Biological Defacement of External Thermal Insulation Composite Systems

Eva Barreira, Vasco Peixoto de Freitas and João M. P. Q. Delgado

Abstract External Thermal Insulation Composite Systems (ETICS) are nowadays often used in Europe. Despite its thermal advantages, low cost and ease of application, this system has serious problems of microbiological growth causing the cladding defacement. This chapter presents the results of a detailed experimental study that was carried out in order to assess the hygrothermal behaviour of façades covered with ETICS, namely to evaluate the influence of orientation on surface humidification, by external condensation and by wind-driven rain. A building located in the University of Porto campus, with its four façades facing the cardinal directions, was monitored during one year. The exterior surface parameters under study were temperature and wind-driven rain. The building interior conditions and the exterior climate were also measured. The tests results were compared with the results of the numerical simulation performed using a commercial hygrothermal model. The conclusions about the results of the experimental and numerical study, their comparison and all the difficulties found to achieve similar results are pointed. This chapter also presents a methodology to assess the risk of biological growth, based on the definition of indices, which combine the effect of surface condensation, wind-driven rain and drying process, three of the most prevalent parameters influencing the surface moisture content. The proposed indices were calculated using data collected during the "in situ" test campaign, which provided information about the exterior climate conditions, the

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Fig. 1 ETICS defacement due to biological growth (bulking located in porto - Portugal)

surface temperature and wind-driven rain on four façades covered with ETICS facing the cardinal directions. The indices were compared with the results of the surface relative humidity measured simultaneously that allowed the validation of the methodology. An example of the practical use of this methodology is also presented in this chapter, with the definition of hazard classes of biological defacement of façades covered with ETICS located in the Portuguese territory.

Keywords ETICS · Biological defacement · Hygrothermal behaviour · "In situ" measurements · Numerical simulation

1 Introduction

External Thermal Insulation Composite Systems (ETICS) are often used in Europe since de 1970s, both in new buildings and in retrofitting. Despite its thermal advantages, low cost and ease of application, this system has serious problems of microbiological growth, causing the cladding defacement. Although no changes occur in the thermal and mechanical performance of the system, biological defacement has an enormous aesthetic impact, which gathers the building's dwellers disapproval and restricts the full implementation of this technology (see Fig. 1). Recent studies allowed to understand the physical phenomenon causing the ETICS defacement and made it possible to develop mathematical models simulating its performance. However, no simple process has yet been developed to predict the risk of ETICS defacement, which may be used by designers and by the building industry.

Studies carried out during the last decade (Blaich 1999; Kunzel and Sedlbauer 2001; Becker 2003; Venzmer et al. 2008) pointed that microbiological growth is due to high values of surface moisture content, which results from the combined effect of four parameters: surface condensation, wind-driven rain (WDR), drying process and properties of the exterior layer.

Exterior surface condensation occurs mostly during the night, when the exterior surface temperature is lower than the dew point temperature, as a result of long wave radiation exchange between the surface and the atmosphere. During clear nights, the atmosphere's emitted radiation decreases considerably and the radiation emitted by the surface is greater than the one that reaches the surface, causing a loss of radiation towards the sky. This negative balance on the surface is maintained until heat transport by convection and by conduction compensate for the loss by radiation (Holm et al. 2004).

WDR results from the combination of rain and wind. Its intensity depends on the building geometry and environment topology, position on the building façade, intensity of rainfall through a horizontal plane, wind speed and wind direction. The most used semi-empirical model says that WDR intensity is proportional to the product of the wind speed normal to the façade and the intensity of rainfall through a horizontal plane (Hoppestad 1955; Nore et al. 2007).

The drying process allows the evaporation of the liquid water accumulated on the surface due to the surface condensation and WDR. Evaporation from the wet surface occurs whenever the saturation pressure at the surface is greater than the vapour pressure of the ambient air (Hagentoft 2001). If the drying process is not sufficiently fast, the surface moisture content remains high for long periods and increases the risk of microbiological growth (Krus et al. 2006).

Several authors refer to the importance of the properties of the exterior layer in the biological growth. Concerning the thermal properties, emissivity is referred as the most relevant as it rules the emission of radiation by the surface. For lower values of emissivity the heat loss during the night reduces and the surface temperature increases. The risk of surface condensation is therefore lower (Krus et al. 2006). Also some hygric properties are referred as having capital influence on the surface moisture content, namely water absorption of the external coating. Lower water absorption allows longer availability of liquid water on the surface as less water is absorbed by the plaster system following WDR and surface condensation (Blaich 1999; Becker 2003; Venzmer et al. 2008). Barberousse et al. (2006) assessed the influence of the coating roughness in the biological growth and stated that it could promote or restrict the adhesion process of the spores and the liquid water retention on the surface.

Although no statistical studies are available, façades covered with ETICS facing North and West are more prone to biological growth than the ones facing East and South, which rarely have any problem. This great influence of orientation in the façades defacement, although known by the researchers and by the producers/appliers of the system, has never been deeply studied. Its real impact in the surface humidification by condensation and WDR is therefore unknown.

Fig. 2 Building under study—located in University of Porto campus

2 Experimental Study

2.1 Setting Up the Test

To assess the influence of orientation in the surface humidification an "in situ" test campaign was carried out during one year (March 2009–February 2010). Instruments were set up on the façades covered with ETICS of a building located in UP campus (see Figs. 2 and 3), whose walls face the cardinal directions. T-type thermocouples were used to assess surface temperature and WDR gauges measured the rain reaching each façade. Surface relative humidity was measured using humidity and temperature probes. They were coupled to a data acquisition system, collecting data every 10 min. Information regarding the accuracy and calibration of the devices is given by Barreira (2010). Black dots on Figure 3 mark the position of the devices on each façade.

Climatic parameters were collected every 10 min by the weather station located near the building under study (see Fig. 3) and the hygrothermal conditions inside the building were also measured. The annual averages of the outdoor and indoor climate are presented in Table 1. Detailed information about the weather station (instruments used and its accuracy) is given by Barreira (2010).

2.2 Results

2.2.1 Surface Temperature

Figure 4 shows the surface temperature of the façades under study and the dew point temperature, during two days of May 2009. During the night, surface temperatures were quite constant and very similar. Even so, the South façade had the

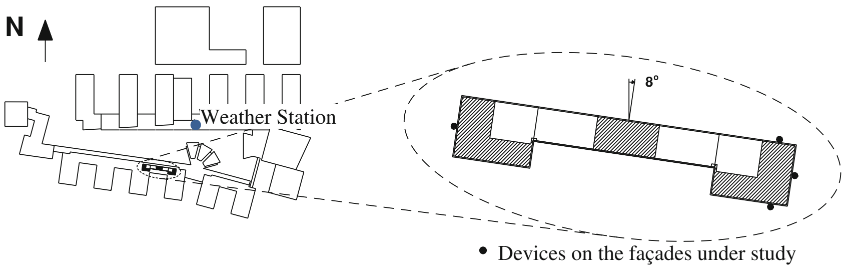


Fig. 3 Layout with the devices and weather station locations

Table 1 Indoor and outdoor climate during the test campaign (annual average)

Climatic parameter	Used devices	Outdoor	Indoor
Temperature	Pt100 sensor	15.4 °C	19.9 °C
Relative humidity	Hygrometer sensor	72 %	67.5 %
Global radiation emitted by the sun	Pyranometer	254 W/m^2	–
Radiation emitted by the sky	Pyrgeometer	335 W/m^2	–
Wind velocity/direction	Anemometer/vane	1.4 m/s/170°	–
Rain (accumulated)	Rain gauge	874 mm	–

higher temperature and the West façade the lower one. The temperature on the North façade was not the lowest as it was expected.

During daylight, when the sky is clear, the differences between the surface temperatures are more obvious. The East and South façades achieved higher values during the morning and the West façade at the end of the afternoon. The temperature of the North façade was the lowest. The peak at daybreak is related with direct solar radiation incident on the façade. When the sky is cloudy, the differences during daylight are smaller and almost independent from orientation (see 17th May). Figure 5 displays the average, maximum and minimum surface temperatures measured for the period under study.

2.2.2 Exterior Surface Condensation

When surface temperature drops below dew point temperature (T_{dp}), calculated as a function of temperature and relative humidity of the ambient air, condensation will occur. The difference between T_{dp} and surface temperature may be called Condensation Potential in degrees (CPd), which implies condensation for positive values. The accumulated value of positive CPd during a period of time allows estimating the amount of water vapour available to condensate and points to the risk of condensation.

Figure 6 shows that hourly CPd was always lower than 2.5 °C and, on average, was around 0.4 °C. Although the major differences had occurred during the cold seasons, on average, there was no significant variation of CPd along the year. The

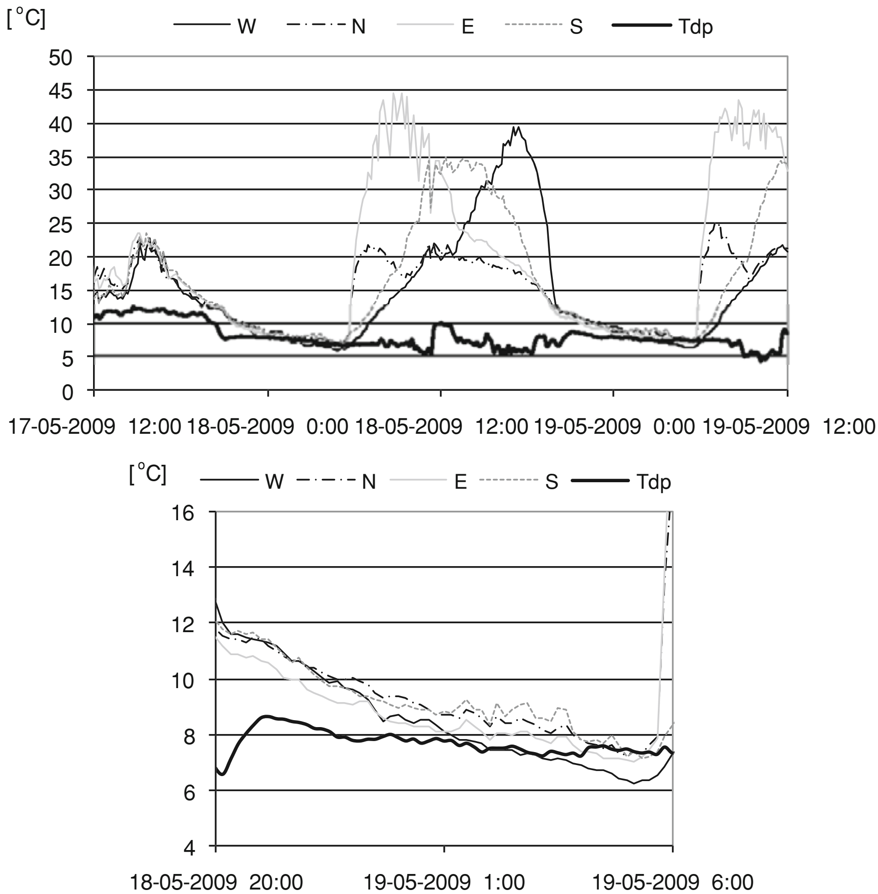


Fig. 4 Surface temperatures and dew point temperature during May 2009

accumulated values of CPd (only the positive temperature differences were considered, the negative values were taken as equal to zero) point to higher risk of condensation during November, December and April. During July and August the risk of condensation was also significant (Fig. 7), which is related with Porto climatic conditions. During summer nights high relative humidity and mild temperature lead to high T_{dp}, worsen the risk of condensation. Considering the annual accumulated CPd, the West façade presented higher risk of condensation, followed by the East, North and South façades.

2.2.3 Wind-Driven Rain

WDR measurements show that, in generally, the South façade was more exposed to rain, followed by the West, East and North façades. The amount of WDR was

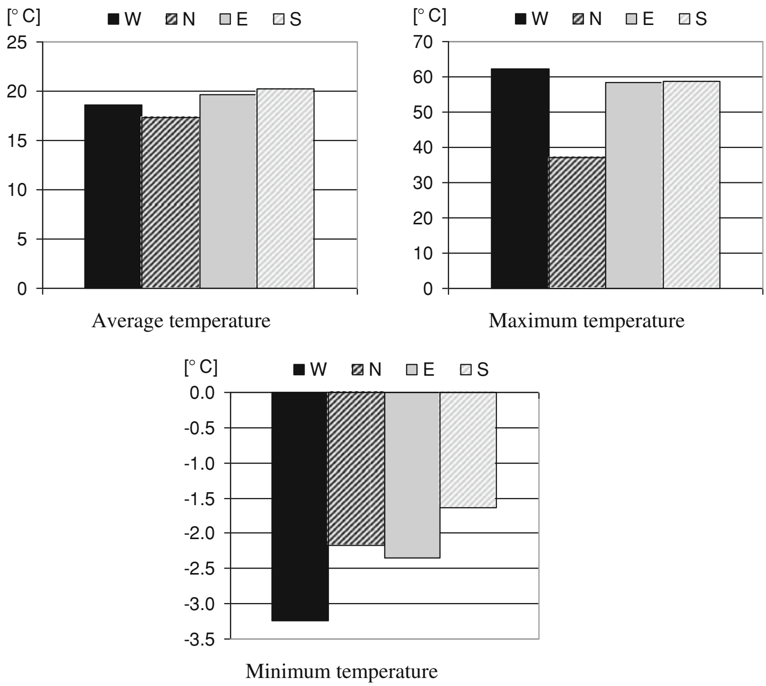


Fig. 5 Average, maximum and minimum temperatures measured during the test campaign

higher during autumn and winter. It must be said that the amount of rain reaching the façade may correspond to maximum values as the WDR gauges were placed near the top and vertical edges of the façades. The values of WDR for the West façade during January and February 2010 are not available due to problems in the gauge (see Fig. 8).

2.3 Discussion of the Results

During the night, surface temperature does not differ much with orientation (see Fig. 4). The small differences are due to direct solar radiation incident on the façades and on its surrounding during the day, which vary with orientation. The North façade did not had the lowest surface temperature during the night (see Figs. 4 and 5).That may be related with the rotation of the façades, about 8 °Clockwise from North (see Fig. 3), and with the exposure to the wind of the North façade, which is aligned with the main façade of the building unlike the other façades (see Fig. 2).

The comparison between the risk of surface condensation (see Fig. 7) and the defacement of the façades under study (North and West façades present more colonization by microorganism than the East and South façades that do not have

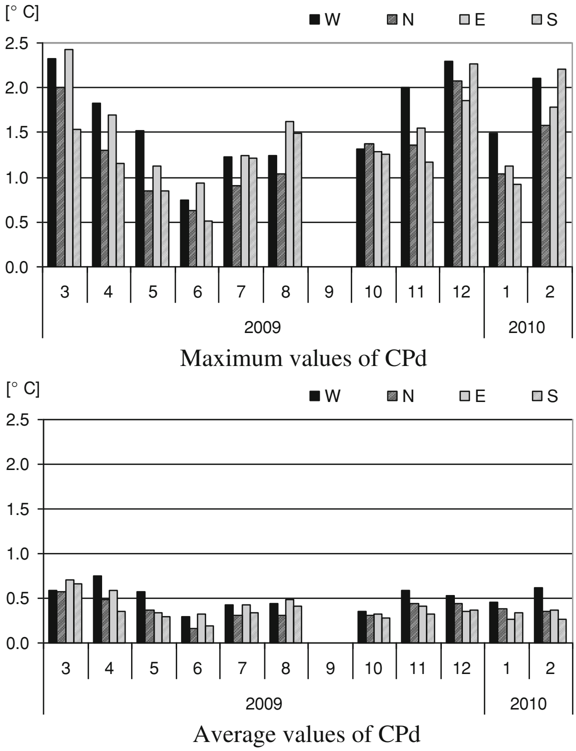
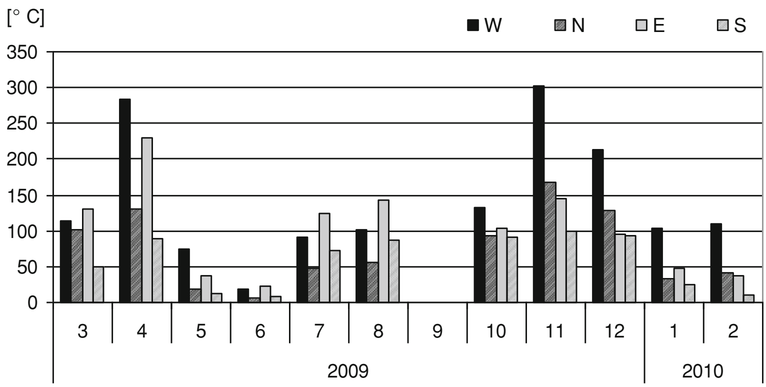


Fig. 6 Maximum and average values of CPd obtained during the test campaign. (In September 2009 there were some problems with the data acquisition system and the measurements were lost)

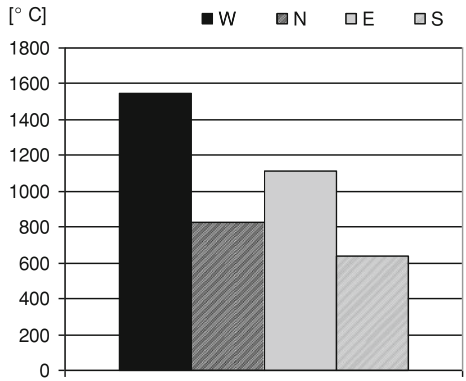
any biofilm on its surface) points to the influence of the drying process in the surface water content and biological growth. Lower temperatures on the North façade during daylight (see Fig. 5) may restrict the evaporation of the condensated water and increase the risk of biological colonization. The West façade had the highest amount of condensation and the second highest amount of WDR. The surface temperature reached during day may not be enough to decrease the water content on the surface and restrict biological growth. The South façade, although having less risk of condensation, had the highest amount of WDR, more than the double measured in the West façade. As it is not defaced, the drying process may have a key role in biological growth on ETICS (Barreira and Freitas 2011a).

In Porto, external surface condensation may be more preponderant to biological growth than WDR, as it occurred during all the year at equivalent intensity (see Fig. 7). During spring and summer, the rain did not reach the façades for longer periods (see Fig. 8) pointing to a smaller influence in the surface water content. Of course, the water run-off along the surface and, specially, its accumulation may increase the influence of WDR in the risk of microorganisms' colonization (Barreira and Freitas 2011b).

In Sects. 4 and 5 is presented a methodology to assess the risk of biological growth on ETICS. It points to the major influence of the drying process based on the drying potential for each orientation. It also indicates that surface condensation



Monthly accumulated values of CPd



Annual accumulated values of CPd

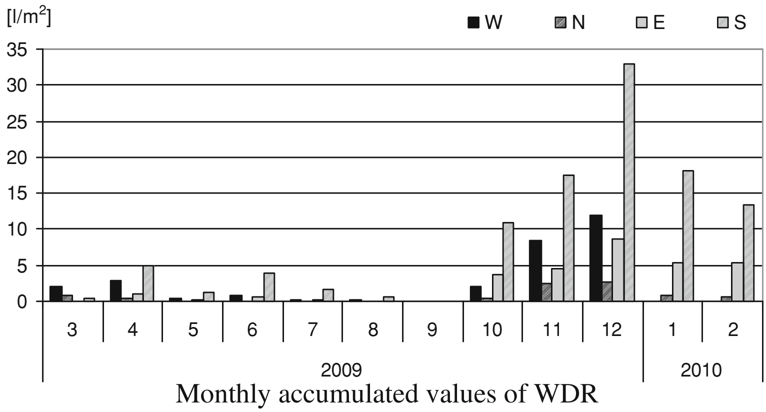
Fig. 7 Monthly and annual accumulated values of CPd obtained during the test campaign. (In September 2009 there were some problems with the data acquisition system and the measurements were lost)

has higher impact on biological growth than WDR, as long as water run-off is not taken into account.

3 Numerical Simulation

3.1 Parameters of the Numerical Simulation

In building physics hygrothermal models are widely used to simulate the coupled transport of heat and moisture. However, only a few allow simulating accurately the exterior surface temperature during the night on a façade covered with ETICS.



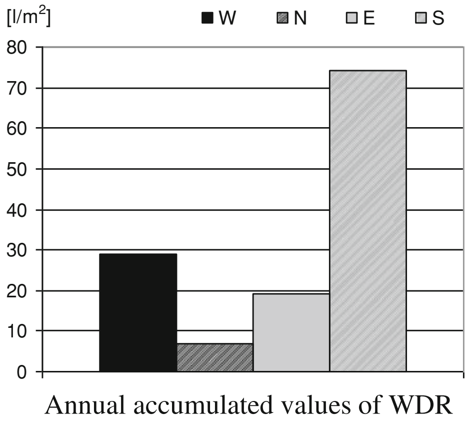


Fig. 8 Monthly and annual accumulated values of WDR obtained during the test campaign. (In September 2009 there were some problems with the data acquisition system and the measurements were lost)

The low thermal capacity of the external rendering and its thermal decoupling emphasises the influence of radiation, which implies including a routine to calculate explicitly the radiative balance on the surface. This radiant balance is affected by the building's radiation, the sky's radiation, terrestrial surface's radiation and solar radiation (Delgado et al. 2010).

The need for heat, air and moisture (HAM) models to better understand the phenomena behind external surface condensation demands for their wide validation. For that reason, from the existing hygrothermal models, it was selected a commercial one (Künzel 1995, WUFI 2008, Kehrer and Schmidt 2008) and the results obtained by numerical simulation were compared with the ones measured during the experimental campaign. The simulations were run using the wall from Fig. 9. The thermal and hygric properties of the materials used in each layer were selected from the software database, as an approach to the existing wall. The

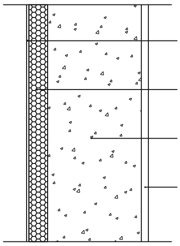


Fig. 9 Wall used for the numerical simulation

hourly climatic data used was measured by the weather station (see Fig. 3) and indoor temperature and relative humidity were measured using probes. Table 1 shows the annual averages of the climatic parameters measured, although for the numerical simulation hourly values were used.

3.2 Discussion of the Results

3.2.1 Surface Temperature

Figure 10 shows the hourly average of surface temperature on the West and South façades, measured and calculated, during one day of November 2009. During the night there is a good agreement between the measured and the calculated values for the West façade. For the South façade, a better agreement was achieved after increasing 4 % the sky's radiation measured (*Sim_a*). This adjustment may be related with the effect of the ground in the façade surface temperature during the night. The ground, with high thermal capacity, absorbs solar radiation during the day that is released during the night as long wave radiation. The amount of radiation absorbed by the ground is not the same for each cardinal direction due to shading caused by the building itself.

During daylight, the differences between the measured and the calculated values are strongly marked. That may be related with the rotation of the façades (see Fig. 3) that could not be considered in the simulation due to limitations of the model. The solar radiation values measured by the weather station were lower than the ones presented in the literature, which may have affected the simulation results, reducing the calculated surface temperature during daylight. The calculation of the sun position in the horizon, performed by the software to calculate the direct solar radiation on the façade, may also have introduced some errors. The differences obtained during a sunny daylight are smaller than the ones obtained with cloudy sky, as the temperatures measured and calculated are much closer (see Fig. 11).

3.2.2 Exterior Surface Condensation

The good agreement obtained for the surface temperature during the night induced similar measured and calculated values for the PCd (see Fig. 12), during the colder months. During the warmer ones the influence of the sun was higher, which implied more divergent results (see Fig. 13).

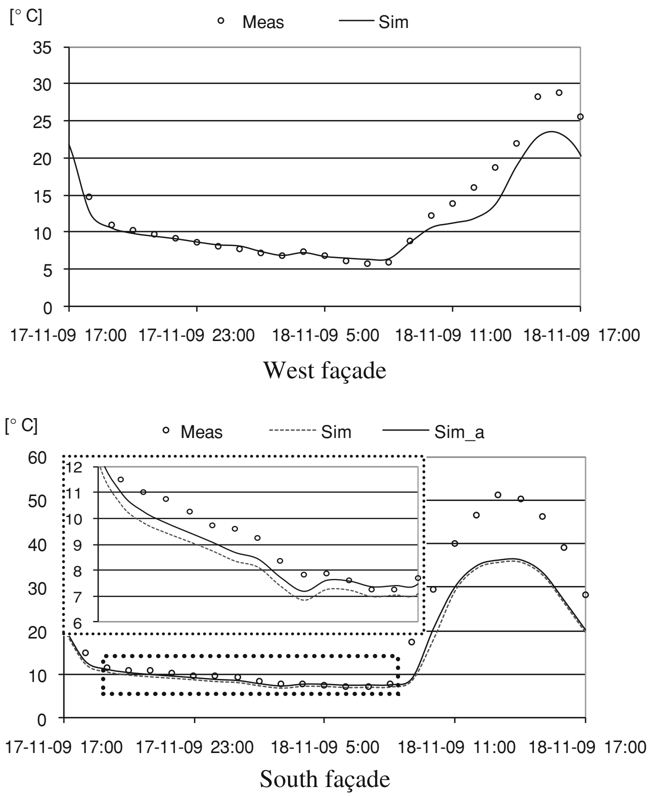


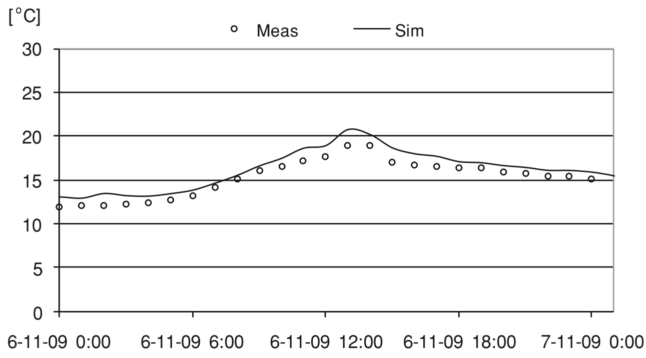
Fig. 10 Surface temperature, measured and calculated, during a clear day in November 2009

3.2.3 Wind-Driven Rain

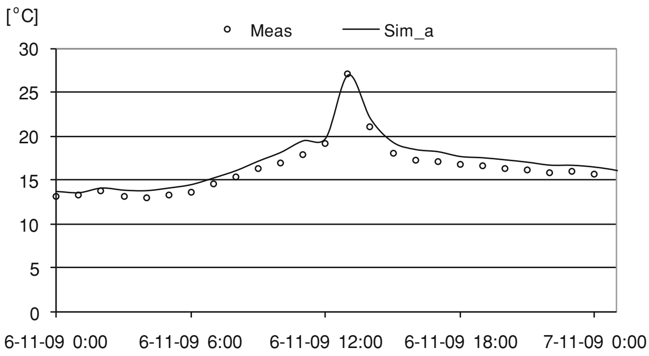
The agreement between measured and simulated values of WDR (see Fig. 14) was only achieved after adjusting the driving rain coefficients used by the software to estimate the rain load on the building component (see Table 2). This adjustment was probably necessary due to the rotation of the façades and the different wind conditions near the building and near the weather station, as the weather station is located between two buildings and the building under study is exposed to open wind (see Fig. 3).

4 Hygrothermal Model to Assess the Risk of Biological Growth

The knowledge gathered during the last decade made it possible to develop mathematical models simulating ETICS performance, considering different conditions of use (Kunzel et al. 2002). However, no simple process has yet been



West façade



South façade

Fig. 11 Surface temperature, measured and calculated, during a cloudy day in November 2009

developed to predict the risk of ETICS defacement. Considering the work already done for mold growing on interior finishes (Adan 1994 Viitanen 1996, Sedlbauer 2001), the relative humidity of the surface or the time of wetness obtained from the surface humidity, might be the better criterion for assessing the risk of biological growth. Nevertheless, the comparison of simulated values with the results of "in situ" tests performed on a façade covered with ETICS showed that there is no go agreement between the simulated and the measured values of the relative humidity, especially when WDR is taken into account (Barreira 2010).

The use of surface relative humidity as a criterion for the risk assessment is, therefore, restricted. The next sections present an alternative methodology to assess the risk of biological growth, based on the definition of indices, which combine the effect of surface condensation, wind-driven rain and drying process, three of the most prevalent parameters influencing the surface moisture content.

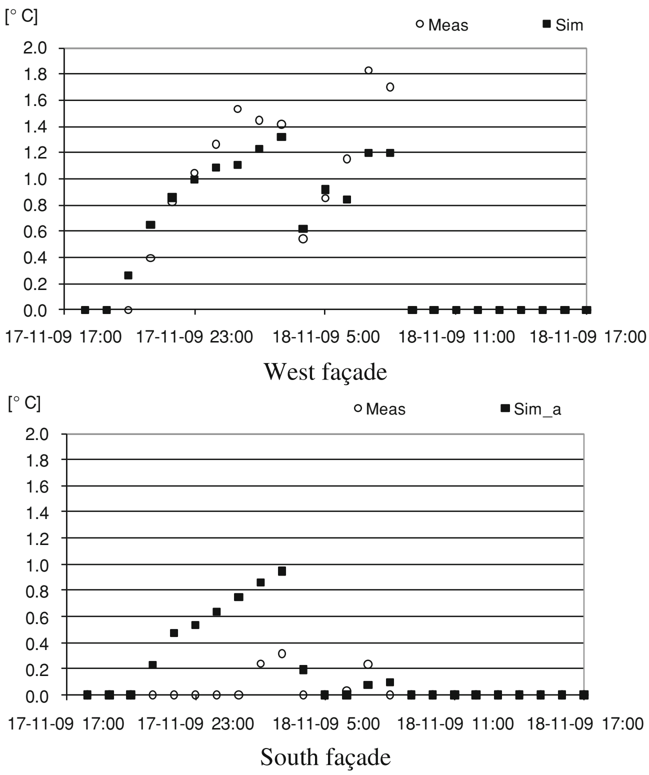


Fig. 12 PCd, measured and calculated, during a clear day in November 2009

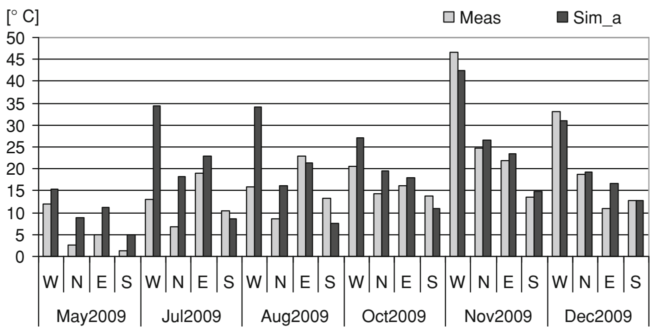


Fig. 13 Monthly accumulated PCd, measured and calculated

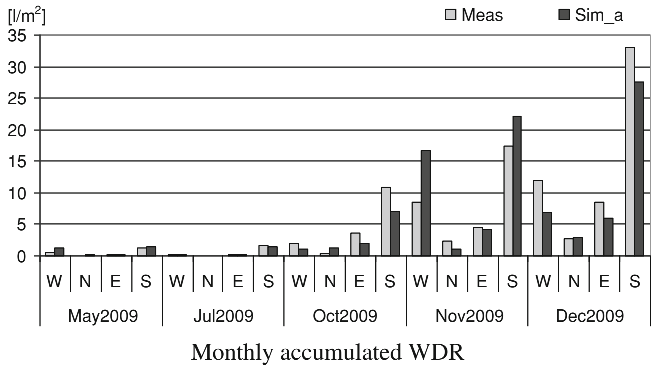


Fig. 14 Monthly accumulated WDR, measured and calculated

Table 2 Driving rain coefficients used for the simulation

Orientation	West	North	East	South
Driving rain coefficients (before adjustment)	0.2	0.2	0.2	0.2
Driving rain coefficients (after adjustment)	0.3	0.2	0.02	0.07

4.1 Assessing Exterior Surface Condensation

Exterior surface condensation can be analyzed using psychrometry principles. When water vapour partial pressure of the air is greater than the water vapour saturation pressure at the surface, condensation will occur (Hagentoft 2001). According to Zheng et al. (2004) the difference between the water vapour partial pressure in the air ($P_v(air)$, in Pa) and the water vapour saturation pressure on the surface ($P_{sat}(surface)$, in Pa) may be called Condensation Potential (*CP*, in Pa), which implies condensation for positive values. *CP* can be understood as the amount of water vapour that is available to condensate.

$$CP = P_v(air) - P_{sat}(surface) \tag{1}$$

The same author refers that to evaluate the amount of condensation, both positive *CP* and its lasted time should be considered. The product of positive *CP* ($CP_{(>0)}$, in Pa) by its lasted time ($\Delta t_{CP(>0)}$, in h) may be called Condensation Potential Equivalent (*CPE*, in Pa.h) and allows estimating the amount of condensated water. To estimate the risk of condensation for a certain period of time *CPE* must be accumulated in time (CPE_a).

$$CPE = CP_{(>0)} \cdot \Delta t_{CP_{(>0)}} \tag{2}$$

4.2 Assessing WDR

The humidification of a façade due to *WDR* may be assessed, for a certain period of time, through the *WDR* Potential Equivalent ($WDRPE_a$, in kg/m^2), which is obtained by integrating in time the intensity of *WDR* (in kg/(m^2 s). $WDRPE_a$ shall be multiplied by 100 in order to reach values that are comparable with CPE_a values.

$$WDRPE_a = 100 \cdot \int_0^t WDR\, dt \tag{3}$$

4.3 Assessing the Drying Process

As condensation also the drying capacity of a wet surface can be analyzed using psychrometry principles (Hagentoft 2001). By analogy, it is possible to establish the concept of Drying Potential (*DP*, in Pa), as being the difference between the water vapour saturation pressure on the surface ($P_{sat}(surface)$, in Pa) and the water vapour partial pressure in the air ($P_v(air)$, in Pa), which implies evaporation for positive values. *DP* can be understood as the amount of water vapour transferred to the air, considering that the surface remains permanently wet.

$$DP = P_{sat}(surface) - P_v(air) \tag{4}$$

To evaluate the maximum ability to dry out, the product of positive *DP* ($DP_{(>0)}$, in Pa) by its lasted time ($\Delta t_{DP(>0)}$, in h) shall be considered and may be called Drying Potential Equivalent (*DPE*, in Pa.h). To estimate this ability for a certain period of time, *DPE* must be accumulated in time (DPE_a).

$$DPE = DP_{(>0)} \cdot \Delta t_{DP_{(>0)}} \tag{5}$$

It must be stated that DPE_a is not useful as a parameter for modeling the real drying capacity of a wet surface, as it is not permanently saturated. After some time, the liquid water evaporates and the vapour pressure at the surface depends not only on the surface temperature, but also on its relative humidity. However, to avoid the use of relative humidity and to simplify the parameters used in the drying process assessment, DPE_a can be employed as an overvalued drying capacity.

4.4 The Model BIO.MOD

The model BIO.MOD defines three indices: BIO.MOD1 that relates surface humidification by condensation (CPE_a) with the maximum drying capacity (DPE_a); BIO.MOD2 that relates surface humidification due to WDR ($WDRPE_a$)

with the maximum drying capacity (DPE_a); and BIO.MOD3 that relates surface humidification by condensation (CPE_a) and due to WDR ($WDRPE_a$) with the maximum drying capacity (DPE_a) and is the one to be considered when analyzing the risk of ETICS defacement due to high amount of surface moisture content (Barreira and Freitas, 2011b).

$$BIO.MOD1 = \frac{CPE_a}{DPE_a} \cdot 10^3 \tag{6}$$

$$BIO.MOD2 = \frac{WDRPE_a}{DPE_a} \cdot 10^3 \tag{7}$$

$$BIO.MOD3 = \frac{CPE_a + WDRPE_a}{DPE_a} \cdot 10^3 \tag{8}$$

5 Validation of the Model BIO.MOD

Using the data collected during the "in situ" campaign (see Sect. 2.1), CPE_a, $WDRPE_a$, DPE_a and the three indices of BIO.MOD were calculated in annual bases, as sketched in Figs. 15 and 16.

Figure 17 shows that index BIO.MOD3, which combines surface condensation with the effect of WDR and assesses the risk of defacement due to biological growth, follows the same trend as the accumulated hours of the surface saturation (relative humidity equal to 100%), measured simultaneously, and allowed the validation of the model. On the other hand, there is also a good relation between the façades defacement per orientation and the annual values of *BIO.MOD3*, as the West and North façades present more colonization by microorganism than the East and South façades that do not have any biofilm on its surface.

The risk of surface humidification due to condensation (*BIO.MOD1*) is greater for the West façade, followed by the North, East and South façades. It depends mostly on the drying process, which is quite clear for the North façade that did not had high values for surface condensation (CPE_a) but had the lowest drying capacity (DPE_a) and, consequently, the highest risk of humidification by condensation (*BIO.MOD1*). The East façade, with one of the highest amount of condensation (CPE_a), did not present very high risk of humidification by condensation (*BIO.MOD1*) due to the drying capacity (DPE_a).

The risk of surface humidification due to WDR (*BIO.MOD2*) is greater for the South façade, followed by the West, East and North façades. The risk is related with the intensity of WDR ($WDRPE_a$) on each façade and there is no clear influence of the drying capacity (DPE_a), although it had slightly reduced the risk in the South façade.

The risk of defacement due to biological growth (*BIO.MOD3*) is strongly dependent on surface condensations (*BIO.MOD1*), as both indices follow the same trend. The influence of the WDR is not very relevant although it slightly increases

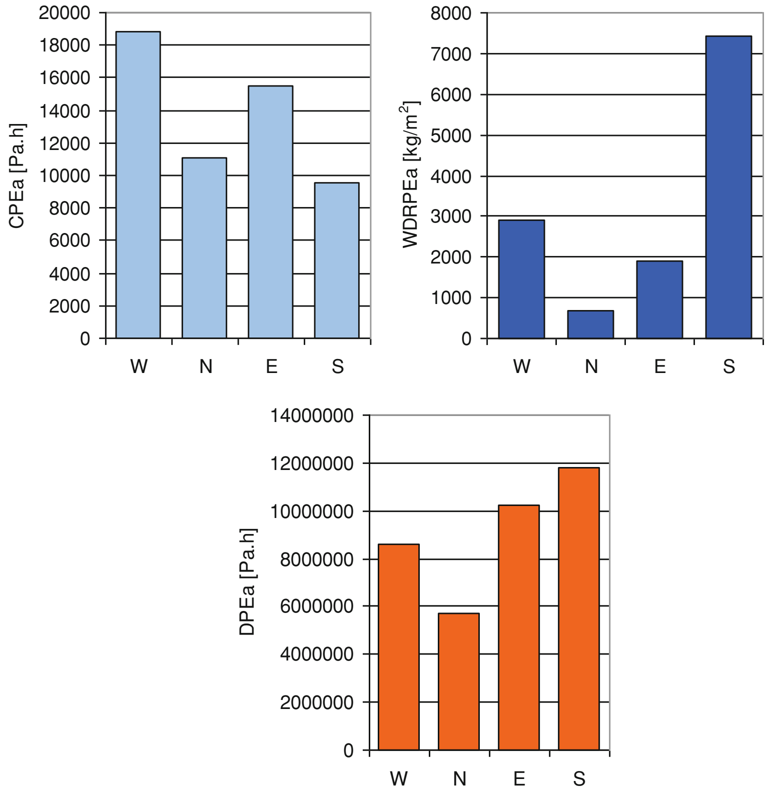


Fig. 15 CPE_a, $WDRPE_a$ and DPE_a per orientation (annual values)

the risk of biological growth. However, it must be stated that this model does not takes into account the water run-off along the surface neither its accumulation, which may increase the influence of WDR in the risk of microorganisms colonization.

6 Risk Map of Biological Defacement in Portugal

As an example of the practical use of the model BIO.MOD, it was defined hazard classes of biological defacement of façades covered with ETICS located in the Portuguese territory. A risk map was created using the index *BIO.MOD3*, on annual bases, calculated with the results of numerical simulation for the same wall, facing North and South, and located in main towns of Portugal. The simulation was performed considering generated climatic data for each town and the interior conditions were assumed to be identical.

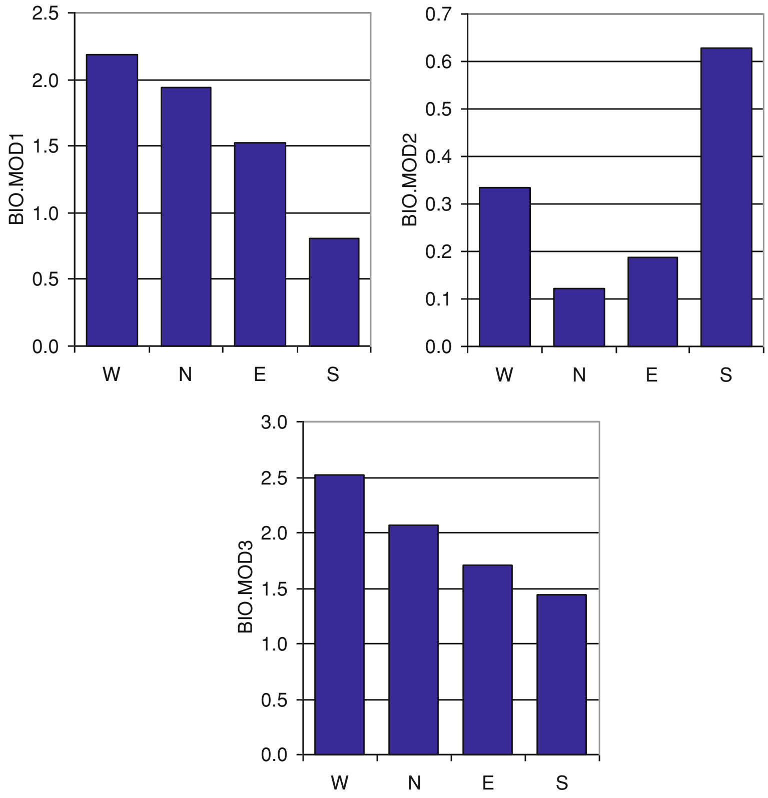


Fig. 16 Indices of BIO.MOD per orientation (annual values)

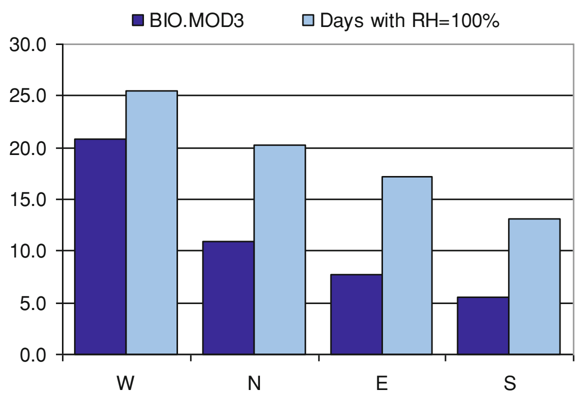
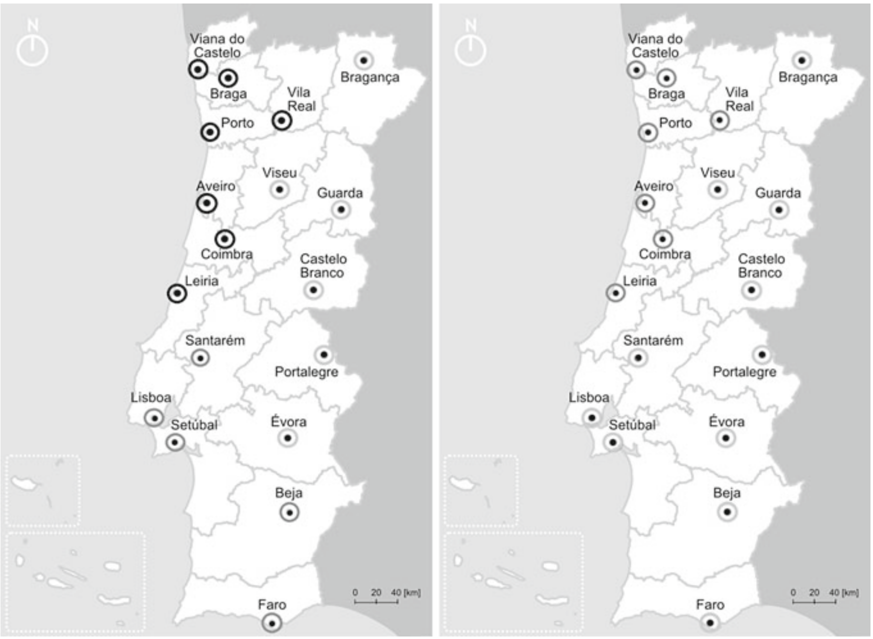


Fig. 17 Index *BIO.MOD3* and days with RH = 100 % per orientation (November 2009)

The hazard classes were established considering three classes of risk, having as top limit the highest value of *BIO.MOD3* obtained: Low Risk, considering values lower than 1.5, Medium Risk, for values between 1.5 and 3.0, and High Risk for



Façades facing North Façades facing South

Fig. 18 Risk of biological defacement on façades facing North and South (*light grey* Low Risk,*grey* Medium Risk and *black* High Risk)

values higher than 3.0. Figure 18 displays the risk of biological defacement on façades facing North and South.

The results show that façades facing North have higher risk of defacement and the towns located in the North West of Portugal present more risk than the ones located in the North country side. In the South of Portugal, the risk is intermediate.

7 Conclusions

The results of the “in situ” tests campaign allowed understanding the effect of orientation in external surface temperature and WDR. During night, orientation had small influence in surface temperature and, consequently, in surface condensation. During the day, surface temperature varies considerably with orientation. Also WDR depends on the façade orientation. It was possible to point that biological growth depends not only on condensation and WDR, but also on the drying process.

The tests results allowed evaluating the performance of a commercial HAM model. Similar values of measured and calculated surface temperature were achieved for the night periods. During the day, due to the sun influence, the differences between the two were greater. The agreement for WDR was difficult to achieve. That may be related with the climatic data used as an input of the software.

It was developed and validated a methodology to assess the risk of biological defacement. This model is based on the definition of indices that relate humidification, by surface condensation and due to WDR, with the drying capacity. The main advantage of this methodology is related with the simplicity of the parameters used and with the ability of knowing the real load of surface condensation, WDR and drying capacity in the façade surface moisture content.

Using the model BIO.MOD it was possible to say that the drying process is the most relevant parameter and that surface condensation has more impact than WDR. It was also possible to establish a risk map for walls covered with ETICS located in Portuguese territory.

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