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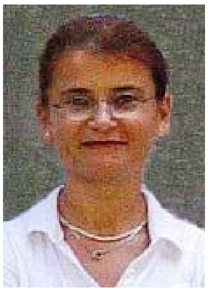
Temperature and moisture conditions in materials – Effects on risk for degradation of rendered autoclaved aerated concrete



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ABSTRACT

Temperature and moisture conditions are, in general, the two major factors influencing the long-term performance of external walls made of porous mineral building materials. Degradation of wall components is accelerated by temperature and moisture induced stresses which lead to cracks and in turn a surface more vulnerable to other degradation agents. The degradation rate depends on both the environmental conditions and the material-inherent and component design properties. Extreme and rapid temperature fluctuations as well as moderate diurnal and seasonal temperature cycles cause thermal stresses and strains in the material, resulting in expansion or contraction and eventual deformation such as cracking or fracture. Material properties such as thermal expansion, elasticity and tensile strength determine if cracking occurs either immeadiately when the surface temperature drops below the initial temperature after rapid cooling or after a period of time if alternating or repeated stresses result in creep and fatigue.

In this paper an attempt is made to evaluate the temperature effects on the risk for degradation of external walls made of rendered autoclaved aerated concrete (AAC) based on temperature measurement data and the material properties. The measurement results are obtained from the continuous microenvironment monitoring carried out on a test cabin built on the roof of the Centre for Built Environment building in Gävle, Sweden. A finite element model (FEM) is used to simply calculate the temperature induced stresses in two different cases; with and without creep and relaxation in the material. According to the microenvironment measurement results the test panels attain maximum surface temperatures up to about 60 °C during summer and experience surface temperature fluctuations between day and night up to about 55 °C during winter. Rapid changes in surface temperatures frequently occur particularly throughout late spring and early summer. The preliminary calculated results indicate that the tensile forces built up during cold spells may be sufficient to crack the surface of AAC panels but the risk for fatigue damages due to combined moisture and temperature cycles induced by radiation from the sun seems to be small. Further studies are needed for better knowledge and reliable information on the degradation mechanisms related to temperature by complementary measurements of stress-strain, stress relaxation, creep and fatigue behaviour of AAC panels under different and cyclic temperature loading.

KEYWORDS

Degradation, microclimate, rendered autoclaved aerated concrete, temperature, moisture.

1 INTRODUCTION

Cement renderings and autoclaved aerated concrete (AAC) are brittle materials with modest tensile strengths and show significant movements due to temperature and moisture changes. Besides diurnal and seasonal cycles, rapid temperature and moisture changes in general cause strains in exposed building materials as a result of expansion and contraction, and these cycles may in turn, if the stress level is high enough, result in fatigue damage. Mainly due to radiation from the sun, the surface temperature may change quickly while the bulk temperature of material changes only slowly. The temperature rise on the surface causes material dry-out at and near the surface zone. When the surface cools down again both temperature and moisture changes cause tensile stresses which may result in surface cracking. Facades facing different directions show differences in condition due to being subjected to degradation agents on different levels. Even material surface characteristics like colour, reflectivity, texture and roughness have effects on the dose of agents and contribute to the heat and moisture transfer mechanisms. The degradation rate is dependent on the condition, which is determined by the microclimate, and the microstructure of the surface material. In the long-term performance evaluation of external walls, particularly those made of porous mineral building materials, it is important to consider temperature effects as much as the moisture effects.

Limited research is carried out, particularly on the degradation of inorganic mineral building materials induced by temperature conditions while most studies are based on initial drying shrinkage properties of cement-based materials. This paper focuses, in general, on the actual temperature conditions in rendered AAC walls, and in particular, on the risk for degradation by thermal cracking. Panels are exposed to large temperature variations, mainly due to solar radiation, with relatively low impact of driving rain on the one side of a test cabin. Panels exposed on the opposite side, however, are hardly ever hit by sunlight and receive significantly higher amounts of driving rain. Our hypothesis is that if the moisture is the principal degradation agent, more signs of degradation of the renderings would be seen on the wet side of the test cabin. If, on the other hand, the varying temperatures are more important, the sunny side of the test cabin would display more damage.

This study is a part of the EUREKA project DurAAC investigating the durability, service life and the maintenance intervals for external walls made of rendered AAC. The exposure and test programme started in May 1999, and has been running since then. The industrial partners of the project are Yxhult AB Sweden, Maxit (Optiroc) AB Sweden and Wacker Chemie GmbH Germany. The programme and some earlier results have been presented by Kus *et al.* [2004].

2 BACKGROUND

Cementitious materials have initial stress and strain conditions as a result of creep during hardening and drying of material. This creep is often assumed to be in the order of 0,03-0,06 % (from water saturation to equilibrium at 50 % RH), which is higher than the value of max. tensile strain of concrete 0,02 % [Bergström *et al.* 1970]. In unfavourable conditions even small changes of material strain may thus result in crack formation. In a material that is not restrained in anyway regarding movements (e.g. a precast building element) the initial stress and strain conditions may be minimized by proper production techniques. In most cases, particularly when mechanical loading is considered, there are restraints against movements to some degree. Movements as a result of uneven temperature and moisture changes in the component are more or less restrained. Stresses and strains in the material usually change during normal use under alternating mechanical loads of different kinds but even changes in temperature and moisture may induce changes in stress and strain.

Thermal and moisture stresses occur when the exterior surface of external walls is exposed to daily and/or seasonal temperature and moisture fluctuations while the internal surface is subjected to a controlled indoor air temperature and RH. The external surface of the wall material endures large variations in temperature due to ambient air temperature and solar radiation. The moisture content of the surface layer also changes rapidly due to these temperature fluctuations and possible wetting of the surface due to driving rain. Damage may occur instantaneously if the stresses are higher than the ultimate strength of the material or at a later stage if repeated stresses result in fatigue of the material. Fatigue is resulted by repeated or alternating load cycling and the effect is dependent on both the magnitude of load and the number of load cycles. Assuming that fatigue in AAC is generated in a similar way as in concrete, the fatigue strength at 2×10^6 cycles will be 57-67 % of the static ultimate strength [Ljungkrantz *et al*. 1997]. Creep under sustained stress depends on the loading as a ratio of the yield strength, the time the load is applied, and the temperature [Neville 1995]. Nielsen [1972] quotes values of ε_c ranging from 1 to 185 for concrete and AAC in compression, depending on different load ratios and time (for a temperature of about 20 °C). Knowledge regarding the material properties which affect the risk for temperature and/or moisture induced cracking of AAC is rather limited, but a simplified estimation of the risk is done based on the information available.

Briefly, the rate, magnitude and frequency of the thermal differentials, the capability of the material to accommodate strain variations and the specific boundary conditions should be considered altogether when assessing cracking potentials. Once the micro cracks arise and further propagate, the material becomes more vulnerable to the other degradation agents accelerating the degradation rate. Excessive water ingress from these cracks increases the moisture content locally which may lead to failures such as loss of adhesion of rendering to the substrate and disintegration of the material. Frost problems may arise for the saturated areas when the temperature falls below zero. Consequently, the durability is impaired and the service life shortened. Material properties determine if the material can withstand the effects of external actions.

3 EXPERIMENTAL PROCEDURES

3.1 Location

The city of Gävle is situated on the east coast of Sweden, by the Baltic Sea, at latitude 60,67° N and longitude 17,10° E, and approximately 5 m above sea level. The climate in Gävle is typical of the middle part of Sweden; the average temperature in summer is about 15 °C with peak temperatures of around 27 °C, and in winter -5 °C with absolute min. about -30 °C. Daylight hours are long (up to 19 hours) during summertime and short in wintertime (down to 4 hours). The summers are relatively sunny with more than half of the days in each month having more than 12 hours sunshine. Average yearly precipitation is around 600 mm and average monthly wind speed all year is about 2 m/s. The exposure station is located on the roof of a building at a height of approximately 7 m. According to the microclimate data monitored at the test site for the time period in question, the yearly average air temperature in winter is 0,8 °C and in summer 13,6 °C, the min. being -22,5 °C and the max. 34,5 °C.

3.2 Test Cabin and Test Panels

Within the framework of the DurAAC project the long-term performance of different rendering systems on AAC is investigated. A test cabin is installed at the exposure site of the Centre for Built Environment (BMG) building in Gävle, Sweden. It is oriented with the long sides facing south-west and north-east, respectively. The indoor temperature is regulated by electrical heaters in order to keep a min. temperature of 15 °C over the year. On each long side, there are 12 test panels including unrendered and untreated AAC as reference panel. Unreinforced AAC panels measuring 600 mm × 1200 mm × 150 mm were used as substrates for the rendering systems tested.

3.3 Materials

AAC having a dry density 423 kg/m^3 is employed as the substrate for the rendering systems tested. The general physical and mechanical properties of AAC are given in Table 1. The general coatings characteristics, of which the measurement results are reported in this paper, are given in Table 2. Panel 1 is untreated AAC (reference panel) but panel 9 is rendered with a coloured surface coating.

Table 1. Properties of AAC [Lättbetonghandboken 1993, Aroni *et al.* 1993]

Thermal conductivity (λ) W/mK	0,110
Coefficient of thermal expansion (α)mm/mm K	8×10^{-6}
Thermal capacity (C) kJ/kgK	1,0 - 1,1
Equilibirium moisture at 40 – 80 % RH (%)	2 - 7
Shrinkage at moisture change from 7 to 2 % µS	180
Young's modulus (E) Mpa	1200
Poisson's ratio (ν)	0,15 - 0, 20
Compression strength MPa (at 10 % moisture content by weight)	2,3
Tensile strength MPa	1/6 of compression strength
Bending strength MPa	1/5 of compression strength

Table 2. Test systems

Panel no	*AAC surface impregnation*	*Primer*	*Undercoat*	*Final coat*	*Colour*	*Thickness (mm)*
1	-	-	-	-	Grayish	-
9	Silane–siloxane emulsion	Acrylic/dolomite–calcite with silicon additive	-	Pure acrylic copolymer /dolomite–calcite	Red	< 1

3.4 Measurements

The exposure and the continuous microenvironment monitoring programme at the test cabin started in May 1999 and have been running since then. Microclimate parameters such as air temperature, air relative humidity, driving rain and radiation (UVA+UVB) are monitored continuously. Surface and bulk temperatures and moisture contents of the test panels are also measured continuously. Wetcorr sensors are used to measure the surface moisture and the surface temperature. Copper-constantan thermocouples are used to measure temperatures at different depths in the material. The moisture contents are also measured at the same depths with resistance type nail electrode pairs. The sensors are scanned at 5-minute intervals and the averages of temperature and resistance are stored every hour by means of a data logger/multiplexer device. For the purpose of the present study data obtained from the measurements carried out at 5-minute intervals are collected during specific time periods in order to capture the most realistic conditions.

3.5 Surface inspection

During the test period samples have been drilled out of the panels on a yearly basis for microstructural investigations by means of light optical and scanning electron microscopy. The changes in surface properties of the test panels during weathering have also been inspected visually. During the summer 2004 a special effort was made for a visual inspection of the test panels at both the north-east and south-west facades by means of a stereo microscope with magnification up to ×40.

4 MEASUREMENT RESULTS

4.1 Material temperature

Measurement data collected through May 1999 to August 2004 indicate that the test panels facing south-west are, as might be expected, subjected to higher solar radiation during longer periods than the test panels facing north-east. Temperature variations are thus both faster and greater on the first mentioned panels. Even during winter, the difference between daily minimum and maximum surface temperatures reaches to about 55 °C. Moreover, the material surface undergoes freeze-thaw cycles beside the extreme temperatures.

The diagram in Fig. 1 demonstrates measured surface temperatures for a selected day. Panel surfaces develop much higher temperatures than ambient air temperature when they are exposed to intense direct solar radiation. It is clearly seen that there is a co-variation between the surface temperature and the UV radiation. Rapid variations in surface temperatures occur specifically during which the sky conditions suddenly change between cloudy, rainy and sunny and can be numerous during one day. The absolute max. surface temperatures recorded are 60,5 °C and 53,2 °C for Panels 9 and 1 at the south-west facade, respectively, when the ambient air temperature is 33,1 °C. The absolute min. surface temperature recorded is as low as -22,9 °C when the ambient air temperature is -21,7 °C. In Fig. 2 differences between surface temperature and the temperatures at 5 mm and 25 mm depth from the surface of the material are exemplified for Panel 9SW. At very short intervals, in less than half an hour, the temperature difference can shift from negative to positive or vice versa. Such a repeated rapid and extreme fall (or rise) in temperature, which is generally faster than experienced under normal circumstances, might cause fatigue between the surface zone and the innermost parts of the material which is in a relatively steady state condition. After a sufficient number of temperature fluctuations, the cumulative synergistic effects of creep and fatigue stresses and strains would lead to ageing which may in turn result in failure as cracking or fracture.

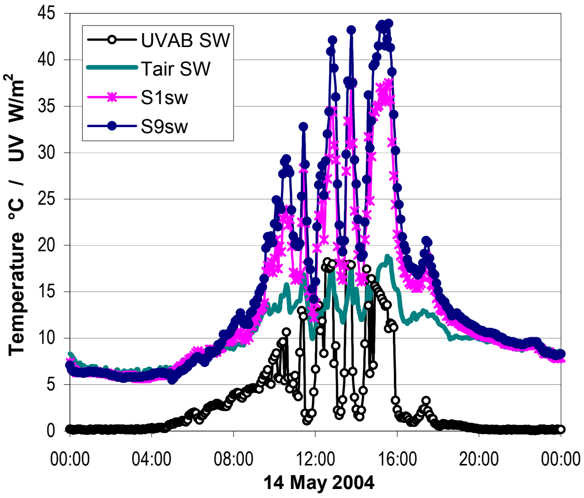

Figure 1. Rapid changes at south-west facade.

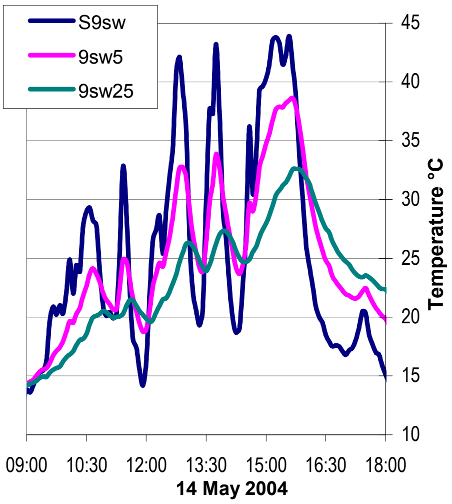

Figure 2. Temperatures of surface and at depths of 5 and 25 mm (Panel 9SW).

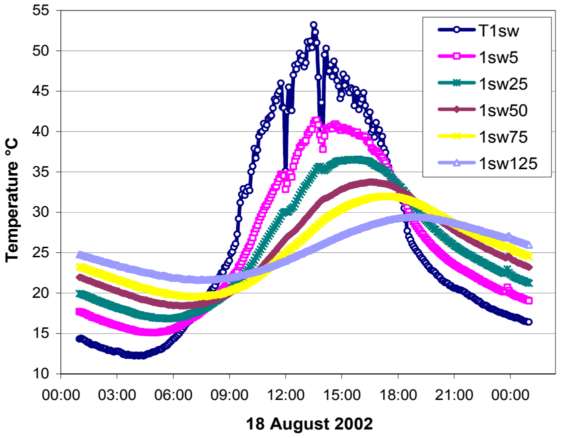

Figure 3. Daily temperature profiles in AAC: 5-min data (Panel 1SW).

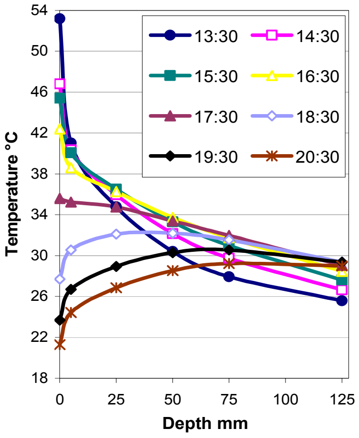

Figure 4. Temperature profiles in AAC measured at specific hours (Panel 1SW).

The greatest diurnal temperature differences and consequently the highest cooling rates occur throughout late spring and early summer. The difference between the daily minimum and maximum temperatures on the panel surfaces of south-west facade reach up to 45,2 °C when the ambient air temperature is min. -4,8 °C and max. 8,6 °C and the surface temperature -7,0 °C and 38,2 °C, respectively. On the panel surfaces of the north-east facade the highest recorded surface temperature is 39,8 °C when the ambient air temperature is 20,3 °C and the min. surface temperature 9,8 °C when the ambient air temperature is 10,4 °C the same day. The highest temperature decrease within 5 minutes for Systems 1 and 9 is 12,1 °C and 11,8 °C, respectively, whereas the highest increase is 12,2 °C and 13,5 °C, respectively. Temperature variations result in large temperature gradients in panel sections. Figures 3 and 4 demonstrate the temperature gradients in AAC (Panel 1SW) measured during 18th August 2002.

4.2 Material moisture

The difference in exposure to driving rain and solar radiation between the facades results in differences in moisture contents. The long-term microenvironment monitoring results indicate clearly that the south-west facade experiences significantly lower amounts of driving rain and thus exhibites relatively low moisture contents. Direct moisture effects are thus of primary concern for the test panels at the north-east facade, particularly for the inorganic test systems without surface treatments, as these panels experience significantly higher amounts of driving rain [Kus *et al.* 2004]. Due to low moisture content freeze-thaw degradation is not considered to be a problem for the rendered panels at the south-west facade. However, stress and strain due to changes in material moisture initiated by the humidity fluctuations in the environment have to be considered for all the panels at both sides.

4.3 Surface inspections

After more than five years of exposure all test panel surfaces, facing either north-east or south-west, are still in quite satisfactory aesthetical condition despite the micro cracks and small discoloration. Very few micro cracks are detected on the test panels of the north-east wall. In general, the coloured surfaces fade more at the south-west facade compared to the ones at the north-east. The micro cracks generally develop around the mineral grains of top rendering coatings, i.e. at the aggregate-paste interphase, and possibly cause the grains to loose and drop after sometime. Randomly distributed individual horizontal and vertical long fine cracks are observed with naked eye on the south-west facade, particularly on the test panels having a smooth plain surface. These cracks probably arise due to thermal stresses. Even though we have not been able to strictly quantify the extent of cracking on the panels, the qualitative evaluation indicates that the panels exposed to temperature variations rather than moisture, display more evidence of deterioration, mainly micro cracking.

5 EVALUATION OF THERMAL- AND MOISTURE INITIATED DEGRADATION

5.1 Risk for thermal cracking

The risk for degradation, particularly thermal cracking, is assessed based on the material properties and the temperature measurements. To simplify the discussion, the material is assumed to be homogeneous, isotropic and linearly elastic (to obey Hook's law). For an infinite plate (in X- and Y-directions, see Fig. 5) with a linear temperature change from one surface to another there is an analytical solution for determining temperature induced normal stress in the heated surface [Timoshenko and Goodier 1970]. According to the analytical solution in Eq. (1), a linear temperature difference of 26 °C results in a compressive stress of about 0,29 MPa on the hotter surface of an AAC component.

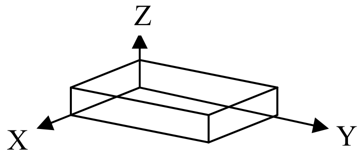

Figure 5. Directions of an infinite plate

$$\sigma = \frac{E \cdot \alpha \cdot \Delta T}{(1-\upsilon)} \qquad (1)$$

where; σ is normal stress in X or Y direction,
E is Young's modulus elasticity,
α is coefficient for thermal expansion,
ΔT is temperature difference between surfaces,
υ is Poisson's ratio of the material.

For a surface, in equilibrium with ambient air temperature and affected by the solar radiation, the temperature profile through the building element is far from linear as shown by the monitoring results

(Figs 3 and 4). To evaluate the temperature-induced stresses and strains, a Finite Element Model (FEM) is used. Silva *et al.* [1999] discuss a similar methodology for estimating temperature induced stresses in walls with ceramic tiles in order to study their performance of adhesion to the substrate. Following simplifications are made in the model;

- Due to symmetry a 2-D model is considered to be satisfactory (a strip through the component is modelled).
- The model uses constant strain elements (linear interpolation of strain).

In the case studied, the moisture changes in the south-west wall are so small that they only result in small variations in stress and strain conditions. Therefore only the stress and strain induced by temperature changes are considered. Calculations are first done for the ideal fully elastic case without relaxation or creep, and then the effects of relaxation and creep are considered. Since the knowledge on creep and relaxation in AAC is limited the discussion is mainly based on qualitative estimations.

5.1.1 Ideal case; neither creep nor relaxation in material

Rise in the surface temperature (by radiation) above the inner temperature of the material results in compressive stress and strain on the surface. When the total temperature difference between surface and the equilibrium temperature inside the element is about 26 °C, the max. stress on the surface is estimated to 0,34 MPa. This may be compared with the analytical solution based on a linear gradient as calculated above; the unlinear gradient gives a somewhat higher stress on the surface. The instantaneous elastic strain (ε) needed, to reach a stress of 0,34 MPa, is about 285 μS. The calculated compressive stress is only 15 % of the yield strength and there should therefore be no risk of cracking neither due to the stress level nor to fatigue. When the surface temperature decreases the stress in the material decreases as well, but the lower surface temperature compared with the inner temperature in the material does not result in tensile stresses on the surface for the idealised case calculated.

During a cold spell the temperature changes in the material, on both the south-west and north-east sides, are not as sudden as those shown in Figs 1 and 2. The temperature gradient is more linear through the material than in the highly dynamic case of radiation effects and the stress may be calculated according to the analytical case. The temperature difference may get as high as -40 °C a few times each winter, which results in a tensile stress of about 0,47 MPa at the surface. This calculated tensile stress is higher than the yield strength of 0,38 MPa, and the surface cracks.

5.1.2 Effects of creep and relaxation

In reality there is creep (and stress relaxation) under constant strain, and it is of great interest to evaluate how this affects the risk for cracking. Creep (ε_c) is often given as a fraction of instantaneous strain (ε) and denoted as fractional creep ($\Phi = \varepsilon_c/\varepsilon$). Due to creep (and relaxation) the stress does not reach the calculated value for the idealized case, but the amount of this effect is not known numerically at present. Tensile stress due to cold spell is somewhat lower than the calculated stress, but it is not known either if it is sufficient to avoid from cracking. During compressive loading due to increased surface temperature the material creeps and the effect of this is pronounced even for short-time loading. The creep results in tensile strain building up when the surface temperature falls again. The fluctuations in surface temperature due to the radiation effect of the sun give repeated tensile stresses during cooling of the surface. The rate of creep alone should be known in order to be able to explain the surface cracking on the sunny side by thermal induced effects. This requires that the tensile stress, caused by creep strain, is higher than the tensile yield strength of 0,38 MPa. To obtain this stress level the tensile strain has to be about 320 μS. The temperature variations of the surface can be as many as 500 per year and the risk for fatigue may be actual when a period of many years is considered. Risk for fatigue requires that the stress level in repeated loading reaches about 65 % of ultimate load, or a tensile stress of about 0,25 MPa. This stress is equivalent to tensile strain of about 210 μS. In both cases mentioned it is apparent that if the tensile stress that cracks the surface depends on creep alone, then fractional creep Φ has to be greater than 0,65. It is therefore most likely that creep is not the sole explanation to the crackings.

5.2 Combined effect of temperature and moisture changes on risk for cracking

The surface dries out during warming up and the shrinkage and creep result in strain. It is well known that shrinkage of AAC is substantial in response to moisture changes at low moisture content (Table 1). The effect of warming up the surface may result in the moisture content changing from an equilibrium at approximately 80 % RH (7 % moisture content, Table 1), and down to approximately 25-30 % RH (2 % moisture content). The resulting shrinkage is then approximately 180 µS (Table 1). The rate of creep is furthermore very much dependent on temperature; at 70 °C the rate is approximately 3,5 times higher than at 21 °C and at –10 °C the rate is about one-half of that at 21 °C [Neville 1995]. The simultaneous effect of changing moisture and temperature increases the rate of creep, but exactly how much is not clear. The effects of shrinkage and creep ratio added require a fractional creep $\Phi=0,45$ to explain the cracking when fatigue is not considered, and $\Phi=0,15$ when expecting a full fatigue effect. The actual reason for cracking is probably somewhere in between. To be able to better evaluate the reasons why the panels are cracking more on the sunny side than the north-eastern side, and to evaluate the risk for such cracks, there is a need for a more detailed study including measurements of material surface conditions.

6 CONCLUSIONS

Measurements show that the temperature changes in AAC panels with surface coatings of different colours are both very fast and can easily be in the order of ± 40 ºC many times each year, but the moisture changes are small due to effective surface treatments. The tensile force built up during cold spells may be sufficient to crack the surface of AAC panels but the risk for thermal fatigue cracking due to repeated loading seems to be small. For a complete study of the risk for thermal induced cracking, which is considered to be real as the panels oriented to south-west show more cracks than those oriented to north-east, a better knowledge regarding creep and relaxation of the material is needed. Future work would include measurements of thermally-induced stresses and strains in the panels and in this way the measurement results could be compared with the calculated values, and in turn, the effect of shrinkage and creep could be estimated.

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