panel. Dark line: calculated, light line: measured, line below: difference between both*

**U- and E-value**

Application of the U-formula on a wall, composed of TIM-elements and a massive inside concrete layer with thickness 18 cm, gave the results of table 5, column 2 (mean temperature in the boards 10°C). Column 3 compares the data with the U-value of an identical wall insulated with a rendered mineral fiber (MF). The use of 10 cm TIM results in a 123% higher U. For 20 cm, the increase even reaches 147%! As stated, however, U is not a correct measure to judge the efficiency of TIM. One should instead evaluate the energy number E, defined above, on a heating season mean basis under the assumption that all gains are effective. In a TIM-wall, solar radiation is injected at the concrete surface, while long wave losses depart from the exterior surface. Steady state heat balances:

*Concrete surface*

$$\frac{\theta_i - \theta_1}{R_1} + \frac{\theta_{se} - \theta_1}{R_{2,\,TIM}} + \tau_{glass}\tau_{TIM}a_{con}q_s = 0 \qquad [1]$$

*Outside surface*

$$\frac{\theta_1 - \theta_{se}}{R_{2,\,TIM}} + \frac{\theta_e - \theta_{se}}{R_e} - e_{Lglass}q_{LW} + a_{glass}q_s = 0 \qquad [2]$$

$R_1$ stands for the thermal resistance from inside to the TIM-oriented concrete side, $R_2$ for the thermal resistance from this surface to the exterior surface and $R_e$ for the outside surface film resistance. $\tau_{glas}$ is the solar transmissivity of the outside glass panel, $\tau_{TIM}$ the solar transmissivity of the TIM-layer , $a_{con}$ the solar absorptivity of the concrete surface, $e_{Lglas}$ the long wave emissivity of the outside glass panel and $a_{glass}$ the solar absorptivity of the outside glass panel. Solving this system of two equations per month gives the concrete ($\theta_1$) and outside surface temperature ($\theta_{se}$) temperature. The first is needed to calculate the average E on heating season basis:

$$E = \frac{1}{(\theta_i - \theta_{em})\sum_{j=1}^{6} n_j}\sum_{j=1}^{6}\left[\frac{(\theta_i - \theta_{1j})n_j}{R_1}\right] \qquad [3]$$

In this formula, $n_j$ are the number of days per month, $\theta_{1j}$ the monthly mean temperature of the concrete surface and $\theta_{em}$ the heating season mean outside temperature. In the MF-wall solar radiation is absorbed and long wave radiation emitted at the outside surface. Balance:

$$\theta_{se} = \frac{\dfrac{\theta_i}{R_{i,\,se}} + \dfrac{\theta_e}{R_e} + a_e q_s - e_{Le}q_{LW}}{\dfrac{1}{R_{i,\,se}} + \dfrac{1}{R_e}} \qquad [4]$$

E in turn is calculated with formula 3, with $\theta_{se}$ instead of $\theta_1$ and $R_{i,se}$ instead of $R_1$. Columns 4 and 5 of Table 5 give the results for a south and north oriented wall, the MF-alternative with a dark surface (long wave emissivity 0.9). Reference year: monthly TRY for Ukkel, Belgium (51°

North). Inside temperature: 21°C. The table proves that even a north oriented TIM-wall is more energy efficient than the mineral fiber alternative. Its use south results in a net heat gain, independent of thickness. This is never the case for the MF-wall. However, once TIM is thicker than 10 cm, net gains stabilize.

*Table 5: U-value of a TIM-insulated wall in comparison with a MF-insulated wall, same insulation thickness*

| Insulation thickness cm | U with TIM W/(m².K) | U with MF W/(m².K) | E with TIM W/(m².K) | E with MF W/(m².K) |
|---|---|---|---|---|
| South | | | | |
| 6 | 0.91 | 0.48 | -2.47 | 0.39 |
| 10 | 0.69 | 0.31 | -2.71 | 0.26 |
| 14 | 0.55 | 0.23 | -2.78 | 0.19 |
| 20 | 0.42 | 0.17 | -2.72 | 0.14 |
| North | | | | |
| 2 | | | 0.71 | 1.03 |
| 20 | | | -0.24 | 0.17 |

Of course, gains are not all effective. Part may be used to overheat the building. This is taken into account by handling a TIM-efficiency $\varepsilon_{TIM}$:

$$E_{eff} = \varepsilon_{TIM} E \qquad [5]$$

with $\varepsilon_{TIM}$ between 1 and 0. 1 means all net gains effective, 0 no usable gain at all [9][10]. In any TIM-application, the first m² show the highest efficiency, with a steady decrease for each m² extra. This leads to the concept of an optimal TIM-coverage: the TIM-area above which the efficiency of the next m² is 0. An example is given in Figure 6. It concerns an energy conscious dwelling with average U-value 0.34 W/(m².K). The optimal TIM-coverage reaches 60% of the opaque facade. More does not produce any additional benefit. An increase, however, of the average U of the dwelling lifts this optimum, see Table 6. The table summarizes the heating demand with and without TIM for the three cases: (1) the reference, (2) the dwelling with the highly insulated facade exchanged for a filled cavity wall and (3) the dwelling without any insulation. TIM delivers the highest benefit in absolute terms for the non-insulated case. In percentage however, the best result is realized if all other envelope parts except the facade are well insulated. Figure 5 and table 6 does not consider buoyancy induced air rotation. One must be aware of its detrimental effects on the energy gain per m² TIM. The measurements on the experimental wall, commented under Air-Tightness, showed that, contrary the average gain of 13.4 W/m² one should have noted

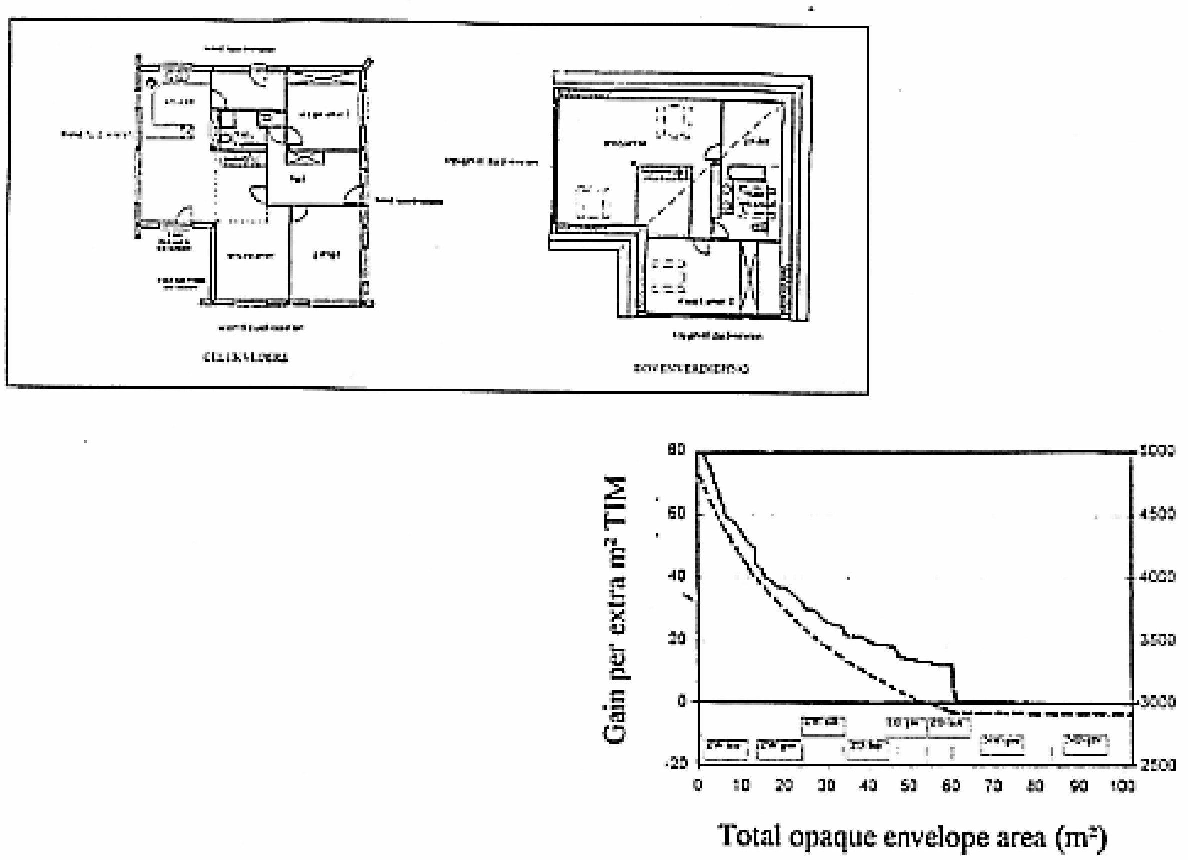

*Figure 6 First and second floor of the dwelling under consideration, decrease in heating demand as function of the opaque facade area, covered by TIM (line=gain per extra m² TIM in kWh/a, points: total heating demand in kWh/a)*

*Table 6 Decrease in energy demand for heating with TIM for the dwelling of Figure 5 (TRY for Ukkel, Belgium)*

| Dwelling<br>$A_{floor}$ =128.8 m²<br>$A_{envelope}$ =326.2 m²<br>Volume =562 $m^3$<br>Compactness =1.23 m<br>Ventilation rate=0.5 $h^{-1}$ | 1<br>$U_m$ without TIM<br>W/(m².K) | 2<br>$E_{net}$ without TIM<br>kWh/a | 3<br>$E_{net}$,opaque facade 60% TIM-covered<br>kWh/a<br>ΔE/E in % | 4<br>$E_{net}$,opaque facade 100% TIM-covered<br>kWh/a<br>ΔE/E in % |
|---|---|---|---|---|
| Base case: insulation of the envelope as planned ($U_{opaque\ fac}$=0.22 W/(m².K)) | 0.34 | 4830 | 2920<br>*-39.5%* | 2910<br>*-39.8%* |

| | | | | |
|---|---|---|---|---|
| Reference: facades=filled cavity walls ($U_{opaque\ fac}$=0.5 W/(m².K)) | 0.42 | 5900 | 3230<br>*-45.3%* | 2910<br>*-50.7%* |
| Reference: no insulation (i.e envelope not insulated, single glazing) | 2.45 | 29800 | 20300<br>*-31.9%* | 16100<br>*-46%* |

between 8 and 15 October 1992, an average loss of 5.7 W/m² was registered at the bottom of the test wall and a gain of only 5.6 W/m² at the top [8]

One conclusion is clear: TIM produces a net gain on heating season basis. This could result in a substantial reduction of the energy consumption for heating, as other authors confirm [11]. The condition however is that no buoyancy induced air rotation around the TIM-layer develops. Hence, in all applications, one should at least cover one side with an airtight foil.

### Transient response

Evaluating the transient response as envelope performance is quite senseless. What matters is the response at zone level. There, the envelope inertia is only one of the parameters. Glass surface, glass orientation, solar protection, ventilation strategy and inside wall thermal capacity are far more important. Of course, a high periodic temperature damping $D_\theta$ (ratio between outside and inside temperature amplitude on a 24 hours basis), a high dynamic thermal resistance $D_q$ (ratio between the outside temperature amplitude and the inside heat flow rate amplitude on a 24 hours basis) and a high admittance Ad (ratio between the inside heat flow rate amplitude and the inside temperature amplitude on a 24 hours basis) are never negative. For TIM-walls, two values per property intervene, one for the wall with and one for the wall without insulation, but with as exterior surface film resistance the total thermal resistance between the outside and the massive part. The first value informs on damping the periodic outside temperature, the second on damping in relation to solar gains. Table 7 gives the calculated results for a TIM element in combination with an 18 cm thick concrete wall. Supposing a daily outside temperature amplitude of 10°C, the (hypothetical) inside temperature amplitude if only TIM-walls were used is 10/36.5=0.3°C. 100 W/m² incident solar radiation at the other hand causes an inside temperature amplitude of 0.84x0.9x0.9x100/(0.8x36.3)=2.3°C, while a MF-wall only gives 0.9x100/(23x36.5)=0.1°C. Heat flow rate amplitude: 11 W/m² for TIM and 0.6 W/m² for the MF-choice. Or, applying TIM clearly increases the risk on overheating. This is illustrated in Table 8, where the living room in the dwelling introduced above has been evaluated as constructed

(Volume of 131 m$^3$, $U_{facade}$=0.22 W/(m².K), $A_{facade}$=39.4 m², $U_{window}$=1.8 W/(m².K), $A_{window}$=14.3 m², $A_{floor}$=58.8 m²) and with the SW-facade exchanged for a 25 m² ‘10 cm TIM-18 cm concrete’ wall [9]. The calculations were done with the code ‘Capsol [12] for the week of July, 21 to 27, Ukkel-TRY, Belgium.

*Table 7: Harmonic properties of a TIM-insulated wall on day basis (first row per thickness: temperature-related, second row: solar gain-related)*

| Insulation thickness cm | $D_q$ m².K/W | Fase-shift h | $D_\theta$ - | Fase-shift h | Ad W/(m².K) | Fase-shift h |
|---|---|---|---|---|---|---|
| 2, $h_e$=23 W/(m².K) | 2.7 | 6.3 | 15.6 | 7.2 | 5.8 | 0.9 |
| $h_e$=1.9 W/(m².K) | *2.7* | *2.7* | *15.5* | *3.3* | *5.8* | *0.9* |
| 10, $h_e$=23 W/(m².K) | 6.2 | 6.8 | 36.5 | 7.7 | 5.9 | 0.9 |
| $h_e$=0.8 W/(m².K) | *6.2* | *2.7* | *36.3* | *3.3* | *5.8* | *0.9* |
| 20, $h_e$=23 W/(m².K) | 11.0 | 7.5 | 64.7 | 8.4 | 5.9 | 0.9 |
| $h_e$=0.5 W/(m².K) | *10.7* | *2.7* | *63.2* | *3.3* | *5.8* | *0.9* |

*Table 8: Mean and maximum temperatures in the living room (dwelling Figure 5)*

| Living room | mean temp. °C | max. temp. °C |
|---|---|---|
| Actual construction | 28.7 | 34.3 |
| +solar protection outside the windows | 23.1 | 26.4 |
| + capacitive construction | 21.6 | 23.4 |
| Actual construction, SW=TIM | 33.8 | 39.8 |
| +solar protection in the TIM-elements | 28.4 | 33.4 |

Severe overheating in the TIM-case is obvious. Inclusion of a solar protection in the elements re-establishes the original transient response. Translate this in: a TIM-wall with solar protection reacts more or less like an opaque wall.

To conclude, the energy gains TIM delivers are accompanied by an unacceptable increase in overheating risk during springtime, summer and autumn. To avoid this, expensive measures are needed, such as including a solar protection in the TIM-elements. An alternative may be cooling the cavity between TIM and massive wall with outside air. A simplified analysis learns that this policy may reduce the heat gains with some 50 to 70%.

### Hygro-thermal stress and strain

When judging hygro-thermal stress and strain, two periods are of importance: annual and diurnal. The annual temperature differences in a wall have as main consequence expansion and shrinkage, the diurnal differences bending. With a MF exterior insulation the temperature difference on annual basis in the massive construction does not pass 10°C, while the diurnal gradient is restricted to some 1.0 to 1.5 °C. As a consequence, cracking, if observed, is most probably the result of initial shrinkage, mechanical loading and settling but not of temperature nor relative humidity variations. With TIM however, the picture changes completely. The annual temperature differences become second hand compared to the diurnal gradients, as shown in figure 7. This figure gives the measured temperatures at the inner and outer surface of a light weight concrete inside leaf in a SW oriented TIM-wall on a sunny winter day (15 January 1991) [see 12].

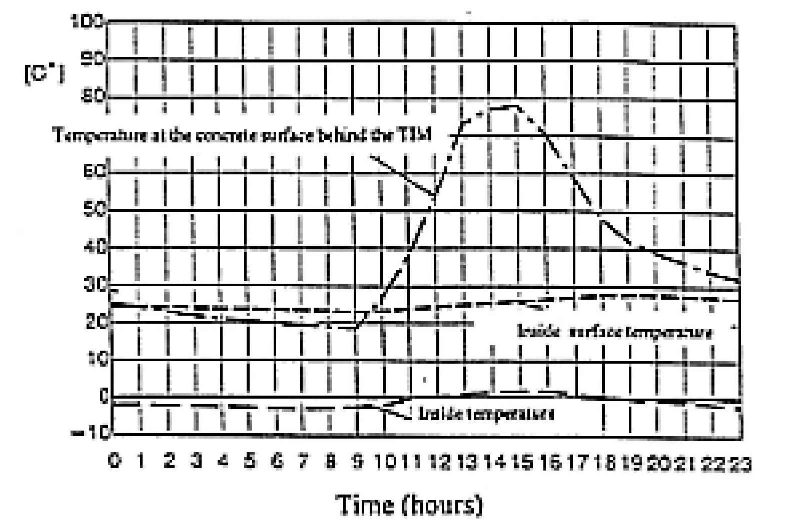

*Figure 7 Temperatures at the inner and outer surface of a light weight concrete leaf behind a TIM-insulation*

A maximum difference between both sides of 60° to 65°C is noted. Temperature profiles in the wall also change continuously. As a consequence, the leaf tends to expand or shrink and bend at any moment. Even if the strain develops in an unrestricted way, the non-linearity of the temperature gradient, see figure 7, induces eigen-stresses. These are proportional to the product $E\alpha$, with E the modules of elasticity of the material and $\alpha$ its thermal expansion coefficient. Cracking starts where these eigen-stresses equal the tensile strength of the wall. Hence, the lower the tensile strength $\sigma_{fr,t}$ or the more it degrades by fatigue, the higher the risk. Risk also increases with the degree of hyperstaticity when hindered deformation adds expansion/shrinkage and bending stresses to the eigen-stress.

One may conclude that cracking in a massive wall behind a TIM-layer becomes more probable as far as (1) the massive wall has a higher degree of hyperstaticity, (2) the material has a lower $\sigma_{fr,t}/E\alpha$-ratio, (3) temperature gradients are steeper and less uniform. Due to the lower average relative humidities (see moisture balance), also initial shrinkage increases compared to a wall with opaque exterior insulation. This further enhances cracking risks. Long-term measurements on a TIM-wall at the Universität Stuttgart confirm these conclusions [12]. Cracks degrade the aesthetics. They also jeopardize the vapor resistance and diminish the air tightness of the massive wall.

Heat gains apparently not only cause additional overheating but also increase the cracking risk. The last effect cannot be eliminated by a selective use of solar protection. The only way to minimise is by applying materials with restricted shrinkage and a low thermal expansion coefficient for the massive wall and by reinforcing it to increase the tensile strength.

### Moisture response

With TIM, rain protection and rising damp measures are in no way different from what is needed in other envelope solutions. Drying of construction moisture, hygroscopic equilibrium of the massive wall and interstitial condensation risk however are quite specific. This is coupled to (1) the higher temperatures in the massive wall behind the TIM-layer in comparison with a wall with opaque outside insulation, (2) the presence of an absolute vapor barrier, i.e. the glass panel, at the outside and (3) the restricted solar absorption by the glass panel.

Higher temperatures in the massive wall accelerates construction moisture drying, when compared to a wall with opaque outside insulation. If, however, the massive part is not tightened at the TIM-side by a high quality vapor retarder, condensation of construction moisture in the TIM-part is obvious (figure 8). Where and how depends of the way the TIM-layer is shielded from the wall. If for that purpose a glass panel is inserted, then some condensate will collect against it without any moisture deposit in the TIM layer. If such absolute shielding is absent, condensation shifts to the TIM layer and the exterior glass panel. The accompanying moisture deposits diminish the overall transmissivity. The water in the capillaries also raises the thermal conductivity of the TIM-material, while run off at the exterior glass-panel may wet the TIM-frames. Once TIM gets damp, it hardly dries, as was seen in the experimental set up, commented under the U- and E-value. Solar absorption at the massive wall’s surface in fact has as negative consequence that even in summer the temperature gradient in the TIM points to the outside. This hampers the moisture from evaporating back to the massive wall.

After a number of years, the wall reaches hygroscopic equilibrium. For an indoor climate class 3 situation (mean annual vapor pressure inside 1500 Pa, inside temperature 21°C) and the Ukkel TRY, this equilibrium scatters around 35% RH, i.e. a moisture ratio of 1%kg/kg in the case of concrete. With an opaque outside insulation, the equilibrium shifts to 55% RH, i.e. 1.5%kg/kg. The consequences were already commented under hygro-thermal stress and strain

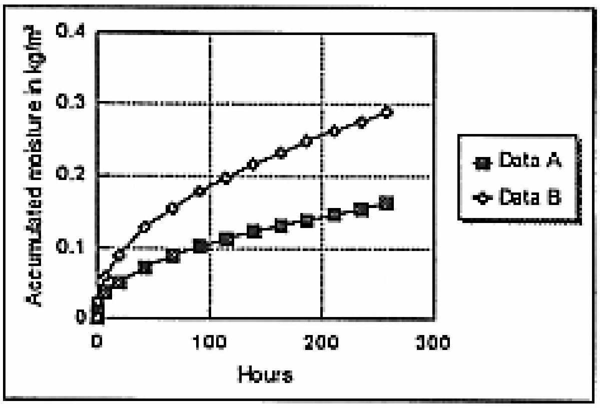

*Figure 8 Condensation of construction moisture in the TIM for a wall, where drying starts in January (Data A), drying to the inside (Data B) (Indoor Climate Class 3, $\theta_i$=21°C,TRY for Ukkel)*

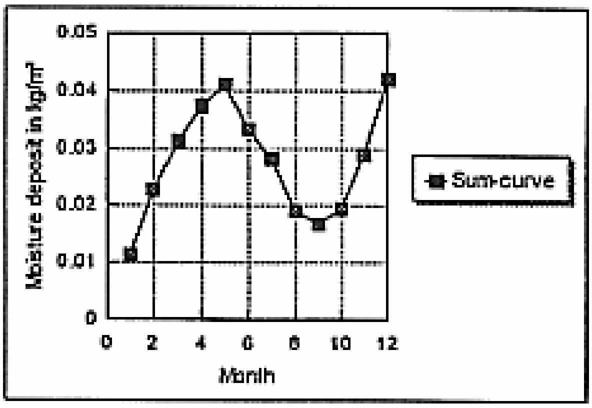

*Figure 9 Interstitial condensation of vapor, produced inside, against the outside glass panel (Indoor Climate Class 3, $\theta_i$=21°C, TRY for Ukkel)*

The low solar absorption at the outside surface finally tends to lower temperatures in the most probable condensation interface, i.e. the TIM-side of the exterior glass panel, than is the case in a wall which absorbs most of the solar radiation at its outside surface. As a consequence, moisture accumulation risk by interstitial condensation against the glass panel and in the TIM-capillaries may increase substantially in the absence of a properly designed vapor retarder (figure 9). A simple analysis shows that an absolute retarder is needed, with a vapor resistance $>10^{13}$ m/s.

The conclusion is straight forward. If a TIM-wall is not designed correctly, it may be quite sensitive to construction moisture and interstitial condensation. If much construction moisture is present, correct design asks for an absolute vapor barrier against the TIM-side of the massive wall. With a low construction moisture content, a vapor-tight transparent panel at the inside of the TIM-layer works well. The elements may also need a drainage system. This should be constructed in a way uncontrolled airflow behind the TIM-layer is not activated.

**Thermal bridging**

As far as structural thermal bridges in the envelope are concerned, things are identical as for traditional choices:

- Restrict their total impact on the average $U_{o,m}$ of the building to $0.1U_{o,m}$, $U_{o,m}$ being the average without thermal bridging
- Realize a temperature ratio $f_{hi}>0.7$. In formula:

$$f_{hi} = \frac{\theta_{si\ min} - \theta^*_e}{\theta_i - \theta^*_e} \geq 0.7 \qquad [6]$$

$\theta_{si,\ min}$ is the lowest surface temperature on the thermal bridge, $\theta^*_e$ the sol-air outside temperature and $\theta_i$ the inside air temperature. Specific thermal bridges are the frames of the TIM-elements. These have a double influence: hampering solar gains through shading effects and decreasing the overall thermal resistance. As table 9 shows, last value may drop quite substantially. If for a 10 cm thick TIM-layer an aluminum frame without thermal break is used, a drop of 46 to 60% is noted, depending of the dimensions of the element. With a timber frame, the loss stabilizes at 11 to 19%, i.e. worse than the performance requirement handed for structural thermal bridges.

*Table 9 Equivalent thermal resistance of a TIM-element*

| Dimensions of the element | | Aluminum frame without thermal break | | Aluminum frame with thermal break | | Timber frame | |
|---|---|---|---|---|---|---|---|
| | $R_o$ $m^2$.K/W | $R_{eq}$ $m^2$.K/W | decrease % | $R_{eq}$ $m^2$.K/W | decrease % | $R_{eq}$ $m^2$.K/W | decrease % |
| 1x1 | 1.15 | 0.45 | 60.5 | 0.68 | 41.0 | 0.93 | 18.9 |
| 2x1 | 1.15 | 0.53 | 53.8 | 0.75 | 34.7 | 0.97 | 15.1 |
| 2.5x1.5 | 1.15 | 0.62 | 45.6 | 0.83 | 27.6 | 1.02 | 11.3 |

Clearly, the frames should be constructed in a very conscious way. At one side, they must provide an excellent thermal insulation. At the other side, they should be as vapor-tight as possible and non-hygroscopic. If hygroscopic and not protected by a vapor retarder at the TIM-side, condensation of sorbed moisture in the TIM-layer may be the result.

## CONCLUSIONS

A consequent performance analysis, as discussed for a TIM-massive wall combination, not only allows to quantify the physical qualities and weaknesses of a solution, it also helps in upgrading the design:

1. TIM should always be produced with an airtight foil at one side at least. All joints between separate boards in an element must be caulked
2. TIM-elements should include a solar protection or be constructed in a way outside air may pass between the TIM and the massive wall
3. the massive wall must be constructed of materials with a low thermal expansion coefficient and restricted hygric shrinkage. Reinforcement must be used when needed to enhance tensile strength
4. if the massive wall is constructed with a material which contains inevitably much construction moisture (concrete or cellular concrete), then an absolute vapor barrier at its outside surface is needed. If not possible, then the TIM-layer must at least be shielded at the inside by a transparent, vapor-tight panel
5. the frame should be vapor-tight, have a low equivalent U-value and be composed of materials with low hygroscopic moisture content.

The five design rules indicate that prefabrication of TIM-elements under well controlled conditions is preferred above assembling them on site. The prefabricated elements should consist of a vapor-tight sandwich construction glass-TIM-glass with exterior solar protection, wrapped in a vapor-tight frame with low equivalent U-value and low hygroscopicity and be assembled in a very dry environment. Once on site, the work is restricted to fixing the separate elements against the massive wall after this is finished with a black colored vapor-tight layer and sealing all joints between the elements, except if a vented solution is foreseen.

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## REFERENCES

1. IEA-Annex 32, ‘Integral assesment of building envelope performances’, reference paper, Leuven, 1996
2. IC-IB, Prestatiegids voor Gebouwen ((1) Het gebouw als geheel, (2) Gevels, (3) Daken, (4) Verticale binnenverdelingen, (5) Vloeren en trappen, (6) Waterdistributie- en -afvoerinstallaties, (7) Thermische en ventilatie-installaties, (8) Electrische installaties, (9) Transport- en communicatie-installaties) *(Performance Guide for Buildings,((1) The building, (2) Envelopes, (3) Roofs, (4) Vertical partition walls, (5) Floors and Staircases, (6) Water Distribution and Sewage, (7) Heating and Ventilation, (8) Electrical Installations, (9) Transport and Communication),* Brussel, 1979
3. Lindauer E, Leonhardt H, Brauchwasservorerwärmung mit transparant gedämmten Bauteilen (Hybridsystem), IBP, Mitteilung 246, 1994
4. Verbeeck G, Hens H, Radiative and conductive heat transfer through transparant insulation material and the effect on the $\lambda$-value, Proceedings of the 4th Building Physics in the Nordic Countries Symposium, Espoo, September 9-10, 1996, pp 731-738
5. Verbeeck G, Hens H, Van Keer R, Eindrapport Energiegebruik voor verwarming en koeling in gebouwen, Transparante isolatie, onderzoeksjaar 1991-1992 *(Final report Energy consumption for heating and cooling in buildings, transparant insulation, working year 1991-1992),* Leuven, 1992
6. Van den Bossche K, Verstrepen E, Transparant isolatiemateriaal, onderzoek naar de thermische, optische en hygrische eigenschappen *(Transparant insulation material, measuring the thermal, optical and hygric properties),* Eindwerk K.U.Leuven, 1995
7. Declercq D, Bepaling van de transmissiefactor voor infraroodstraling van een capillair, transparant isolatiemateriaal *(Determination of the transmissivity for infra-red radiation of a transparant capillary insulation material),* Eindwerk K.U.Leuven, 1996
8. Herroelen B, Torfs B, Fysisch model voor transparante isolatie *(Physical model for transparant insulation),* Eindwerk K.U.Leuven, 1995
9. Meekels P, Meireman P, Energiebesparing door en hygrothermische prestaties van transparante isolatie *(Energy efficiency by and hygro-thermal performance of transparant insulation),* Eindwerk K.U.Leuven, 1995
10. Verbeeck G, Hens H, Constales D, Van Keer R, Transparante isolatie: numerieke modellen en evaluatie in situ van de prestaties van het systeem in het VLIET-HAMTIE K20 proefgebouw, REG-potentieel (*Transparant insulation: numerical models and field testing of the performances in the VLIET-HAMTIE K20 test building, RUE possibilities*), Eerste Jaarverslag, IWT, 1996
11. Munding M, Boy E, Performance of Transparant Thermal Insulation in a South-East Eurpean Climate-Case Study for Budapest, Heat and Mass Transfer in Building Materials and Structures, Hemisphere Publishing Company, 1991, pp 645-654
12. Physibel SV, Users Guide for the Computer Program CAPSOL, 1994 (Users number KULLBF)
13. Transparent gedämmte Altbauten, Untersuchung des Einflusses von transpareneten Wärmedämmsystemen auf altbauübliche inhomogene Aubenwandkonstruktionen, Heft 3: Statisches Verhalten von transparent gedämmten Aubenwänden, Teilbericht des Instituts für Tragwerksentwurf und -konstruktion, Universität Stuttgart, Forschungsvorhaben 0335003 P, IRB Verlag, Stuttgart, 1993, 236 pp.