Rehabilitation of Concrete Walls Using Additional Thermal Insulation

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ABSTRACT

Exterior walls of concrete buildings frequently exhibit surface deterioration due to corroding reinforcement. The usual method of concrete repair of these walls is expensive, and the results may be less than perfect. Diffusion calculations demonstrate that it is possible to dry the exterior walls of concrete buildings in a Central European climate by attaching additional thermal insulation to the outside of these walls. Laboratory and field tests confirm that it is possible to actually arrest the rebar corrosion.

Calculations using the WUFI-IBP/ORNL hygrothermal computer model show that exterior walls of concrete buildings will dry by means of additional thermal insulation in some North American climates too. This method makes it possible to arrest the rebar corrosion without the usual concrete repair and, at the same time, save heating or cooling energy.

INTRODUCTION

Background

Exterior walls of concrete buildings frequently exhibit surface deterioration due to corroding reinforcement. The usual method of concrete repair of these walls requires numerous repair steps (Figure 1), and the results may be less than perfect.

For steel corrosion in reinforced concrete, the following physical conditions have to occur at the same time. If one of the following conditions is missing, there will be no corrosion.

- The presence of oxygen is necessary. The concrete porosity makes the penetration of oxygen inevitable.
- The passivation of the rebar surface must be neutralized by chlorides or carbonation. (The penetration of chlorides is only a problem for bridges contaminated by deicing salt and marine structures. Carbonation of concrete is a slow but unavoidable process.) When deterioration is visible, the rebar surface is evidently depassivated.
- The concrete moisture must enable an electrolyte.

Thus, rebar corrosion can only be arrested by reducing the concrete moisture level in such a way that there is no sufficient electrolyte. Experiences with existing residential and office

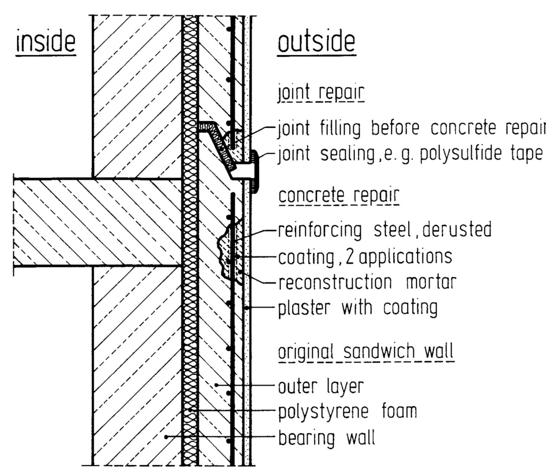

Figure 1 *Exterior wall of a concrete building with common concrete repair.*

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Table 1. Investigated Types of Additional Thermal Insulation Systems

Type	Additional Thermal Insulation	Weather Protection
1	None (zero test)	No additional
2	60 mm (2.4 in.) polystyrene foam	Synthetic stucco (EIFS)
3	60 mm (2.4 in.) mineral wool	Inorganic lightweight stucco (EIFS)
4	60 mm (2.4 in.) fiberglass	Ventilated cladding

buildings in a Central European climate show that the concrete walls inside the buildings are considerably carbonated, but the rebars do not corrode there. It can be concluded that there is no electrolyte present in the dry but carbonated concrete.

Therefore, adding insulation to the exterior side of a concrete wall appears to help it dry out by making the concrete warmer, thus increasing the vapor pressure of the moisture in the concrete. It can be demonstrated by steady-state diffusion calculations that it is possible to dry the exterior walls of concrete buildings in a Central European climate by attaching an additional thermal insulation to the outside of these walls (Figure 2). The tests mentioned below verify that it is possible to actually arrest rebar corrosion by means of additional thermal insulation (Marquardt 1994, 1995, 1998; Cziesielski 2001).

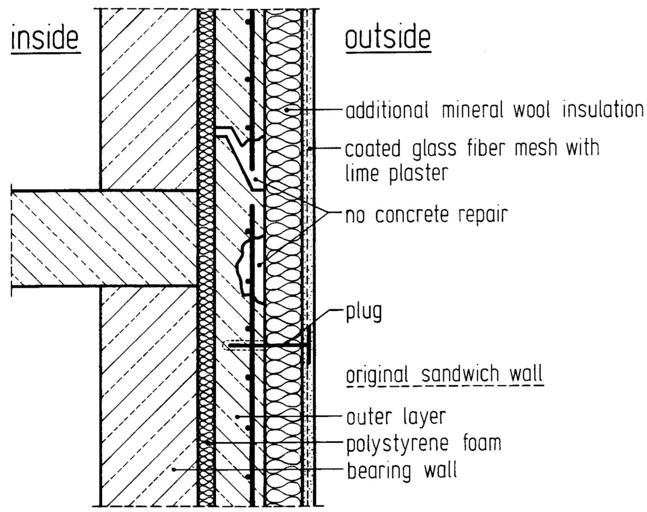


Figure 2 *Exterior wall of a concrete building with alternative repair using an exterior insulation and finish system (EIFS).*

Hypothesis

Some North American climates are similar to the climate in Central Europe. For that reason, it may be possible to arrest rebar corrosion in exterior walls of concrete buildings by means of additional thermal insulation in North America too. The objective of this paper is to verify this hypothesis by using the WUFI-IBP/ORNL hygrothermal computer model (Karagiozis et al. 2001).

First, this paper will summarize and discuss laboratory tests, long-term field tests, and in-situ tests, followed by calculations regarding Central European and North American climates and a discussion of the results.

TESTS

Laboratory Tests

In a first step, reinforcing steel specimens were stored in industrial atmospheres of different relative humidity. After some time, the mass loss (material consumption) due to corrosion was investigated. The tests confirmed the well-known fact that corrosion does not occur in atmospheric conditions with a relative humidity of up to 50%, whereas 60% relative humidity or more causes increasing steel corrosion depending on the reinforcing steel type used.

In a second step, accelerated carbonated concrete specimens with steel bars were stored in atmospheres of different relative humidity. After some time, the specimens were investigated for steel corrosion with the following results:

- All steel bars showed basic corrosion caused by the carbonation of the concrete specimens.
- After four years of investigation, the basic corrosion level did not change in specimens that were stored in climates with a relative humidity of 60% or 70%, and, for specimens stored in a climate of 80% relative humidity, the rebar corrosion increased negligibly.
- When stored in climates with 90% relative humidity, the rebar corrosion in the specimens showed a significant growth over time.

Long-Term Field Tests

To verify the above-mentioned hypothesis, long-term field tests were carried out on a residential building without air conditioning in Berlin, Germany. Two exterior insulation and finish systems (EIFS) and a ventilated cladding were attached to the building in September 1987 (Table 1).

Temperatures and moisture in the concrete sandwich exterior walls with and without the additional thermal insulation systems were recorded for more than five years. The combined transducers for temperature and relative humidity (for measuring the equilibrium humidity, i.e., the equilibrium moisture content of a material at a given relative humidity) were installed (protected against rain and sun) in the atmosphere, in the bearing walls and the outer layers of the investigated concrete walls (Figure 3), as well as in the inhabitated apartments behind the investigated walls.

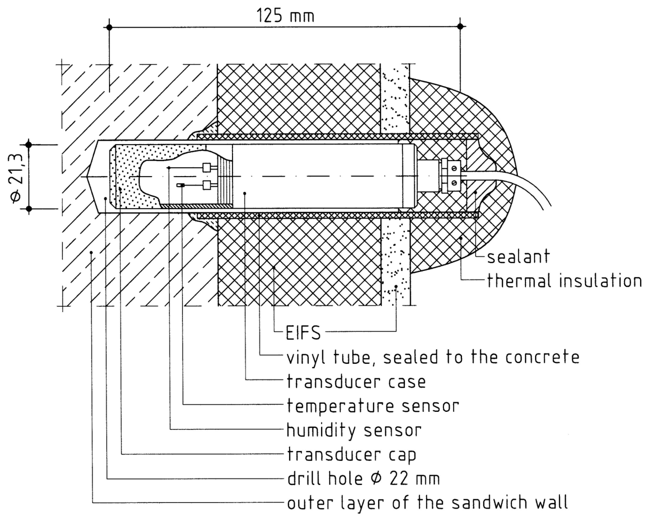


Figure 3 *Combined transducer for temperature and relative humidity, e.g., located in the outer layer of a concrete sandwich wall with an EIFS.*

The measurements were recorded automatically using a personal computer:

- The outer layers of the sandwich walls dried significantly behind the additional thermal insulation and, after a few years, the concrete moisture level was in an equilibrium at the measured relative humidity of 40% to 70% (Figure 4).
- The load-bearing walls dried too and, after a few years, the concrete moisture level was in an equilibrium at the measured relative humidity of 30% to 60%.

The drying process was slower when less vapor permeable materials were used on the exterior of the concrete wall.

Practical In-Situ Tests

To investigate the reliability of the above-mentioned method in practice, three series of field tests were carried out:

- Steel bars were placed in the ventilated cavity between the cladding and the additional fiberglass insulation (Type 4, cp. Table 1).
- Steel bars were also mounted between the different additional thermal insulations (Types 2, 3, and 4, cp. Table 1) and the outer layer of the original concrete wall.

In the course of one year, the thermal insulation systems were opened every three months and the steel bars were examined:

- The bars that were only protected against rain, i.e., in the cavity just behind the cladding (Type 4), were clearly corroded (Figure 5), while the rebars mounted between the fiberglass insulation and the concrete wall were free of any corrosion (Figure 6).
- The rebars mounted between the mineral wool insulation (Type 3) and the concrete wall were almost free of corrosion.
- The rebars mounted between the diffusion delaying polystyrene foam insulation (Type 2) and the concrete wall were partially corroded.

After the visual observation, the mass loss (material consumption) of all steel bars was investigated. It was obvious that the thermal insulation systems of Type 3 and Type 4 were suitable to assess the rebar corrosion in concrete exterior walls. Type 2 seemed to be insufficient; however, in this practical test, the steel bars showed corrosion in atmospheric conditions and not in realistically carbonated concrete.

Discussion

The laboratory tests show that steel corrosion in reinforced concrete can be arrested if the concrete moisture level is in an equilibrium of less than 80% relative humidity in relation to the surrounding atmosphere. This result does not depend on the reinforcing steel type and has been confirmed by Raupach (1992a, 1992b).

The field tests demonstrate that it is possible to arrest rebar corrosion in concrete walls in Central European or similar climates by applying thermal insulation. Additional corrosion protection (as used for common concrete repair) is not necessary (Figure 7)

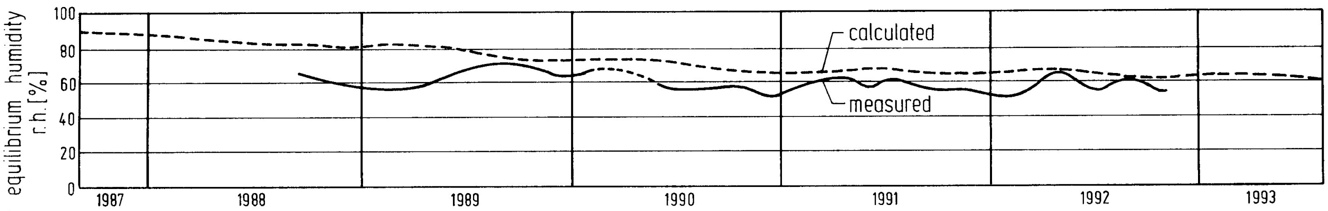
- because the concrete walls with additional thermal insulation will get moisture in equilibrium with a relative humidity of 30% to 70% after a few years of drying, and
- because, on the other hand, steel in carbonated concrete specimens needs more than 80% relative humidity in order to corrode (cp. the laboratory tests).

Thus, there will be no corrosion growth of the reinforcement in concrete exterior walls with additional thermal insulation. Practical in-situ tests have confirmed the advantages of this method if suitable thermal insulation systems are attached to the exterior walls. In fact, it can be established that rebar corrosion in these exterior walls will be arrested so that a state-of-the-art concrete repair of such walls—which is expensive and may be imperfect—becomes unnecessary.

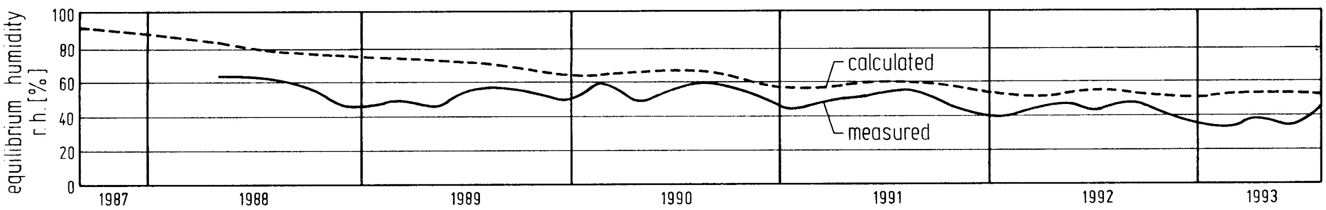
CALCULATIONS

Calculations of the Long-Term Field Tests in Central European Climate

The measured equilibrium humidity is compared with computer calculations using the WUFI–IBP/ORNL hygrothermal model (Künzel and Gertis 1996). In contrast to the above-mentioned steady-state diffusion calculations, the advantage of this model is that it does not ignore the time-



(a)



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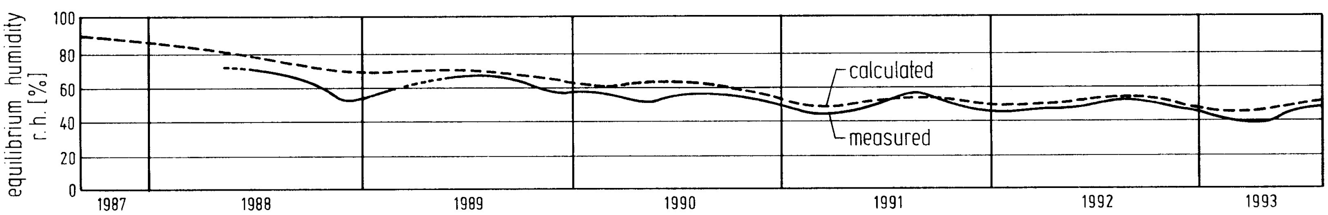

(c)

Figure 4 *At a height of 20 m (65.6 ft), measured and calculated equilibrium humidity in the outer layers of concrete exterior walls with thermal insulation: (a) EIFS made of 60 mm (2.4 in.) polystyrene foam with synthetic stucco, (b) EIFS made of 60 mm (2.4 in.) mineral wool with inorganic lightweight stucco, (c) 60 mm (2.4 in.) fiberglass with ventilated cladding.*

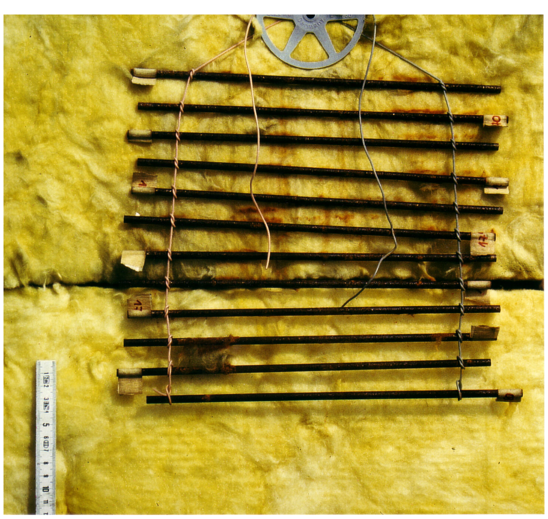

Figure 5 *Unprotected steel bars after one year of in-situ storage behind the ventilated cladding in front of the fiberglass insulation.*

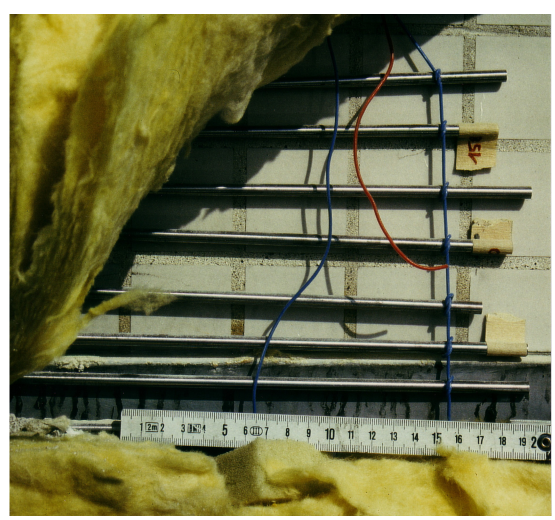

Figure 6 *Unprotected steel bars after one year of in-situ storage between the fiberglass insulation and the outer layer of the concrete exterior wall.*

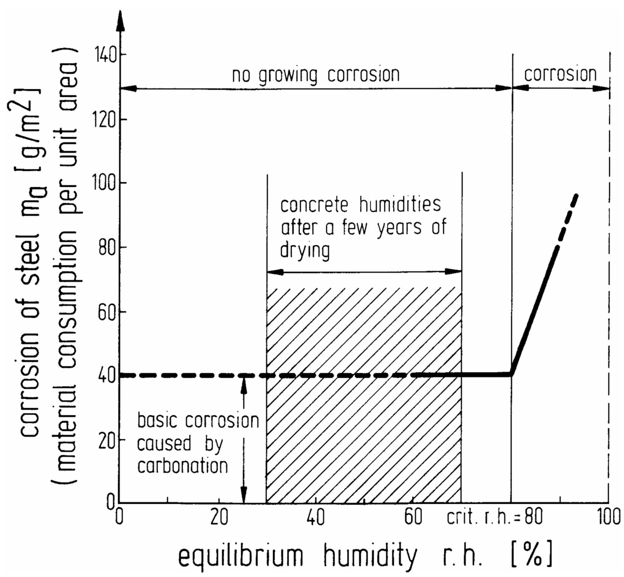

Figure 7 *Scheme of arresting rebar corrosion in concrete exterior walls using additional thermal insulation.*

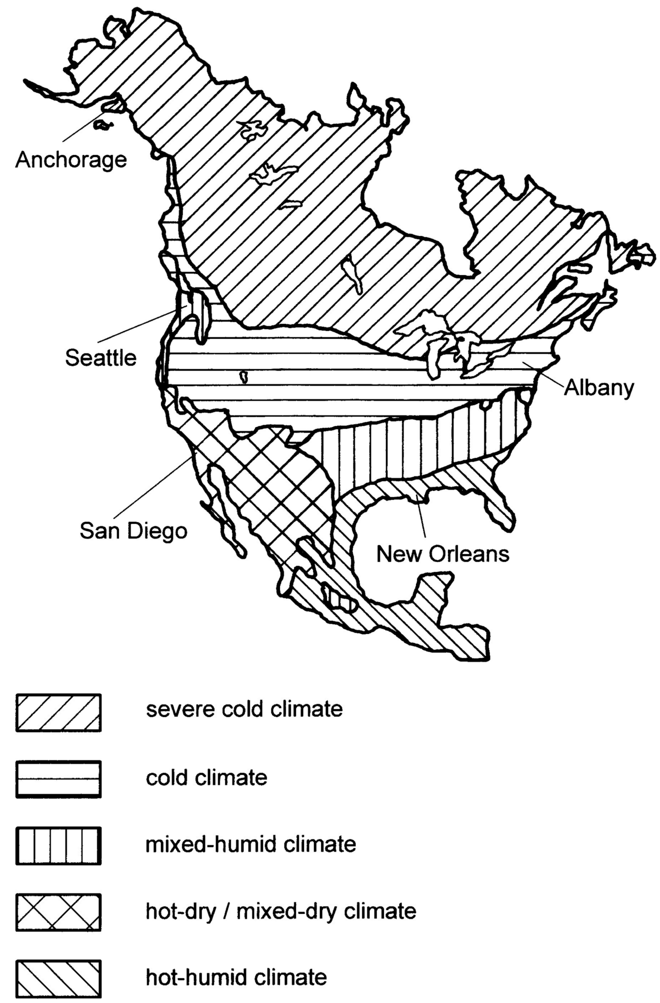

Figure 8 *Climatic zones of North America: in each zone, concrete walls with additional thermal insulation have been calculated using the WUFI-IBP/ORNL hygrothermal model for the mentioned city.*

dependent hygroscopic effects, such as nonlinear dependencies of hygroscopic material properties, moisture storage, freeze-thawing mechanisms, liquid transport, and latent heat (Karagiozis et al. 2001).

The WUFI-IBP/ORNL model cannot calculate the airflow in a ventilated cavity; therefore, the wall with a ventilated cladding (type 4, cp. Table 1) is simulated using the outdoor climate in the cavity. Although

- the estimated equilibrium humidity at the starting point of the calculations seems to be higher than the real one and
- the model uses a simplified climate (not the real weather),

it is obvious that the computer calculations approximate the measurements closely (cp. Figure 4).

Calculations with North American Climates

North America can be divided into five climatic zones (EEBA 2002). Each zone is represented by one city for which computer calculations are made using the WUFI-IBP/ORNL hygrothermal computer model (Figure 8). The indoor climate is a controlled climate according to the North American industry standard.

- θ_i = 24°C (75°F)
- ϕ_i = 50% or 55% relative humidity (TenWolde and Walker 2001)

The calculated concrete walls have additional thermal insulation (cp. Figure 2)

- by an EIFS made of 100 mm (4.1 in.) polystyrene foam with 8 mm (0.3 in.) synthetic stucco or
- by an EIFS made of 100 mm (4.1 in.) mineral wool with 8 mm (0.3 in.) inorganic lightweight stucco.

The calculations using the WUFI-IBP/ORNL hygrothermal computer model are made with the parameters according to Table 2. The results are shown in Figures 9 and 10.

Discussion

The calculations mentioned above present the following results (Marquardt 2003):

- Attaching an exterior insulation and finish system (EIFS) the concrete moisture level will lower the equi-

Table 2. Parameters Used for the Calculations by Means of the WUFI-IBP/ORNL Model

Height of the building Orientation of the façade Original sandwich wall Initial conditions	10 to 20 m (32.8 to 65.6 ft) North (lowest solar radiation = lowest drying possibility) 150 mm (6.1 in.) bearing concrete wall, 50 mm (2.0 in.) polystyrene foam insulation, 65 mm (2.7 in.) outer concrete layer θ_0 = 20°C (68°F), ϕ_0 = 80% relative humidity

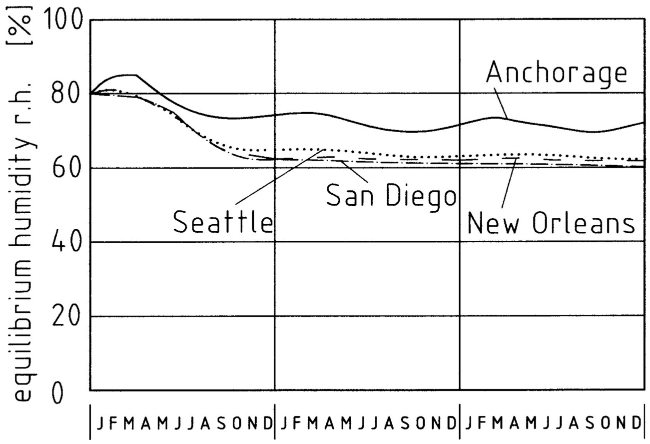

Figure 9 *WUFI-IBP/ORNL calculated equilibrium humidity (relative humidity) in the outer layer of a concrete wall with an EIFS made of polystyrene foam with synthetic stucco in Anchorage, AK, Seattle, WA (≈ Albany, NY), San Diego, CA, and in New Orleans, LA.*

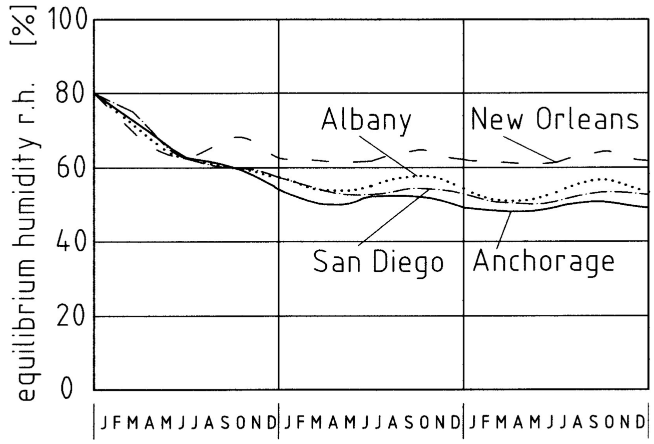

Figure 10 *WUFI-IBP/ORNL calculated equilibrium humidity (relative humidity) in the outer layer of a concrete wall with an EIFS made of mineral wool with inorganic lightweight stucco in Anchorage, AK, Albany, NY, San Diego, CA, and New Orleans, LA.*

librium humidity to less than 80% after several months in all North American climates (cp. Figure 9 and Figure 10). In most North American climates, concrete walls behind EIFS made of mineral wool dry faster than behind EIFS with polystyrene foam, thus confirming the Central European results (cp. Figure 4)—with the exception of the hot-humid climate of New Orleans, LA.

- As stated above, the growth of corrosion of the reinforcement in concrete exterior walls with additional thermal insulation will be impossible if the equilibrium humidity in the concrete is less than 80% of relative humidity.

Thus, additional thermal insulation arrests the rebar corrosion in all North American climates. This is possible because of the North American industry standard (50% or 55% relative humidity); however, the indoor climate may become more humid

- without a dehumidifier in the air-conditioning equipment or
- with reduced ability of the unit to remove moisture (TenWolde and Walker 2001).

For that reason, the equilibrium humidity in the concrete walls will increase in a hot-humid climate and may cause rebar corrosion. (In a hot-dry or severe cold climate with lower indoor humidity, the equilibrium humidity in the concrete walls will decrease, of course.)

CONCLUSIONS

It can be established that rebar corrosion in exterior concrete walls will be arrested in some North American climates by suitable additional thermal insulation, i.e., by exterior insulation and finish systems (EIFS). Thus, a state-of-the-art concrete repair of these walls—which is expensive and may be imperfect—is rendered unnecessary. At the same time, this rehabilitation method saves heating or cooling energy.

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