

# The influence of moisture on the thermal conductivity of AAC

**ABSTRACT:** In recent years, questions emerged about how high level moisture contents might affect heat technical properties of building materials. Yet, existing standards and scientific publications, respectively, do not provide conclusive insights into the area of high rated moisture, since they are valid for the equilibrium moisture area only. Taking instructions of calculation according to harmonized European standards (EN ISO 10456, DIN EN 1745) as a basis, typical moisture contents of freshly produced AAC would theoretically involve immense surcharges on  $\lambda$ , which would drastically affect thermal conductivities and, in turn, increase heating costs. Moreover, increasing risks of mould formation and other damages would be expected. Our experiments clearly demonstrate that actual increases in  $\lambda$  at production moisture levels are far below values stated in the European standards. In addition to this fundamental perception recent investigations have shown that the surcharge of moisture content under typical condition of AAC use in buildings the moisture conversion factor  $F_m$  is not higher than 5%.

In several investigations a lower value for  $F_m$  have been found and can be used in the future for starting points of further investigations and tests.

## 1. Consequences of high rated moisture in masonry

High rated moisture can involve a whole variety of damages in building materials, emanating from physical (freeze-thaw-weathering, moisture expansion and shrinkage), chemical (carbonation, corrosion, crystallisation of salts) or microbial processes (i.e. mould growth). In contrast to frost damages occurring only at sub-zero temperatures, chemical and biological processes are promoted by ambient temperatures. Actual amounts of moisture that cause damages strongly depend on the type of building material. In wood, it is assumed that biological degradation only occurs at water contents above 20 M.-%. However, next to temperature and humidity, effects of the substrate properties must be considered, too. Building materials without biologically utilizable components like autoclaved aerated concrete (AAC) are typically not affected by mould-formation at surface moisture contents below relative humidities of 80%. Figure 1 shows an overview on consequences of a high rated moisture caused by the production procedures of autoclaved aerated concrete (AAC).

The transport of humidity in buildings is accompanied by the transport of thermal energy and, hence, has major impact on the insulating properties of building materials. With regard to currently typical production moisture contents of 35–45 M.-% for AAC, an ac-

curate and reliable acquisition and evaluation of hygro- and thermo technical processes in AAC is mandatory for the manufacturer.

## 2. Mechanisms of moisture-accumulation and -transport in AAC

In recent years, a variety of questions emerged on how high level moisture contents might affect the thermal conductivity of AAC, possibly increase heating costs and, moreover, increase the risk of mould formation due to the formation of thermal bridges. Yet, existing standards and scientific papers, respectively, do not provide conclusive insights into the area of high rated moisture,

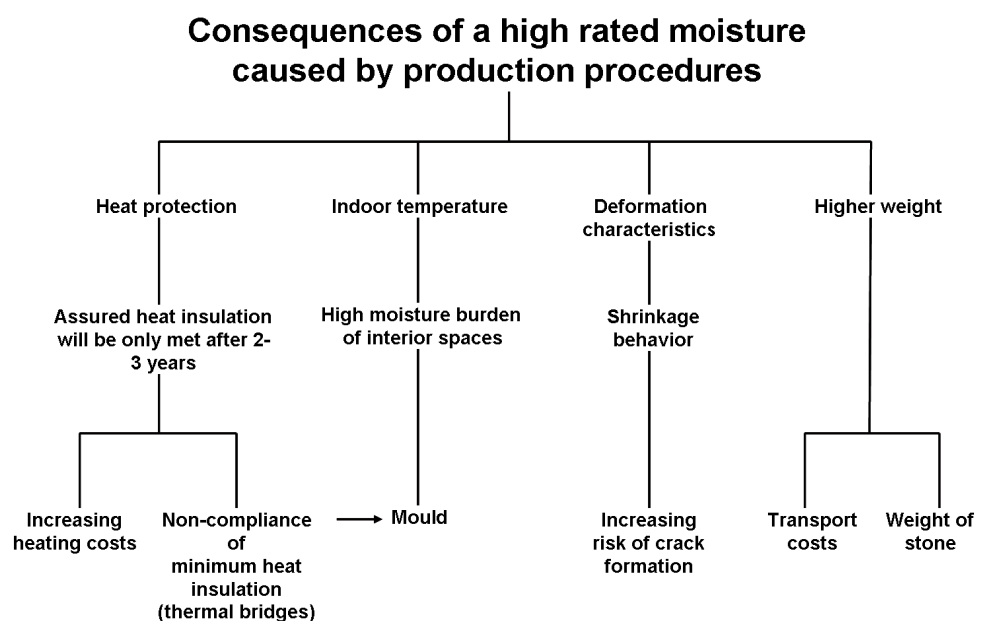


Fig. 1. Consequences of a high rated moisture caused by the production procedures of AAC.

since they are valid for the equilibrium moisture area only. Within the hygroscopic range, water molecules are adsorbed to the internal surface of AAC. The amount of such physically bound (equilibrium) moisture largely depends on the internal surface of AAC given by portion and crystallinity of the calcium silicate hydrates and the number and size of nano- and micro pores. In case moisture contents exceed the absorptive capacity of the inner surface, water is additionally bound in macropores by capillary forces. This condition occurs over a long time even with diffusion of water vapour, but can be reached very rapidly when in contact with free water.

In porous materials like AAC, moisture is transported mainly by water vapour diffusion, surface diffusion of liquid water and capillary action (The influence of convection is regarded as neglectable when flow-through processes due to air-pressure gradients between the inside and the outside of the building do not occur). According to K. F. Lippe (Advances in Autoclaved Aerated Concrete, Wittmann (ed.), 1992, Balkema, Rotterdam, p. 99 ff) moisture movement is dominated by water vapour transport in the hygroscopic range. In this case, heat transport due to water vapour diffusion is considerably large. In the state of high moisture content (above the hygroscopic range) an increasing contribution of liquid water movement by surface diffusion to the total water transport has to be considered.

### 3. Moisture surcharges on $\lambda$ according to European regulations

According to current European standards, the influence of moisture is calculated by using the following formula:

$$\lambda_{\text{moist}} = \lambda_{10,\text{dry}} \cdot F_m$$

with

$\lambda_{10,\text{dry}}$  = thermal conductivity in dry condition in W/mK,

$F_m$  = moisture conversion coefficient (according to EN ISO 10456).

The  $F_m$ -value is calculated as follows:

$$F_m = e^{f_u \cdot (u_2 - u_1)}$$

with

$F_m$  = moisture conversion factor,

$f_u$  = mass related moisture correction coefficient (according to DIN EN 1745, table A.10, the  $f_u$ -value for AAC is fixed to 4 kg/kg);  
 $u_1$  = mass related moisture content of first clause of boundary conditions,

$u_2$  = mass related moisture content of second clause of boundary conditions.

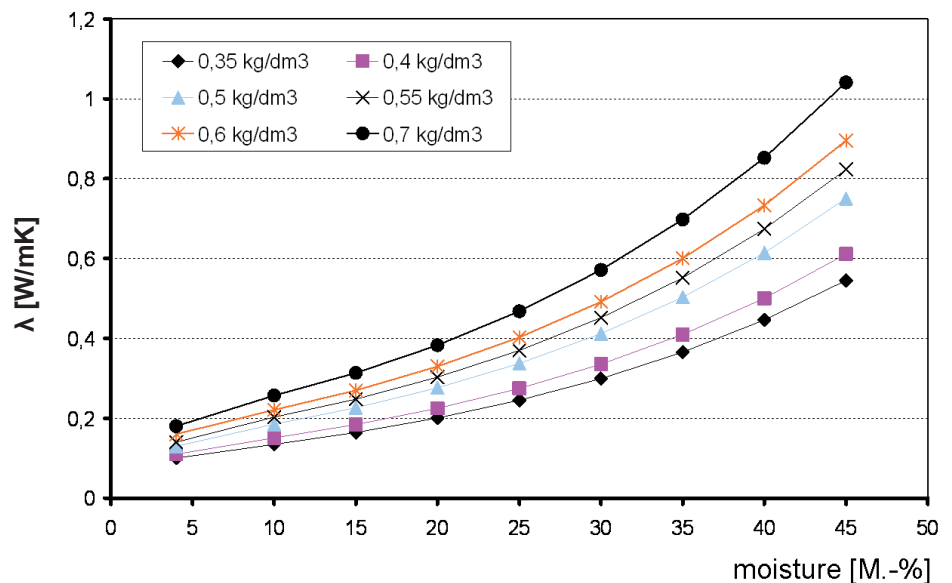


Fig. 2. Calculated  $\lambda_{\text{moist}}$ -values for different dry densities and moisture contents between 4 M.-% and 45 M.-% according to EN ISO 10456 using the fixed moisture correction coefficient  $f_u = 4$  (according to DIN EN 1745, table A.10).

Due to the exponential function, this formula leads to extreme  $\lambda$ -values when applied for high level moisture contents (Figure 2). From former investigations at Ytong it is known that even extreme moisture contents of 35–45 M.-% observed in freshly produced AAC exhibit at most two-fold increases in  $\lambda$ , instead of six-fold increases as calculated according to the European standards.

One way to circumvent this dilemma is given in the German standard DIN V 4108-4 (annex B) giving the option to prove the moisture conversion factor on an experimental basis. This approach was leading to the following formula for the calculation of  $\lambda_{\text{moist}}$ :

$$\lambda_{\text{moist}} = \lambda_{10,\text{dry}} \cdot F_m$$

With  $F_m = 1.05$

We have to state that in case this  $F_m$  value is applied for moisture rates higher than the equilibrium moisture content, it is leading to undervalued results for  $\lambda_{\text{moist}}$ . For this reason, Hebel and YTONG together with the Forschungsinstitut für Wärmeschutz e.V. (FIW, Munich, Germany) initiated detailed investigations on the correlation between high moisture contents and thermal conductivities (T. Schoch, Autoclaved Aerated Concrete, Limbachiya and Roberts (eds.), 2005, Taylor & Francis, London, p. 319 ff).

Measurements were carried out on three class P2 0,35 blocks from Schrobhausen (one sample each) and at two class P4 0,60 blocks from Alzenau (two samples each).  $\lambda$ -values were detected starting with the production moisture (40 and 45 M.-% respectively), which was stepwise reduced to the dry state. The freshly produced blocks were directly wrapped in moisture sealed foil. In the laboratory the blocks were cut into specimens of 220 x 220 x 40 mm and subsequently ground coplanar. The specimens were packed in foil, stored at 10°C and finally subjected to heat conductivity measurements (each measurement took 1½ hours). Afterwards, the plates were dried by 5–10 M.-% at 60°C, stored at 10°C and the meas-

urements started again. This procedure was retained up to the drying process at 105°C. The results for the P2 0.35 plates (real apparent density 350 kg/m<sup>3</sup>) taken from three blocks are shown in Figure 3. With the P2 block R<sup>2</sup> is resulting in 0.9436, with the P4 in 0.9971. Figure 4 shows the measured data referring to two plates taken from one block P4 0.60 (real apparent density 0.525 kg/dm<sup>3</sup>). The slight dispersion of the measured data indicates that the boundary conditions of the experiment have been maintained properly. In case of a systematic measurement error an increased dispersion would be expected with augmented moisture contents. Some of the prior investigations carried out in the equilibrium moisture area (23°C, 80% relative humidity) have shown that during a measuring period of < 3 hours practically no moisture transportation procedures can be observed.

Both plots (Figure 3 and 4) revealed similar conversion formulas for  $\lambda_{\text{moist}}$  (see figure legends), and, thus, nicely reconfirm the results of former Ytong investigations. For Xella's internal conversion a median allowance  $F_z = 0.0070$  was established, which has been used for all measurements up to now.

$$\lambda_{\text{moist}} = \lambda_R / F_m + F_z \cdot u \cdot \rho$$

with  $\lambda_{\text{moisture}}$  = thermal conductivity [W/mK];

$\lambda_R$  = calculation value of heat conductivity [W/mK];

$F_m$  = moisture conversion factor 1.05 according to DIN V 4108-4,

$F_z$  = moisture surcharge on V.-% 0.0070;  $u$  = mass related moisture content [M.-%];  $\rho$  = dry density [kg/dm<sup>3</sup>]

The following diagram (Figure 5) compares Xella's measurements with calculations done according to the European standards (dry density = 400 kg/m<sup>3</sup>,  $\lambda_R = 0,10$  W/mK. The measurements show a considerably lower additive allowance and no exponential increase in dependence of moisture than the calculation.

#### 4. Regulations of the thermal insulation in Germany

The first DIN 4108 "Wärmeschutz im Hochbau" was published in 1952 and was valid till the early nineteen-eighties. Due to overestimated equilibrium moisture contents, manufacturers calculated rated  $\lambda$ -values by adding a fix surcharge of ~30 % on  $\lambda_{10,\text{dry}}$ . Before that time, virtually no requirements for heat protection in masonry were effective. In 1981, the revised version of DIN 4108 allowed the utilization of harmonized European standards in terms of a fixed  $F_m$ -value of 1.2 leading to a moisture surcharge of 20 %. From 1996 to 2001 again new and/or revised parts became effective, permitting the determination of individual surcharges on an experimental level (DIN V 4108-4, annex B). The resulting  $F_m$ -value for AAC of

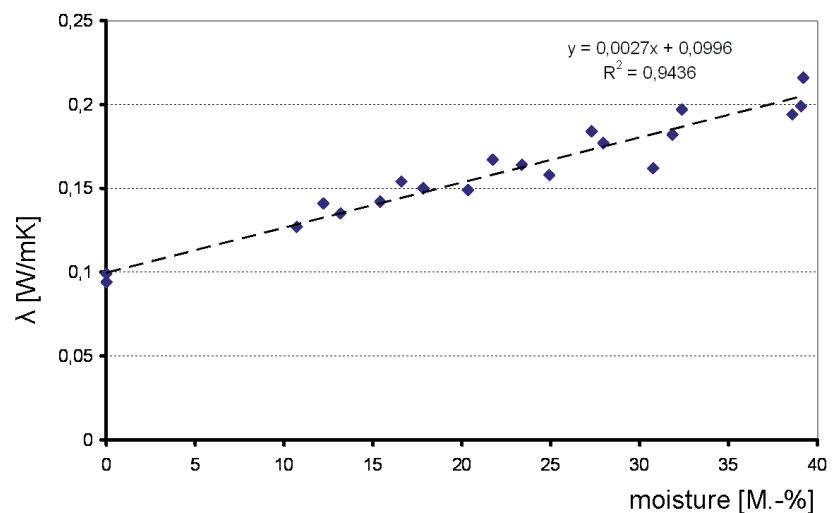


Fig. 3. Dependence of  $\lambda$ -values from moisture contents as detected for a class P2 0.35 AAC (Xella plant Schrobenhausen, Germany). Deduced general conversion formula:  $\lambda_{\text{moist}} = \lambda_R / 1,05 + 0,0076 \cdot u \cdot \rho$  (in kg/dm<sup>3</sup>).

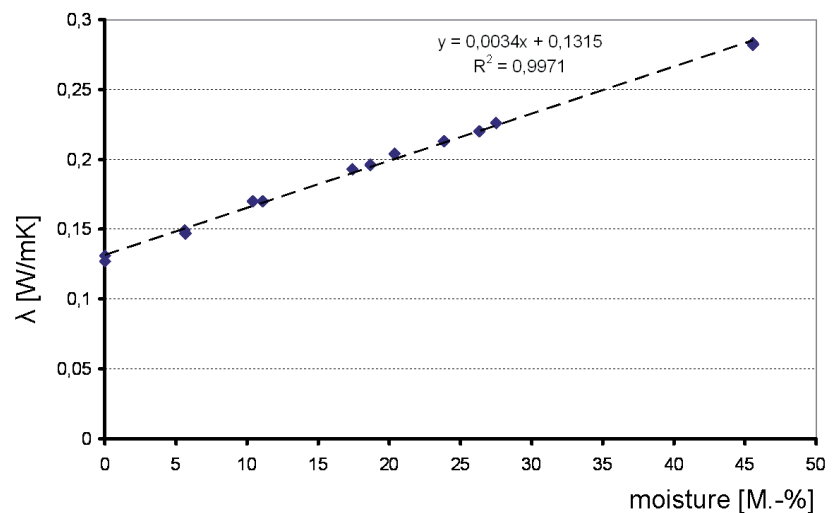


Fig. 4. Dependence of  $\lambda$ -values from moisture contents as detected for a class P4 0.60 AAC (Xella plant Alzenau, Germany). deduced general conversion formula:  $\lambda_{\text{moist}} = \lambda_R / 1.05 + 0,0064 \cdot u \cdot \rho$  (in kg/dm<sup>3</sup>).

1.05 equals a surcharge of 5%. According to this standard, the  $F_m$  is not allowed to exceed a value of 1.03.

#### 5. Recent investigations

In the last two years several measurements have been carried out to define the  $F_m$ -surcharge of AAC. In the upcoming revised EN 1745 - next to a static using of the surcharge described in EN ISO 10456 - the measurement of the actual  $F_m$ -value will be allowed. According to the current document of the revised standard the moisture conversion coefficient ( $f_u$ ) and the moisture conversion factor ( $F_m$ ) can be derived from tests, carried out at several practical contents. As commonly agreed, the practical moisture content of material can be obtained by using the 23°C/80% or 23°C/50%

condition for curing the samples with reference to EN 12664.

To obtain the moisture conversion coefficient and/or the moisture conversion factor for currently produced AAC, the Xella RD centre together with local branches of Xella ordered tests at the University of Padova (Italy- hereafter named as "A") and at the "Prüf- und Zertifizierungsstelle der Stadt Wien (hereafter named as "B)". These tests comprised several dry densities of AAC in a range of 330 to 575 kg/m<sup>3</sup>.

The values of the apparent thermal conductivity have been measured on dried material and later on the same samples conditioned by 23°C and 80% relative humidity. Starting from these measurements, the density increasing due to the moisture content has been determined and then a correction coefficient of thermal conductivity due to this moisture has been calculated. The calculation of the  $F_m$ -factor has been carried out based on the formula given in EN ISO 10456 (exponential function).

The following table summarise the results of measurement in "A" for a density class of 350 and 450 kg/m<sup>3</sup>. The table shows only the average values of the measurements carried out on minimum 3 samples.

After conditioning the moisture content within the sample was in the range of 3.3 to 3.9% by mass, taken into account the above mentioned process of carbonation.

Table 1

RESULTS OF THE TEST IN LABORATORY "A".

Average value of dry density in kg/m <sup>3</sup>	Average dry thermal conductivity $\lambda_{10,dry}$ in W/(mK)	Apparent density $\rho_{moist}$ in kg/m <sup>3</sup>	Thermal conductivity $\lambda_{10,moist}$	Apparent reference density $\rho_{dry}$ in kg/m <sup>3</sup>
335	0,0943	350,66	0,0993	338,0
456	0,1314	470,60	0,1397	455,3

Note: The apparent reference density considers the differences in the densities before conditioning and after drying the specimens after the measurements. In the literature this effect is also described as the carbonation process during the measurements due to the increasing water content. The water content after conditioning together with the carbon dioxide in the air pores lead as acid attack to partial transformation of the CSH-phase to another carbonate phase with higher density and has therefore nothing to do with the increase of thermal conductivity resulting from the higher moisture content. Unfortunately, this influence is not sufficiently described for the test set-ups and demands further investigations. The carbonation process especially influences the measurements in test with thin specimens and cannot be easily transformed into the real situation in buildings.

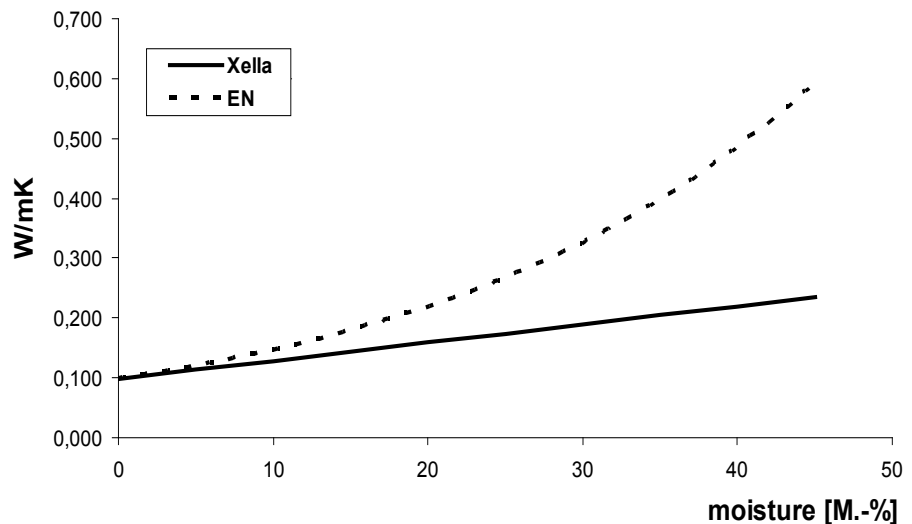


Fig. 5. Dependence of  $\lambda$ -values from moisture contents. Measured results (Xella, solid line) in comparison to calculated data according to European regulations (EN ISO 10456, DIN EN 1745, dashed line).

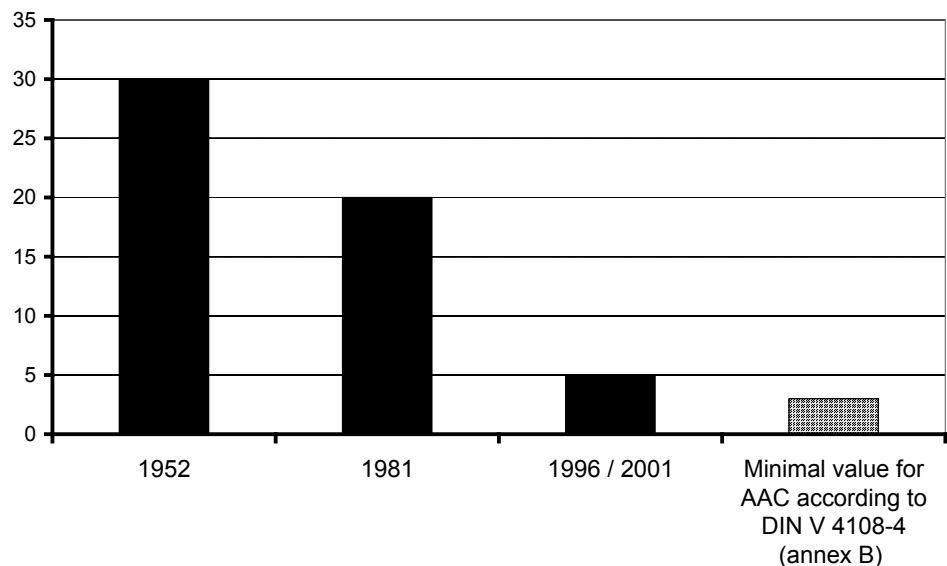


Fig. 6. Development of the moisture surcharge on  $\lambda$  in Germany from 1952 to today.

According to the results a moisture conversion coefficient of 0.78 has been obtained and therefore with applying of the above shown formula for the calculation of the moisture conversion factor the  $F_m$ -factor of 1.02 for the density class 450 and 1.03 for the density class 350 have been computed. Even an ignorance of the carbonation effect led to a conversion factor approximately 1.05.

The test carried out in the laboratory "B" with the raw density classes 400; 500 and 600 kg/m<sup>3</sup> arrived at the conclusions that a moisture conversion factor of 1.05 properly describes the increase of the thermal conductivity due to moisture influences. The resulted mean average moisture content after conditioning of the samples was 0.025 kg/kg across all investigated raw densities.

## 6. Conclusion

The increase of the thermal conductivity due to the moisture content of AAC can be properly described as a linear relationship and hence the exponential function according to EN ISO 10456 overestimated the influence. Especially, for calculation of critical surface temperatures in order to avert mould growth or other adverse effects, the linear approach leads to more accurate forecast than the function applicable in EN ISO 10456. Normally, the moisture content of AAC decreases shortly, therefore the moisture content driven by the production process disappears after 1 to 2 years depends on the climate situation around the erected building.

To evaluate the typical behaviour of AAC in terms of the thermal conductivity during lifetime of the building a typical average value for the moisture content might be used. One possibility is the application of the obtained moisture content of the material after conditioning and measuring based on the EN 12664. The specimens should be conditioned to constant mass in an environment 23°C and 50% r.H. or 80% r.H. respectively.

The results coming from the measurement of the dry thermal conductivity and moist thermal conductivity can be used for determination of the influence of moisture. It must be more taken into account that the raw density under the test conditions is additionally driven by carbonation. The measured moisture content who leads to the moisture conversion coefficient and in the consequence to the conversion factor should be corrected by the influence of carbonation. The influence of carbonation can be recognized by drying of the samples after conditioning. The difference between the original (before conditioning) and the measured raw density can be defined as carbonation effect. This effect is typical for a test set-up with thin AAC samples and does not normally occur within the AAC masonry if the CSH are abundant and well stacked (Tobermorite). The following tests and investigation should more take into account this effect and may have clearer instructions for the laboratories in order to handle this on the same basis in all independent laboratories.

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