DURABILITY OF AUTOCLAVED AERATED CONCRETE
A field study of industrial buildings

E. BOHNER
Building Materials, Royal Institute of Technology, Stockholm, Sweden
(since Oct. 1998 Institute of Building Materials, Prof. H.S. Müller, University of Karlsruhe, Germany)
K. ÖDEEN
Building Materials, Royal Institute of Technology, Stockholm, Sweden

Abstract
Field inspections and further tests have been carried out in order to identify damages and degradation factors for the external wall components made of autoclaved aerated concrete. Within this project 24 industrial buildings in the area of Örebro and Kumla in Sweden have been inspected to get information about all damage types and to rate the status of the AAC-plaster system. The buildings had one of three different types of surface treatments. They were built over three decades beginning in the 1960’s. The inspected external AAC-walls were either untreated or if treated, organically or inorganically based thin plaster systems were applied. In-situ measurements of the moisture content within the first 15 mm below the surface were carried out by a conductance type electric moisture meter.
The evaluation of damages was performed with regard to differences in plaster system, plaster thickness and colour, AAC’s density, location and orientation of the walls.
To detect possible changes in properties of the AAC, capillary water absorption tests and water vapour diffusion tests were performed at core samples from three buildings of different age and surface treatment.
Of main interest have been moisture-related damages in organic and inorganic based plaster systems. The level of moisture content is directly related to damage and is also connected to the degree of damage. AAC-walls treated with organic plaster systems showed most moisture-related damage. Where organic plaster systems were used, the level of degradation of the AAC was in general conspicuously higher than that at the walls which were coated with inorganic plaster systems.
Damage causes and possible degradation systems are provided for the different plaster systems.

Keywords: autoclaved aerated concrete, durability, plaster
1 Introduction

Autoclaved Aerated Concrete (AAC) is a building material, which is used all over the world. It is a purely mineral-based building material made from sand, water, limestone and a very small amount of aluminium powder. These raw materials are combined to provide a building material with a large number of air pores. One way to use the building material is to construct external walls of industrial buildings with AAC-components. In Sweden, thin plaster systems are usually applied to the surface of these walls.

Since little is known about the degradation processes of AAC and the interaction of AAC and the plaster system under long time exposure to the environment, the aim of the work which underlies this paper, is to detect and to describe all damage types which occur at the buildings, at the components and in the materials during their service life. One further scope is to identify degradation factors and mechanisms of plastered AAC-wall systems. It is desirable to develop a methodology for assessing the progressive degradation effects of local agents and other circumstances on components and assemblies to identify the future maintenance and replacement needs of a building.

2 Moisture and properties

Autoclaved aerated concrete is a porous building material. As a consequence, there is a strong interaction between water, water vapour and the porous system. Most properties of porous materials depend on the moisture content (Künzel 1971; Svanholm 1983; CEB-Manual 1978; Yxhult AB 1993).

- The compressive and tensile strength vary with the moisture content. There is a distinct increase in strength after drying out from a moisture content of 10% to almost 0%.
- The modulus of elasticity in compressions shows an increase, in drying, of about 15%.
- The thermal conductivity increases linearly with the moisture content.
- The permeability varies according to the moisture content in the material – the lower the moisture content in the pores the greater the permeability.
- Shrinkage and creep increase with excessive drying.
- Frost damage can appear if the moisture content of AAC exceeds a critical value.
- The resistance against chemical attack depends on the moisture content.
- The resistance against accidental fire also depends on the amount of moisture in the material, and is higher with higher moisture content.

Under the given climatic conditions, the moisture content is determined by the total porosity and the pore size distribution. The bulk density of steam-cured aerated concrete is within the range of 300 to 1000 kg/m$^3$. The most common dry densities for load-bearing products and reinforced AAC-elements are 400 kg/m$^3$ and 500 kg/m$^3$. These values refer to the oven-dried material. The moisture content of the delivered material may be 20 to 35% by weight. This moisture dries out gradually until an equilibrium is reached at 4 to 6% by weight in external constructions (CEB-Manual 1978). The drying out process lasts about one to three years under normal conditions.
The structure of autoclaved aerated concrete is micro-crystalline and formed mainly by tobermorite platelets, which are more stable than normal cured concrete (RILEM Recommended Practise). The structure is characterised by pores and can be clearly divided into three regions. One of these regions consists of air pores with a radius of 50 to 500 \( \mu \text{m} \) introduced by gas development or surface-active agents during the manufacturing process. Another region is identified by microcapillaries of 50 nm or less, which is the gap of the hydration products developed in the wall between the air pores. In the third region, there are a few pores of 50 nm to 50 \( \mu \text{m} \), which are called macrocapillaries (Tada and Nakano 1983).

There are different moisture transport mechanisms in porous materials. In a dry state, all pores are empty and therefore water vapour diffusion dominates. If the moisture content increases a little, the AAC enters a state where adsorption of moisture to the capillary wall takes place and capillary condensation occurs in the fine capillaries. This condition is hygroscopic, and moisture movement is dominated by water vapour transport. With a further increase in the moisture content, the microcapillaries are completely filled with water. This condition occurs over a long period of time with just diffusion of water vapour, but is reached very rapidly when in contact with free water. If the moisture content becomes very high, some pores are filled by capillary condensed water. In this case, these fine pores cannot contribute to vapour diffusion any more and water driven by capillary forces migrates through them instead.

Excessive drying below the equilibrium results in an increase in shrinkage and even in shrinkage cracking. Shrinkage increases if the AAC is alternately humidified and dried (Duorjadkin and Malinowski 1965).

3 Conditions of field investigations

During the field inspection, 24 industrial buildings were inspected in December 1997 and February 1998. The buildings were predominantly industrial halls commonly used as mechanical workshops or stores. The oldest building was built in 1960 and the youngest in 1996. The range of age is therefore 36 years.

All buildings were situated in local industrial parks in Örebro and Kumla in Sweden. The global climate in that region can be assumed as being equal for all buildings. It is moderate and is characterised as an inland climate with moderate \( \text{SO}_2 \) levels \(< 20 \text{ mg/m}^3 \) (Nevander and Elmarsson 1994).

The external walls of all inspected buildings were constructed with components of autoclaved aerated concrete (AAC) manufactured in Sweden by Yxhult AB. The wall elements were rectangular and were fitted with groove and tongue joints.

The surface treatment of the external walls of most buildings was with thin plaster systems. The investigation distinguishes only between mineral and organic plasters. The organic plasters for AAC are normally based on an acrylic resin binder with siliceous fillers and grains forming the surface texture. The inorganic thin plaster systems usually consist of a two-layer lime-cement mortar. The thickness of the plasters varies from 0.5 to 5 millimetres. The walls of some inspected buildings were only thinly painted or were untreated.
4 Damage and causes

The investigation of the 24 industrial buildings showed a multitude of varying damages. Many types of damage occurred frequently and mostly with similar causes.

4.1 Construction damage

Construction damage is damage that is actually caused by false design having an impact on structural elements of the building.

4.1.1 Cracks between structural components

All constructions consist of several different structural components. They have different functions and therefore their constitution and behaviour varies. The connection of these components often causes problems, and cracks appear at the joints. These cracks are usually in the plaster if the connection allows a certain movement of entire adjacent components (for example the connection between normal concrete and AAC). The reasons for the movements are usually the component’s different behaviour with regard to thermal expansion, creep and shrinkage.

4.1.2 Cracks within AAC-components

Stresses within a structural component can have several causes. If stresses exceed the ultimate strength of AAC, they cause cracks. Sometimes deep cracks arise due to poor performance of the support for the AAC-elements. Connecting the AAC-elements with joint sealers, which are too stiff, causes cracks. Deterioration by ageing causes stiffness within the joint sealers, which does not allow the elements to move properly.

4.2 Mechanical damage

The damage found most often was mechanical damage. This can occur at any place and in any size in a wall. Scratches and impacts of all shapes flaw the surface treatment, and the AAC. The reinforcement is often uncovered or even damaged. Traffic consisting of cars and other vehicles is the main cause of damage. Therefore mechanical damage appears particularly at places with a high traffic volume (e.g. ramps), and at the lower parts of the wall, usually up to a height of three meters above ground.

4.3 Damage caused by bad design

All bad-design damage in this study was actually caused by water or moisture problems. The degree of damage and the appearance vary quite strongly. Figure 1 illustrates where these types of damage usually appear. Damage connected to poor performance of the concrete base occurs extremely often. If the base is not high enough, rainwater splashes from the ground to the wall and imbrues the surface of the wall up to a height of about 0.8 m. The moisture content within the AAC can then become very high. This promotes the occurrence of cracks due to shrinkage, and the growth of algae and lichens, as well as strong discolourations. The degree of damage depends on the direction of the wall, the microclimate and the type of ground in front of the wall. Asphalt or any kind of plain, hard surface (e.g. slabs) intensifies the effect of humidification.
Fig. 1: Moisture-related damage at a typical industrial building. Common locations of damage are indicated

Where AAC is not covered with plaster, water infiltrates and diffuses behind the properly plastered surface. Then, there is little chance for it to dry out if the plaster is tight. A wall can have areas where the moisture content at its surface is very high. If the moisture content exceeds an assigned value and the surface is not toxic, algae and lichens can grow on the plaster or the AAC and strong discolorations can occur. This phenomena occurs quite frequently. It is evidence of a high moisture content of the wall wherever it occurs.

The performance and design of the roof edge have a high influence on the appearance of damage. A common mistake is to fix any equipment onto the surface of the wall, for example cables or boxes, so that rainwater can drop down on the facade, splash against it, or sometimes it cannot be drained off. All problems combined with high moisture contents of AAC can occur as discolorations and algal growth. Deep and wide cracks in irregular patterns occur, which introduce the peeling of plaster.

4.4 Frost damage
Frost damage was rare and was usually caused by design errors, which made it possible for water to penetrate the AAC regularly. Where the AAC was laid open and was not, or was inadequately plastered, frost damage appeared if the close surrounding of these places was coated with a water vapour tight plaster.

4.5 Cracks and crack pattern
Cracks can have different causes. They occur both as vertical and horizontal cracks as well as without a specified pattern. The causes are often moisture-related, as for example shrinkage cracks, or cracks which follow the reinforcement and the production joints of the AAC-elements. These inhomogeneities are weak points considering AAC’s behaviour under the influence of moisture and temperature variations.

4.6 Damage due to bad use and lack of maintenance
Regular maintenance is necessary if the plaster tends to age quickly. Great problems occur if the plaster gets too old and has already lost its function. Protection
against water ingress is not present and the susceptibility of the plaster-AAC system to damage increases. Missing or badly performed repairs of damage can aggravate the condition of the walls.

4.7 Damage and degradation of plaster

The surface of the wall is affected by weather and by the whole environment of the building. It can show discolourations and bleaching caused by solar radiation, disintegration, weathering, dust deposit and traffic. Degradation of plaster occurs as peeling, bleaching, chalking or the formation of blisters. Often the bond between the plaster and the substructure is lost, where the expansion of the coating increases due to thermal expansion and changes in the moisture content.

5 Evaluation of field inspections

The field inspections showed a multitude of different damage types and provided values of the walls’ moisture content. A gradation of the damages was performed with regard to the different damage types, the degree of damage and the orientation of the walls to all points of the compass.

During the field inspections the moisture content below the outer surface of the external walls was measured by a conductance type electric moisture meter equipped with non-insulated pin-electrodes of 15 mm. The instrument provides the value of the highest moisture content between 3 and 15 mm within the AAC below the surface. The measurements were executed at different heights above the ground. In general the moisture content in the first AAC-element above the concrete base was higher. Average values of the moisture content over all of the walls were 24% by weight for the first AAC-element and 20% by weight for the second AAC-element.

A grading of the measurement was done with regard to the location of the measurements. The evaluation distinguishes between measurements next to the corners and at central areas of the wall. Measurements in unprotected damage spots (where the plaster was removed for example due to mechanical damage) provided information about the permeability of the plaster system. If the moisture content in a spot was similar to the moisture content at a place next to it, which was well plastered, it could be stated that the plaster system was very permeable to water vapour. This was seen mostly with mineral plaster systems.

5.1 Results of field inspections

It can be stated that the frequency of damage is much higher if the moisture content of a wall is high. Damage that can be related to a high moisture content in the AAC, is for example, moisture-related cracks, almost all design damage as growth of algae and lichens, discolourations and frost damage. Furthermore damage occurs due to inhomogeneity of AAC and peeling of plaster more frequently, where the moisture level is high within the AAC. Algal growth and moisture-related discolourations occurred more frequently at the northern and western facades of the buildings and were worst at base elements close to the ground. Most frequent types of cracks seen during the inspection, were vertical cracks at the southern side of the buildings. They usually appeared in base elements with a small crack width (0,1 mm – 0,4 mm).
can be explained by a higher amplitude of temperature and moisture content due to solar radiation, which causes an increased tendency to shrinkage. Frost damage occurred in only a few cases. They were usually caused by design errors. Damage that appeared most frequently, was mechanical damage. It was normally concentrated in the first two metres above ground and occurred most frequently next to doorways, portals and entrances or where the ground in front of the wall allowed vehicles to come too close.

5.1.1 Plaster type
At buildings where degradation of the organic plaster system was already noticeably active, the moisture content below the outer surface was in general conspicuously higher than in mineral plaster systems. The measurements at walls with organic plasters provided an average value for the moisture content of 24% by weight. Mineral plaster systems provided an average moisture content of 19% by weight. The difference in moisture content is confirmed by the results of the inspection. Organic, acrylic based plasters showed a multitude of different damage types and most of them were cracks and algal growth obviously due to a high moisture content in the plaster and AAC. Only a few signs of degradation were observed in the inspections of the inorganic plaster systems.

5.1.2 Plaster thickness
The frequency of damage and the level of degradation decreases with the thickness of the plaster. The walls, which were protected by plasters with a thickness of at least 2 mm, showed the best conditions.

5.1.3 Colour of plaster
To examine the influence of the colour of the surface treatment, the facades of all 24 buildings were graded into dark and light colours. In general, the condition of light coloured facades was much worse. They showed more moisture-related damage and the crack frequency was higher. The in-situ measurements provided an average moisture content of 24% by weight at the light facades. This is noticeably higher than the measured moisture content of 17% by weight at the dark coloured facades. Thus, it can be assumed that the moisture level within the outer parts of a wall’s cross-section is related to the colour of the surface treatment. Dark facades dry out more quickly because the temperature rises faster and to a higher level, due to solar radiation, after penetration by rain.

5.1.4 Density of AAC-components
A higher density of the AAC has a good influence on the condition of the wall. All moisture-related cracks occurred more frequently in AAC with a lower density. The results of the moisture measurements support this assumption. The average moisture content under the surface of walls with a density lower than 500 kg/m$^3$ was 25% by weight. AAC-walls of a higher density had an average moisture content during the measurements, of 19% by weight. The higher moisture content in AAC-walls of lower density is caused by an increased tendency of capillary water absorption of the material.
6 Capillary suction and water vapour diffusion

Capillary suction tests and water vapour diffusion tests were executed at core samples that were taken from external walls of three buildings. The tests were intended to help detect possible changes in properties of the AAC due to degradation in the course of time. The buildings were of a different age and had different surface treatments (untreated, organic and mineral plaster systems). The tests were executed at different depths of the core samples, which comprised the entire cross-section of the external walls. The tested sections were the outer surface of the wall’s cross-section, ten millimetres below the outer surface, the centre of the core sample and the inner surface.

6.1 Results of the capillary suction test

The test showed that the amount of absorbed water is significantly higher in sections of the organically plastered wall. A possible answer for this behaviour is that the plaster and the AAC have got little micro-cracks that support the water absorption. Sandin showed the negative effect of cracks on the moisture balance of organic plaster systems that have been applied to AAC (Sandin 1983). Cracks can effect an increased water uptake. Increase in movement from wetting and drying out procedures, which will secondarily cause more severe cracks is a possible after-effect. After several years, organic plasters with acrylic binders are strongly affected by ageing and degradation. They lose their elasticity and plastic deformation capacity. They are no longer able to achieve all deformations of the AAC. Figure 2 shows the amount of absorbed water at four surfaces within the cross-section of the organically plastered external wall. The plastered outer surface absorbed most, the central surface least water.

Although the organically plastered building is 22 years younger than the other two tested buildings, it showed most damage. It furthermore exhibits the highest values for moisture content measured with the electrical method.

There was almost no difference in the amount of absorbed water between the outer surface of the untreated and the mineral-based plastered wall. It is obvious that the mineral plaster is very permeable and can only have a very small influence on capillary water absorption of the surface.

The central section of the core samples absorbed the least amount of water. It can again be interpreted that the central section is not as affected by the environment as are the surfaces. Carbonation may be the reason for the outer and inner sections and the section 10 mm below the outer surface to absorb considerably more water than the central section. Carbonation is a process where carbon dioxide in the air and water reacts with the calcium hydroxide in the concrete. This reaction can cause a change in AAC’s structure. These inferences are assumptions and can be verified only by further chemical and microscopic examinations of the structure.
6.2 Results of the water vapour diffusion test

To determine the diffusion factor at different depths of the wall cross-section, the ‘Wet Cup-Method’ was used with a relative humidity difference of 66 to 100% at 20° Celsius. The test showed that the outer surface of the organically plastered wall has a very small diffusion coefficient, whereas below the outer surface, the diffusion coefficient is highest. The AAC below the outer surface would guarantee that the wall dries out very quickly. However, this is hindered by the organic plaster system with its high diffusion resistance factor. The capillary water absorption test illustrated that the amount of absorbed water at the outer surface and 10 mm below the outer surface was highest at the organically plastered wall, which is probably caused by a change in the AAC’s structure and by micro-cracks. The system contributes to an accumulated moisture content. The duration of a moist state within the AAC is therefore longer than in inorganic or untreated systems. This surely leads to an accelerated degradation process of the AAC.

The test of the untreated wall showed that the diffusion coefficient of the untreated outer surface was considerably higher than that below that surface and the centre of the wall cross-section. This guarantees a faster drying out process after penetration. It seems to have a good effect on the wall since the surface of the untreated facade showed nearly no cracks or moisture-related damage during the inspection. The higher value for the diffusion coefficient indicates that the structure of the AAC at the surface seems to be influenced by the environment.

The values for the diffusion coefficient of the mineraly plastered AAC guarantee a fast drying out of the penetrated wall and differ not very much along the cross-section. This provides for the assumption that a permeable mineral plaster does not have a bad effect on the structure of AAC.
7 Conclusions

Based on these field studies and the laboratory tests it can be concluded that inorganic plaster systems generally degrade to a lower degree than organic systems. The users of the buildings do not usually consider the different maintenance requirements of the different plaster systems. Omission of maintenance of organic thin plaster systems is the start of degradation and results in further damage. The time for renewing treatments of organic plasters is much shorter than for inorganic plaster systems. Organic, acrylic based plasters showed a multitude of different damage types and most of them were cracks and algal growth due to a high moisture content in the plaster and AAC.

Only very few signs of degradation were observed during the inspections of the inorganic plaster systems. Thus, mineral surface treatments seem to be more suited for a moderate climate. Inorganic plasters can allow higher and quicker capillary water absorption, but also a shorter drying out period due to their high water vapour permeability. Therefore, they stay dryer in the outer part of a wall between periods of saturation although they could have higher peak values of moisture content.

It can be stated that the occurrence of damage is much higher if the moisture content of a wall is high. Visible moisture-related damage on a facade appear for example as cracks, frost damage, growth of algae and lichens, discolourations and peeling of plaster. Although the field inspections were executed in a region with a moderate climate, the visible effects of a more severe microclimate were found to dominate in all damaged areas seen during the inspection. Design factors combined with the microclimate in certain points of the building, can effect the plaster and the AAC more severely than the influences of the average meso and global climate. The detailed design of buildings, for example, the height of the concrete base and the performance of the facades, are very important factors for durability.

8 Acknowledgement

Kjell Nygren, M.Sc., at the Swedish manufacturer of AAC, Yxhult AB, has given highly appreciated support in the structuring of the work and also in the discussion and analysis of the results.

9 References


