Rain Protection of Stucco Facades

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ABSTRACT

In the 1960s extensive investigations were carried out at the open air test site of the Fraunhofer-IBP (specializing in building physics res. building science) testing the driving rain protection of masonry walls coated with innovative synthetic resin renders (polymeric stuccos). Some of the exposed test walls did not perform as well as others, and a correlation between the water absorption and the vapor diffusion properties of the facade coatings was established. This correlation was subsequently introduced into the German Standard for exterior rendering systems in regions with a high wind-driven rain load.

When models were successfully applied in the middle of the 1990s to simulate transient heat and moisture transport processes in the building envelope, parametric studies confirmed that the empirical correlation established 40 years ago was indeed appropriate to classify the rain protection characteristics of facade systems under Central European climate conditions. Today validated hygrothermal calculation tools may be employed to design facade systems for different climate zones. Thus, adequate definitions of water absorption and vapor permeance limits may be specified by hygrothermal simulations depending on expected exposure conditions.

INTRODUCTION

When the load-bearing capacity of clay brick masonry and other block work was improved by better production control, exterior walls became slimmer as building materials were still scarce after World War II. In the beginning this led to problems with rainwater penetration despite an unchanged driving rain protection offered by the traditional stuccos (also called *renders* or *renderings*) applied to these walls. To illustrate this, the typical water content of a brick wall with traditional exterior stucco under German climate conditions is plotted in Figure 1 for two orientations. While the rain-protected north wall contains only hygroscopic moisture, the exposed west wall is clearly affected by wind-driven rain. The maximum penetration depth of the precipitation water reaches approximately 20 cm (8 in.). This is generally not a problem with regard to the interior surface of this 38 cm (15 in.) thick brick wall. However, if the same conditions prevail in a slimmer wall (e.g., 20 cm or 8 in.), the elevated moisture will come very close to the interior surface, and the water content in the interior plaster may cause mold growth or staining by salt efflorescence. Furthermore, the elevated water content of the masonry increases the thermal transmittance of the wall, which causes additional energy losses and lower surface temperatures. These are the reasons why special stuccos and coatings with polymeric compounds were initially developed in the early 1960s with the aim of reducing the water uptake of external walls during driving rain events. Subsequently, large-scale field tests were performed and an empirical relation for the hygric characteristics of rain-protecting stuccos and coatings was derived, which still holds today. The tests leading to this empirical relation and complementing results from modern hygrothermal simulations will be summarized in this paper.

FIELD TESTS

The following tests were carried out at the IBP field test site in Holzkirchen, which was created in 1951 (Künzel 2003) for testing building materials and envelope systems and

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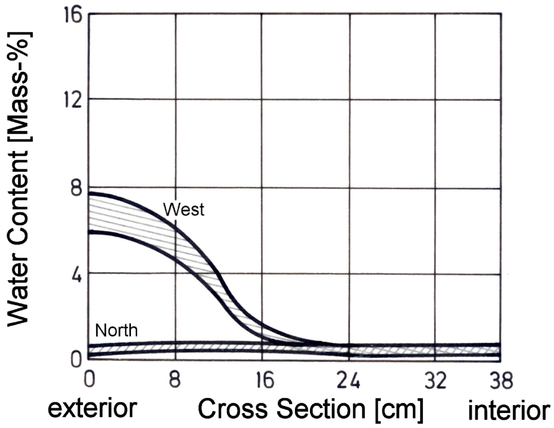

Figure 1 *Measured water content profiles in the clay brick masonry (15 in. thick) beneath traditional stucco of a residential building (Schüle 1966).*

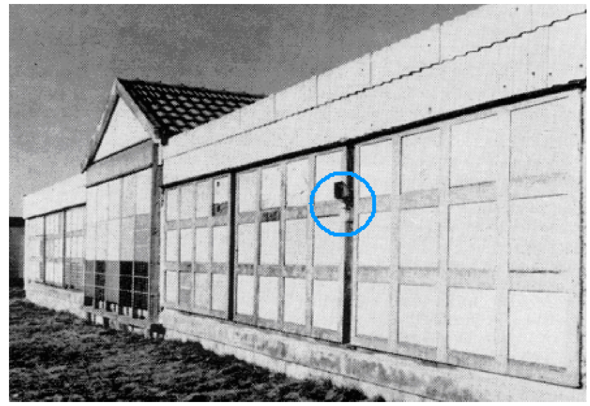

Figure 2 *West façade of test hall with removable wall elements in 1962. The circle marks the position of the driving rain gauge.*

subsystems exposed to natural weather. The site is located in the south of Munich, close to the Bavarian Alps, and was selected because of its rather severe outdoor temperature fluctuations and driving rain incidents compared to most other locations in Germany. In order to examine a wide range of bricks, stuccos, and coatings, a test hall was erected containing removable façade elements pointing west (driving rain exposure) and east (sheltered by roof overhang). The west side of this hall with the 50 cm × 50 cm (20 in. × 20 in.) perimeter sealed wall elements between wooden frames is depicted in Figure 2. The wall elements consisted of perforated clay brick or autoclaved aerated concrete (AAC) masonry with lime or lime-cement stucco. On the exterior surface of some elements, water-repellent coatings were applied. During the test period from October 1960 to March 1962, the interior of the test hall was kept at 20°C (68°F). At certain intervals, the water content of the wall elements was gravimetrically recorded by weighing the wall sections after removing them from the façade.

The variation in water content of different brick wall elements is shown in Figure 3. While all elements pointing to the east (sheltered side) dried out continuously at nearly the same rate, the drying process of the west-facing elements was clearly affected by driving rain events. One wall element even regained the high initial water content after a rainy period in May. If the façade elements had appropriate driving rain protection, the moisture behavior would have been almost independent of the orientation, i.e., wall elements exposed to the west would not contain any more moisture than those facing east.

One way of improving the degree of rain protection is to reduce the capillary suction of the stucco by adding a water repellent to the makeup water of the stucco. Test results in Figure 4 show that the degree of water repellency depends on the concentration of the impregnation in the stucco mixture. In this investigation a silicone content of at least 5% of the makeup water is necessary to achieve good rain protection performance of the stucco. Alternatively, a water-repellent coating or impregnation may be applied to the finished stucco. In order to find out what compounds of a stucco or coating guarantee an appropriate rain protection for exposed façades, numerous combinations need to be tested. Since extensive field tests are expensive and time-consuming, an alternative way to determine the rain protection performance of stuccos and coatings is needed.

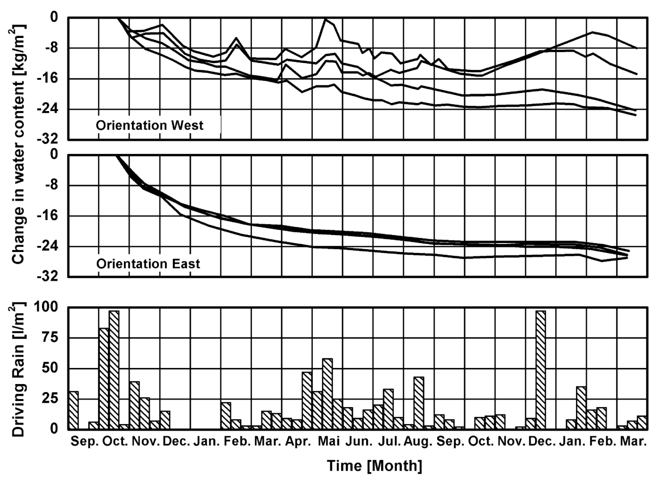

Figure 3 *Measured water content variation of initially wet (construction moisture) brick wall elements with lime or lime-cement stucco with and without paint coat (Künzel 1966). The driving rain load (below) was determined by a rain gauge at the west façade (Figure 2); the east façade is sheltered by a roof overhang.*

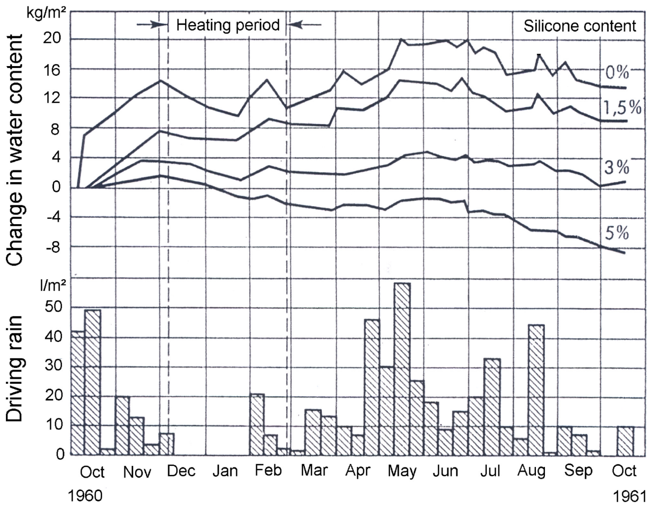

Figure 4 *Measured water content variation of exposed (see driving rain load below) aerated concrete wall elements with lime stucco. To the make-up water of the stucco, 0% to 5% of a silicone impregnation was added (Künzel 1964).*

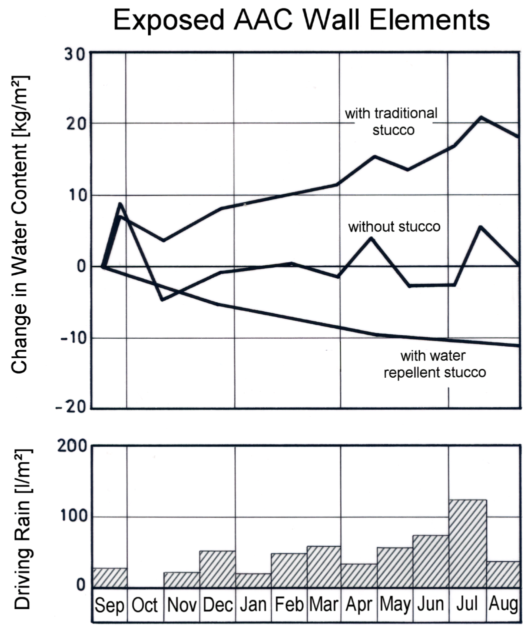

Figure 5 *Monthly driving rain load and water content of aerated concrete wall elements without stucco, with traditional lime-cement stucco or water repellent stucco.*

DEFINITION OF RAIN PROTECTION CHARACTERISTICS

In order to relate the moisture behavior of external walls to the well-defined hygrothermal characteristics of the exterior layers (stucco or coating), the natural wetting and drying processes must be analyzed. Examining the moisture behavior of AAC wall elements with and without different types of stucco in Figure 5 shows that the water content variation is determined by the balance between rainwater absorption and the subsequent water release in dry weather. From the slopes of the curves it may be concluded that the wall with water-repellent stucco does not absorb any significant amount of rain. That means the capillary transport capacity of this stucco is very small and the initial moisture of the AAC blockwork dries out by vapor diffusion through the stucco layer. The water absorption of the wall element with traditional stucco is similar to the one without stucco. However, the water release is considerably diminished by the stucco layer. The capillary transport in the wall that accelerates the drying process of the blockwork without stucco seems to be obstructed. This capillary obstruction appears only during the drying process. Therefore, the remaining moisture transport in the stucco is likely to be pure vapor diffusion, which is much less efficient than capillary suction.

When wind-driven rain hits the façade and a continuous water film forms on its surface, the water uptake of the wall element is controlled by the water absorption coefficient (*A* value) of its surface layer. In the laboratory the water absorption coefficient is determined by immersing the stucco surface in water and plotting the water uptake in kg/m^2 over the square root of time (see EN ISO 15148). In most cases this plot results in a straight line whose slope is defined as the *A* value (units: kg/[m^2·h$^{1/2}$] or kg/[m^2·s$^{1/2}$]). Thus, the water absorption by the façade (m_{abs}) during a spell of heavy wind-driven rain t_{rain} can be described by the following equation:

$$m_{abs} = A \cdot \sqrt{t_{rain}} \qquad (1)$$

Once the wind-driven rain stops, the surface layers will dry out rather quickly. Because the interface between stucco and masonry may form a resistance to liquid flow, the moisture flux from the masonry to the stucco is generally not sufficient to keep the water content of the stucco above the critical water content for capillary conduction. Therefore, the bulk of the precipitation moisture from the wall has to dry out through the stucco by vapor diffusion. Thus, the vapor diffusion resistance of the stucco or coating is likely to determine the drying process of the whole wall. This hypothesis is also supported by the field test results in Figure 5. Laboratory tests that have been carried out to demonstrate the moisture-accumulating effect of the traditional stucco (in Figure 5) confirm the hypothesis. In this experiment AAC samples, with and without stucco, were sealed all around except for one surface that was immersed in water for 32 hours. Afterward the samples were taken out of the water and left to dry in the laboratory for 60 days. During the experiment, the water content of the samples was recorded

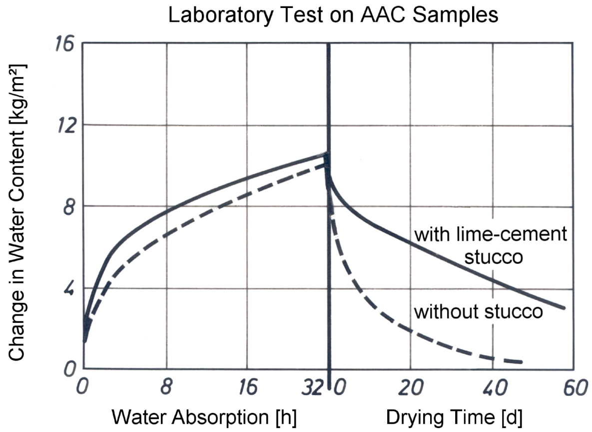

Figure 6 *Water absorption (32h immersion in water) and subsequent drying for ca. 50 days in laboratory air of aerated concrete samples untreated and with stucco applied to the unsealed surface (Künzel 1964).*

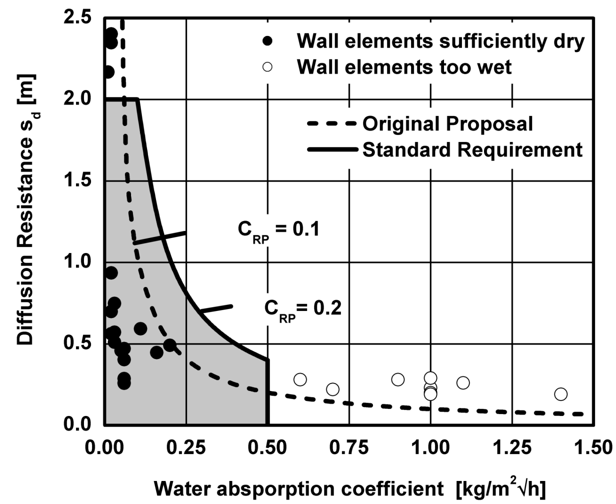

Figure 7 *Measured hygrothermal parameters of stuccos and coatings with good and unsatisfactory field test performance. The hyperbola for CPR = 0.1 forms the empirical performance dividing line upon which the present standard requirements (indicated in grey) are based.*

by weight measurements whose results are plotted in Figure 6. While the samples with and without stucco take up almost the same amount of water by capillary absorption, the sample with stucco dries significantly slower. After a short initial period, the water loss of this sample is a linear function of time, indicating that the stucco indeed acts as a constant resistance to the drying process of the AAC block.

In Europe the vapor diffusion resistance of a material layer is usually described by its diffusion equivalent air layer thickness (s_d value: s = thickness, d = diffusion) in meters (see EN ISO 12572). The s_d value describes the thickness of an air layer (stagnant air) with the same diffusion resistance as the tested material layer. The amount of water drying out (m_{dry}) during a typical period of dry weather (t_{dry}) can therefore be described in a simplified way by the diffusion equation:

$$m_{dry} = \frac{\delta_{air}}{s_d} \cdot \Delta p(\theta, \varphi) \cdot t_{dry} \qquad (2)$$

with δ_{air} (kg/[m^2·s·Pa]) being the diffusion coefficient of water vapor in air and Δp (Pa) the average vapor pressure difference between the wet masonry beneath the stucco and the outdoor air during the dry period. This vapor pressure difference is a function of the representative outdoor air temperature and humidity for typical dry periods at the location of the façade. To avoid any moisture accumulation in an external wall, m_{dry} has to be greater than m_{rain}. Therefore, the combination of Equations 1 and 2 leads to the following relation:

$$A \cdot S_d < \delta_{air} \cdot \Delta p(\theta, \varphi)\frac{t_{dry}}{\sqrt{t_{rain}}} \qquad (3)$$

where the product of A and s_d must be smaller than the parameters on the right-hand side of Equation 3. Apart from δ_{air}, which is a constant parameter (its dependence on ambient pressure and temperature is of minor importance here), the typical periods of wetting (t_{rain}) and drying (t_{dry}), as well as the average vapor pressure difference during dry periods, depend on the local climate. Since it is rather difficult to determine the climate-dependent parameters separately, they are lumped together in a constant driving rain protection coefficient C_{RP}. Thus, Equation 3 can be represented by the hyperbola,

$$A \cdot S_d < C_{RP} \,. \qquad (4)$$

C_{RP} can be derived from field experiments by plotting the water absorption coefficient A and the vapor diffusion resistance s_d of stuccos or coatings with good and bad performance history in one diagram. The classification of stuccos and coatings in Figure 7 is based on the moisture behavior of the exposed façade elements described above. If the elements facing west (driving rain exposure) dried as fast as those facing east (sheltered side), the driving rain protection offered by the stucco was considered appropriate. In that case, the influence of wind-driven rain is compensated by the more favorable drying conditions prevailing at the west side of the test hall because it is not shaded by a roof overhang. The driving rain protection is inappropriate if the water content of the west-facing elements is significantly higher than the water content of the sheltered (east-facing) elements. The hyperbola in Figure 7, defined by the rain protection coefficient C_{RP} = 0.1 kg/(mh$^{1/2}$), appears to form an adequate performance limit.

Because driving rain is not the only possible moisture source in walls, the vapor diffusion resistance of the exterior

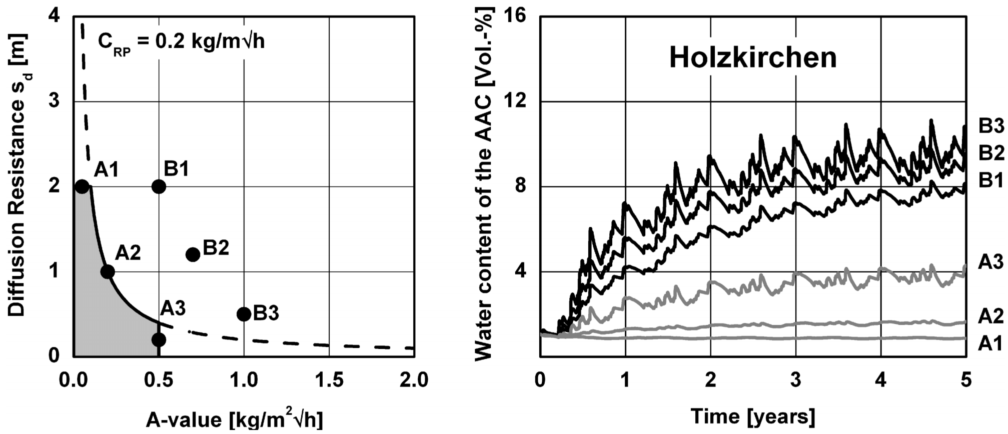

Figure 8 *Left: Hygrothermal characteristics of the stucco layers selected for the simulations. Only the stuccos A1 to A3 comply with the standard performance criteria. Right: Simulated water content variation of the masonry with the stuccos specified on the right, for the climate of Holzkirchen (Germany).*

surface layer should be limited even if no rain water absorption takes place. In order to prevent interstitial condensation problems, the maximum s_d value is set to 2 m (i.e., permeance of stucco layer > 1.6 perm). There is a similar threshold for the A value, which should not be too high even if the drying potential is sufficient due to thermal performance requirements. Therefore, the A value may not exceed 0.5 kg/(m^{2}h$^{1/2}$). Taking into account these two limits and the fact that the large open plane around the field test site of Holzkirchen and its altitude of 680 m above sea level result in rather severe climate conditions, the rain protection coefficient C_{RP} was increased slightly to 0.2 kg/(mh$^{1/2}$) for the German standard on rain-protecting stuccos and coatings (see grey area in Figure 7). These requirements have not been altered since their introduction into the German standard on rain-protecting stuccos and coatings in the late 1960s because practical experience confirmed their usefulness. As recently as 2001 these requirements were also implemented into the German standard on energy savings in buildings (DIN 4108).

VERIFICATION OF THE STANDARD REQUIREMENTS BY HYGROTHERMAL SIMULATIONS

When the concept of rain-protecting stuccos and coatings was developed in the 1960s, there were no hygrothermal simulation models available to verify or modify this empirical relationship. It is different today when such tools are frequently employed for building envelope design and moisture damage prevention. In this paper the PC program WUFI® (Künzel 1995) will be applied with climatic data from Karagiozis et al. (2001). WUFI® has been extensively benchmarked and validated on numerous field and laboratory data, especially for façade systems exposed to wind-driven rain. The excellent agreement achieved between measured and calculated results (Künzel 1995; Künzel and Kieβl 1996) provides the needed level of confidence for conducting this analytic study.

Considered is an external wall of a residential building consisting of 36 cm (14 in.) AAC blockwork (bulk density 600 kg/m^3) with interior gypsum plaster (10 mm) and light colored (a_s = 0.4) exterior stucco on lime-cement base (15 mm). Having a U-factor of 0.35 W/(m^2·K) or 0.06 Btu/(ft^2·h·°F), this wall complies with modern energy requirements. The indoor climate varies from 20°C (68°F) and 40% RH in winter to 22°C (72°F) and 60% RH in summer. The selected locations for the building are Holzkirchen (Germany), where the field test took place in the 1960s, and the coastal U.S. cities of Boston and Seattle. The external wall will be exposed to the orientation with the highest driving rain load, which is west in Holzkirchen (annual sum: 400 L/m^2), northeast in Boston (400 L/m^2), and south in Seattle (250 L/m^2). The climate data for cold years at the specified U.S. locations come from the WUFI-ORNL/IBP database. The hygrothermal material properties of the wall construction are taken from its material database. For the parametric study, the water absorption and vapor diffusion characteristics of the exterior stucco are varied over a range of $0.25 \le s_d \le 1.0$ m and $0.05 \le A \le 1.0$ kg/(m^{2}h$^{1/2}$). They are selected in such a way that three stuccos (A1 - A3) comply with the standard requirement and three stuccos (B1-B3) do not (see Figure 8).

Starting in January the water content of the wall is calculated on an hourly basis over a period of five years by repeatedly applying the same climatic data set. In the beginning the walls are air dry, which means in practice that all materials contain sorption moisture in equilibrium with an ambient humidity of 80% RH (EMC_{80} of ACC = 1 vol.-%). In reality most walls contain a fair amount of construction moisture (ca. 15 vol-% for AAC blockwork) when the building has just been erected. This was also the case in the field tests described above. Ninety percent of all external walls, however, will dry down to the so-called practical moisture content (ca. 2 vol-% for AAC blockwork) if appropriately protected from wind-driven rain.

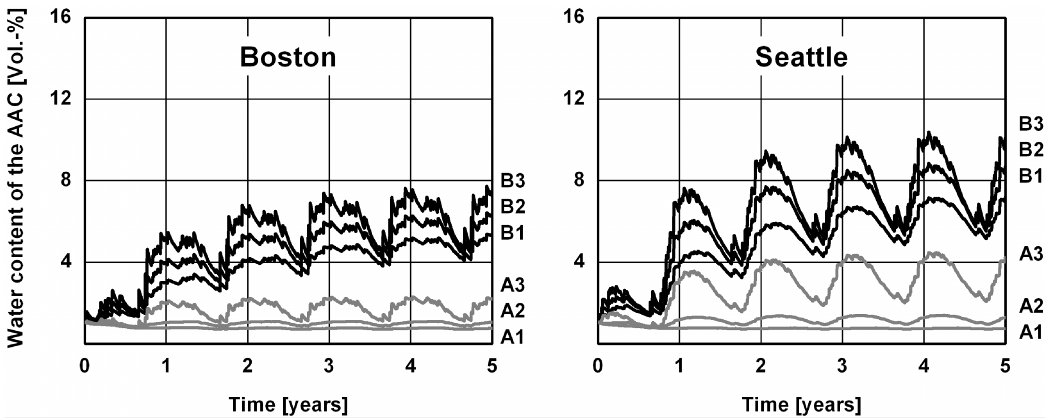

Figure 9 *Variation of the masonry water content with the stuccos specified in Figure 8 for the climate of Boston and Seattle.*

The simulated water content variation of exposed AAC walls with the stuccos specified in Figure 8 (left) are plotted on the right-hand side of the same figure. None of the stuccos with $C_{RP} > 0.2$ kg/(mh$^{1/2}$) shows an acceptable rain protection performance. In all cases the average water content rises above 8 vol.-%, which represents eight times EMC_{80} or four times the practical moisture content. The walls with the stuccos that comply with the standard requirement perform much better. The water content of the walls with the stuccos A1 and A2 stays below the practical moisture content of AAC (2 vol.-%). The wall with the stucco A3 reaches a mean water content of nearly 4 vol.-%. This will not do any damage to the wall, but its U-factor will be increased by ca. 15% compared to the dry situation. However, this is probably the worst case because the capillary interface resistance between stucco and AAC blockwork had been neglected for the calculations. In total, the results of the hygrothermal simulations seem to confirm the validity of the empirical specifications for rain-protecting stuccos developed 40 years ago.

To find out whether these specifications could also be transferred to other parts of the world, the hygrothermal simulations were repeated for the coastal climates of Boston and Seattle in the United States. The water content variation of the same wall samples as before is plotted in Figure 9 for the most exposed orientations of Boston and Seattle. The results show the same tendency as in Holzkirchen. Again, the stuccos that comply with the standard requirements (A1-A3) do reasonably well, while the application of a stucco with the properties B1, B2, or B3 leads to an unacceptable moisture content in the external wall.

CONCLUSIONS

In regions with high driving rain loads, stuccos and coatings that are directly applied on masonry should have special moisture-related characteristics in order to protect external walls from degradation and diminished thermal resistance. The performance criteria for an appropriate rain protection provided by the exterior surface layer include specific limits for water absorption and diffusion resistance. They were developed by evaluating field test results from the alpine region of Germany. Hygrothermal simulations confirmed the effectiveness of these performance criteria for stuccos applied to exposed walls in Germany and northern coastal regions in the United States. For climatic regions with lower driving rain load or higher average temperature compared to those investigated here, less stringent specifications may be also adequate. In this case, hygrothermal simulations may help to modify the specifications appropriately.

In order to guarantee that products comply with the described specifications concerning water absorption and diffusion resistance, quality control standards must be implemented. The hygrothermal characteristics should not degrade with time. In Germany, rain-protecting stuccos and coatings are also used for external insulation systems (EIFS) because their low water absorption helps to keep the insulation layer dry. In recent years the application of stucco with mineral binders has increased. Generally, mineral stucco is very permeable and provides a good drying potential for the wall when used in combination with fiber insulation. However, its high vapor permeability may also be a disadvantage in cooling climates.

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