# Material development and optimisation supported by numerical simulation for a capillary-active inside insulation material

G. Scheffler, J. Grunewald

*Institute of Building Climatology, Faculty of Architecture, Dresden University of Technology*

ABSTRACT: This article summarises two simulation studies done within the research project INSUMAT, funded by the European Commission. The first is a study of the influence of material parameters on the desired performance of capillary-active insulation, while the material properties were changed in different steps of simulation. The investigation delivers predications about the limits of physical properties that can provide a sufficient thermal insulation at a low level of moisture accumulation. The second study is a practical application as part of the circle of material optimisation carried out within the research project. The properties of newly developed materials were determined in the laboratories for input to simulation programmes. Then the material performance under specified conditions could be predicted and the material producers were provided with information about success of their new developments. The process of material development could be optimised in this way.

## 1 INTRODUCTION - PROBLEM DESCRIPTION

There has been a trend change in the building sector from new constructions to insulation, retrofitting and restoration of existing buildings. The moisture-protection of old buildings and the need to reduce the energy consumption and $CO_2$-emission require an upgrade of the hygro-thermal properties of the envelope parts of buildings. When exterior insulation is not applicable to old facades interior insulation remains the only solution.

The research project INSUMAT, funded by the European Commission, aimed at the development and optimisation of internally applied capillary-active insulation materials that are able to avoid initiation of moisture problems and can upgrade the thermal resistance of facades sufficiently.

Recently, the use of these insulation boards without vapour barriers for thermal insulation, mainly in the basement range is increasing. The boards consist of high capillary activity materials being able to redistribute condensation water quickly and to perform a low moisture level in this way. Thus a diffusion open wall structure originates where mould growth is prevented (due to a low moisture level and the alkaline pH-value of the material) and which is thermally upgraded.

The functionality of such systems depends on the quality of the work carried out at the building site. In case of ideal contact between the insulation boards and the facade wall, the systems will function. In case of an air gap in between, the systems can fail.

The problem scheme shown in Fig. 1 explains the physical processes for ideal and not ideal contact between the board and the wall. In case of ideal contact the connecting mortar works as a retarder. The condensation layer emerges between both materials where the insulation takes the water and leads it back

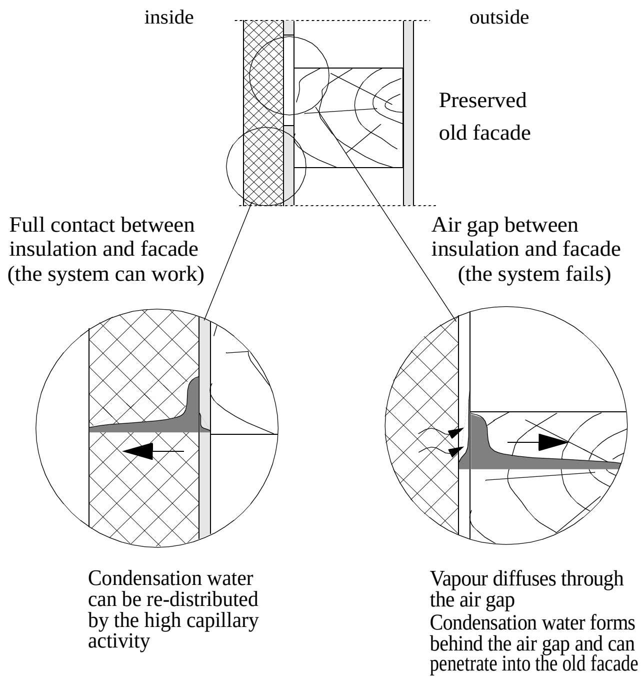


Figure 1. Problem scheme

to the inner wall surface. The system works properly and a low moisture level inside the structure is realised. In case of an air gap between the insulation board and the wall structure the water vapour diffuses through the insulation and condensation takes place at the old structure's surface. The water can not be conducted back by the insulation due to the missing connection which leads to a moisture penetration of the old structure, enabling damages and mould growth.

The intended solution shown in Fig. 2 introduces a two-layered insulation system that fulfils the thermal insulating as well as the moisture retarding task. The capillary active thermal insulation layer has a low thermal conductivity and a high water conductivity at the same time while the vapour permeability is fair. The second layer, called retarder layer, has a low water conductivity, a low vapour permeability and a higher thermal conductivity. This system could perform a diffusion-open, thermally sufficient inside insulation. The functionality of the system does not depend on the adhering method (air gaps between the insulation and the old facade are permitted).

The material properties of the system must be adjusted in such a way, that the condensation zone forms always between the insulation and the retarder layer (no contact of the condensation water to the old facade). The insulation layer with its high capillary activity re-distributes the condensation water backward to the indoor room and performs a low moisture level as well as a sufficient thermal insulation in this way. The retarder layer controls the outward directed vapour flux. The vapour flux must be adjusted according to the properties of the old construction and its climatic zone.

The intended solution can be achieved by an iterative material property optimisation. This process consists of the three steps shown in Fig. 3. Material properties vary due to changes in the mechanical production processes as well as in the chemical recipes during production. These properties are determined in the laboratory and afterwards usen in the simulation which allows predications about the material behaviour in a relatively short time. From these predications the material production can be influenced until the requirements are met.

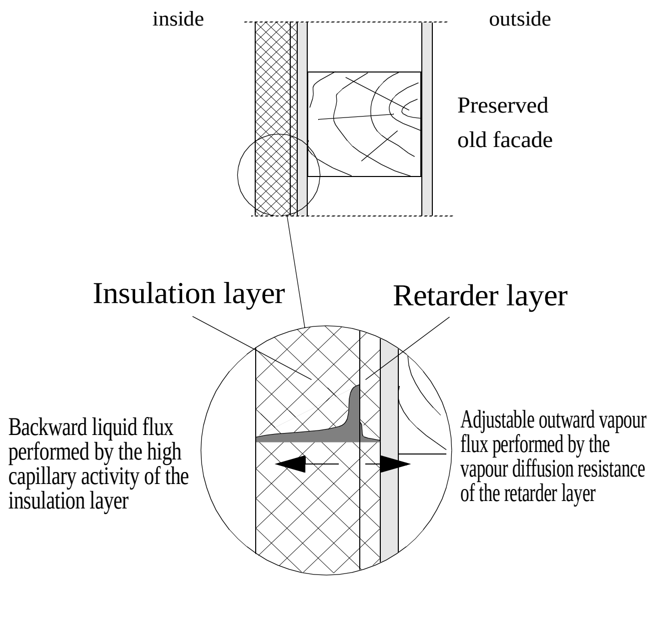


Figure 2. Intended problem solution

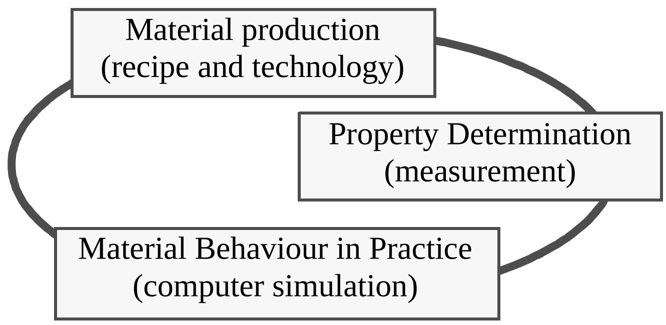


Figure 3. Steps and correlation of material property optimisation

Within the second study the material properties of the existing insulation and in interaction with the glue-mortar, that connects the insulation material to the structure, had to be adjusted precisely.

## 2 MATERIAL DEVELOPMENT STUDY

### 2.1 *Idea and proceeding*

The idea of this study was to find out the physical limits and analyse their sensitivity for the functionality of the intended solution, shown in Fig. 2, that are given by its material properties. A standard wall structure had been calculated under DIN 4108 (winter) norm conditions, together with a two-layered insulation board with an air gap between old structure and new material. During that process the properties of the two-layered insulation material were changed in order to find the best solution.

### 2.2 *Structure*

For the development a simple and general structure was taken, consisting of a 365 mm brick layer (old structure) where a combined insulation plate of 50 mm thickness was applied from the inside, leaving a 5 mm air gap in between. The insulation plate was divided into a 40 mm insulation layer and a 10 mm retarder layer. The plate material was a capillary active insulation material as the first component. The other one, the retarder layer was a new material, derived from the same insulation material by changing material properties.

This structure had been calculated with the simulation software DELPHIN4 (Grunewald J. 1999 and 2000) developed at the Institute of Building Climatology, Dresden University of Technology.

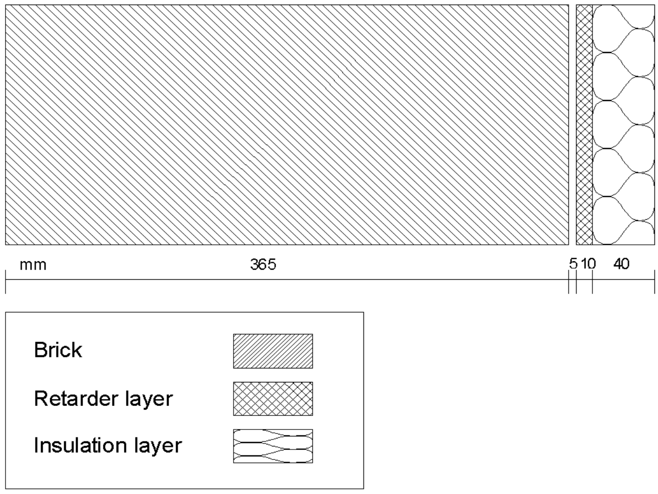


Figure 4. Structure scheme

## 2.3 *Calculations*

The simulation was subdivided into three series which are shown in Table 1. The first calculation group (test1 to test7) was meant to give an overview about the influence of changing single parameters. An initial material (the new material with a reduced capillary conductivity) was assumed and varied as shown in Table 1.

The calculations were done with conditions specified in DIN 4108 (outside: -10°C, 80%RH; inside: 20°C, 50%RH) for 60 days. The moisture and temperature fields had been calculated as well as the u-value, which is shown in Table 1, too.

Only two of seven variants show a good moisture behaviour, i.e. low water mass inside the brick: test5 and 7 where only test5 seemed to be useful. The variation under test7 does not lead to moisture accumulation but on the other hand it is almost vapour tight. The other tests show too much introduced moisture. See the graphics of Fig. 5, Fig. 6, Fig. 7 and Fig. 8.

The following test series were based on variant test5. While thinking about condensation inside the structure and about the behaviour of the insulation layer itself, it became clear that the retarder layer should have a lower capillary conductivity. The high capillary conductivity of the insulation layer improves the liquid water flow out of the structure. To ensure this the condensation layer must be located at the inner boundary of the insulation and the bordering material. Both of them must have different moisture conducting properties. If they were equal the moisture would be distributed into both directions, into and out

Table 1. Outline of test material parameter variation

| | RETARDER LAYER, from insulation material | | | THERMAL INSULATION (capillary active) | | | |
|---|---|---|---|---|---|---|---|
| test number | thermal conductivity | vapour conductivity | capillary conductivity | thermal conductivity | vapour conductivity | capillary conductivity | U - value [W/m²K] |
| 1st calculation group | | | | | | | |
| test1 | $\lambda$ original | $D_v$ original | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.66 |
| test2 | $\lambda$ - | $D_v$ original | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.63 |
| test3 | $\lambda$ + | $D_v$ original | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.73 |
| test4 | $\lambda$ original | $D_v$ + | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.65 |
| test5 | $\lambda$ original | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.69 |
| test6 | $\lambda$ original | $D_v$ original | $K_l$ - | $\lambda$ original | $D_v$ + | $K_l$ original | 0.67 |
| test7 | $\lambda$ original | $D_v$ original | $K_l$ - | $\lambda$ original | $D_v$ - | $K_l$ original | 0.66 |
| 2nd calculation group | | | | | | | |
| test5-1 | $\lambda$ original | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.69 |
| test5-2 | $\lambda$ original | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ + | 0.69 |
| test5-3 | $\lambda$ original | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ ++ | 0.69 |
| test5-4 | $\lambda$ original | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ +++ | 0.68 |
| 3rd calculation group | | | | | | | |
| test5-5 | $\lambda$ + | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.73 |
| test5-6 | $\lambda$ ++ | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.75 |
| test5-7 | $\lambda$ +++ | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.76 |
| test5-8 | $\lambda$ ++++ | $D_v$ - | $K_l$ - | $\lambda$ original | $D_v$ original | $K_l$ original | 0.78 |

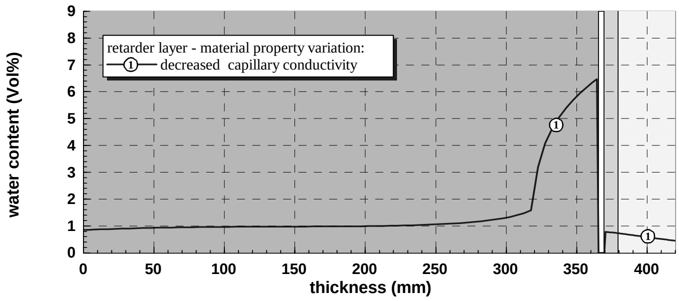


Figure 5. Water content versus location after 60 days for test1

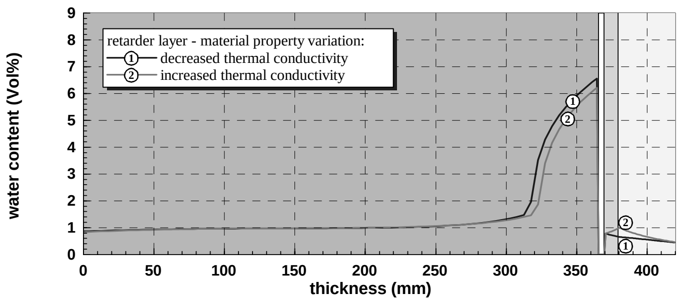


Figure 6. Water content versus location for test2 and test3

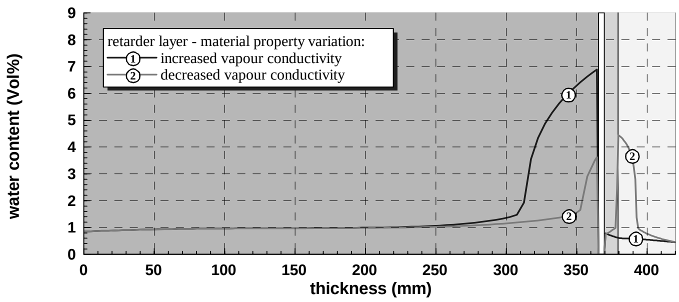


Figure 7. Water content versus location for test4 and test 5

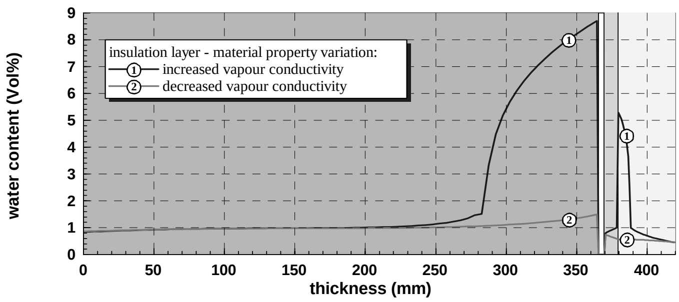


Figure 8. Water content versus location for test6 and test7

of the structure.

The influence of the difference between both capillary conductivities is shown by the second test series. There the material parameters of the insulation material itself were changed in a way that the capillary conductivity was increased gradually. It can be seen from the calculation results (shown in Table 1 and Fig. 9) that due to the higher capillary conductivity of the insulation the moisture is lead faster to the surface and evaporates. The insulation plate becomes dryer but the impact on the old structure (brick) does not change.

Another important material parameter is the thermal conductivity. A low thermal conductivity leads to a low u-value which is desired. An, in comparison to

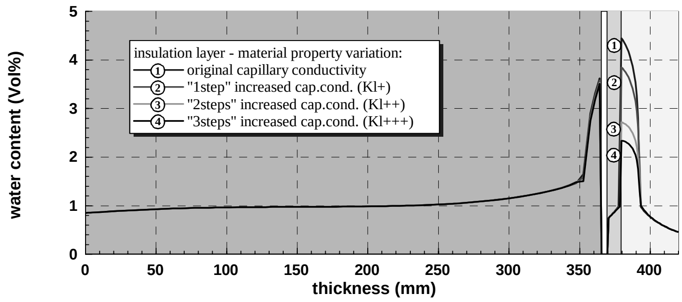


Figure 9. Water content versus location for test5-1 to test5-4

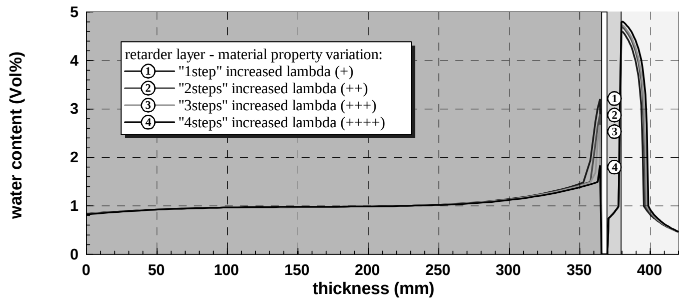


Figure 10. Water content versus location for test5-5 to test5-8

the insulation material, higher thermal conductivity of the retarder layer could concentrate the condensation layer between both materials. This effect relieves the old structure.

On that account the third test series increases the thermal conductivity of the retarder material. The results of the calculation are shown in Fig. 10. An increase of the retarder layer's thermal conductivity reduces the amount of vapour which diffuses through. Thus less condensation takes place at the old wall structure. For the calculated U - values see again Table 1.

## 2.4 *Summary*

The combined insulation plate is working satisfactory if the water condenses between both materials. The new material would fulfil two tasks, reducing the vapour flux on the one hand and reducing the heat flux on the other, while the insulation layer keeps its task with the good capillary characteristics. The plate offers a good alternative to other inside insulation materials because it does not make the wall vapour tight and it is easy to apply allowing an air gap between plate and old structure.

The study shows that the system is physically possible. The possible scope of the material properties can be defined. Remaining difficulties might result from the plate's thickness coinciding the thermal behaviour and from production itself. The insulating characteristics have to be kept while the whole thickness cannot exceed practical limits. Moreover, it is difficult to produce one slab consisting of two materials with very specially designed properties and a continuous connection in between.

## 3 MATERIAL OPTIMISATION STUDY

### 3.1 *Motivation*

In the frame of the INSUMAT project a material optimisation had been carried out. In this study not the properties the material should possess were given and a matching material had to be found, but the material producer developed an insulation material by changing the production process and/or the chemical recipe and gave it to the laboratory where its properties were determined. With that data the simulation was performed and predictions about the material behaviour in practice could be derived. The received information was given to the material producer who could follow or stop the development into several directions until the material would meet all requirements. A scheme of this optimisation circle is already given in Fig. 3.

### 3.2 *Study conditions*

Within the research project this optimisation was realised by *Calsitherm Silikatbaustoffe GmbH*, a producer of insulation materials made of calcium silicate and Dresden University of Technology, where measurement and simulation were performed.

Calsitherm produced different materials in 8 series. These materials were named as follows whereby the first material is the original which was modified during optimisation:

- CalciumSilicate Standard AA
- CalciumSilicate T7-2
- CalciumSilicate T7-14
- CalciumSilicate V62
- CalciumSilicate T8-6
- CalciumSilicate T8-12
- CalciumSilicate T9-13
- CalciumSilicate T11-12

Samples were sent to the laboratory in Dresden, where properties as dry bulk density, particle density, porosity, sorption and retention characteristics and water transport characteristics were measured and determined. These data became part of the input for the simulation program DELPHIN4. For simulation the insulation material was attached to the interior of an existing structure whereby two possible ways of application were considered; a good connection between old structure and insulation material by the glue mortar and no connection with an air gap between them. The chosen structure was supposed to be a typical case of an old building with a preservable facade as they appeared in the early 20$^{th}$ century. A drawing of the structure can be seen in Fig. 11.

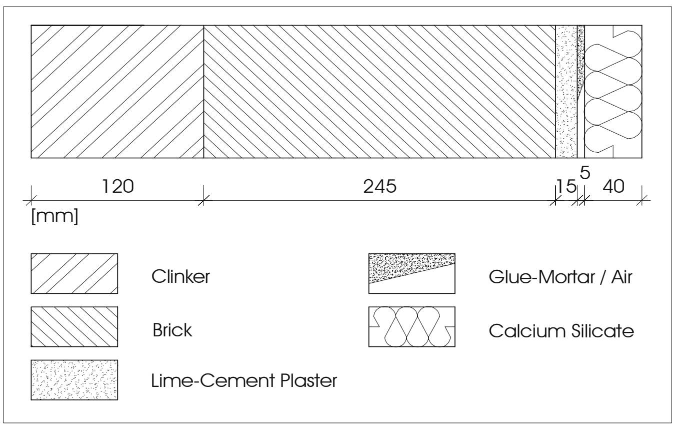


Figure 11. Structure of simulation

As climatic boundary conditions almost the same were chosen as before. At the outside -10°C and 80%RH were applied while at the inside there was applied 20°C and 60%RH for 60 days of calculation. The initial conditions of the structure were 15°C and 55%RH which, due to the fast nivellation, did not affect the behaviour of the structure.

### 3.3 *Calculations*

Moisture and relative humidity fields of the structure were the desired output from computation after those 60 days of calculation. Fig.12 shows the moisture profile at calculation end for the 8 materials well connected to the old structure. The materials can be divided into three groups that show similar moisture performance. Fig. 13, Fig. 14 and Fig. 15 picture these groups separately.

Group 1, containing materials Standard AA and V62 performs rather poor; the moisture that condensates between glue mortar and insulation moves into both directions which is due to a too low water conductivity. The aspired effect to lead the introduced moisture quickly out of the structure does not take place, see Fig. 13.

The materials of group 2, T7-2 and T7-14, show a better moisture behaviour (Fig. 14). Most of the condensation water is lead capillarily to the inner wall surface where it evaporates. But a small amount of moisture also moves into the old structure. The moisture physical performance of group 2 could be described as fair due to two facts; first the old structure is affected (by T7-2) and second the moisture does not move very quickly out of the structure which leads to a high moisture level inside the insulation. The water conductivity is too low.

Fig. 15 shows the moisture profiles of group 3, consisting of calcium silicate T8-6. T8-12, T9-13 and T11-12. Here the water conductivity is higher which leads to a lower moisture level inside the insulation. The old structure is not affected (the peak in the mortar is due to the hygroscopic moisture content of the mortar). A relative humidity field of all 8 materials for the good connection can be seen in Fig.16.

In contrast to their behaviour with a good connection between insulation and old structure, all materials show a more critical behaviour if there is an air gap between, see Fig. 17. The water vapour condensates at the plaster’s surface and penetrates the old structure. No classification can be derived from there.

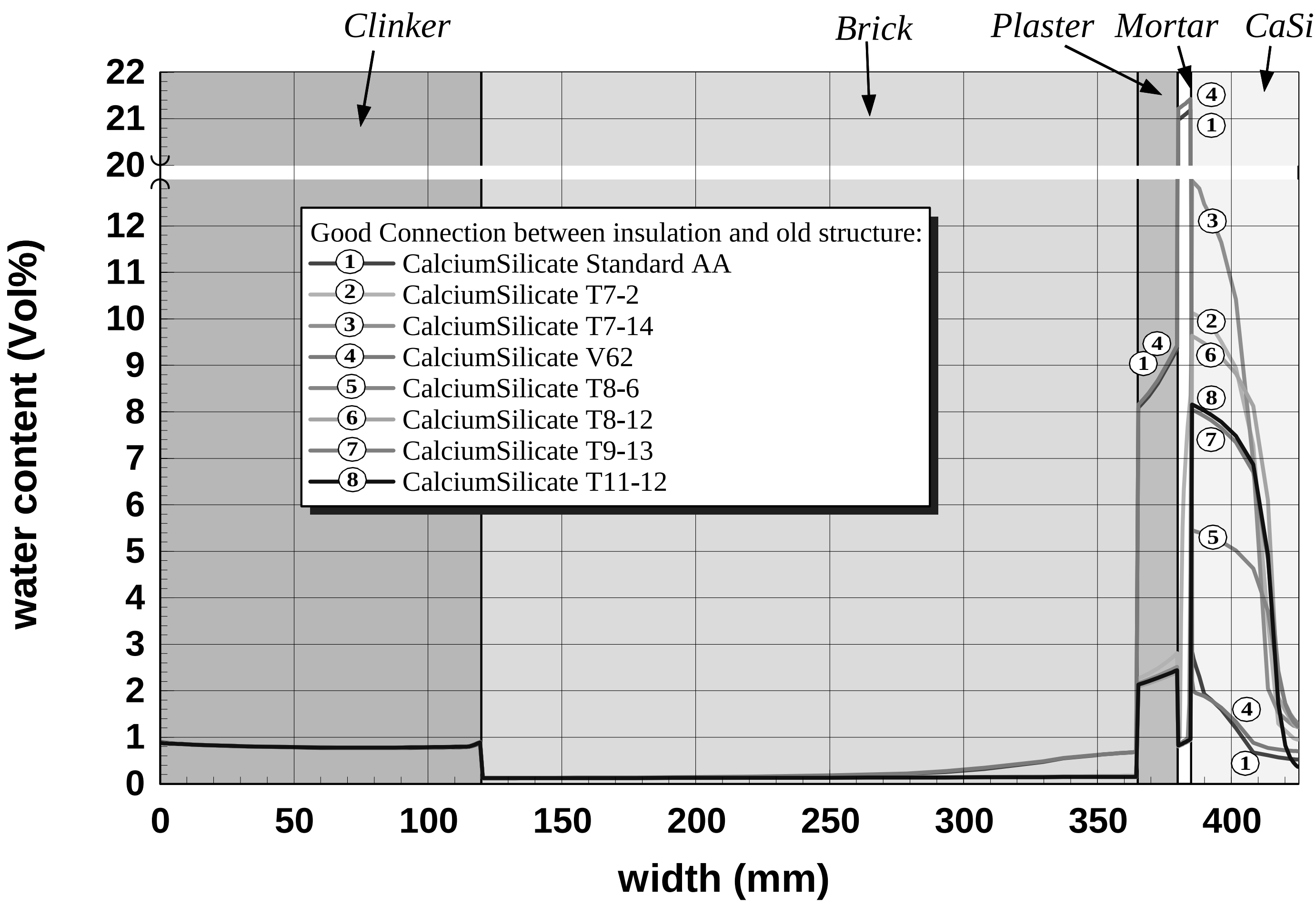


Figure 12. Water content versus location for all 8 materials after 60 days

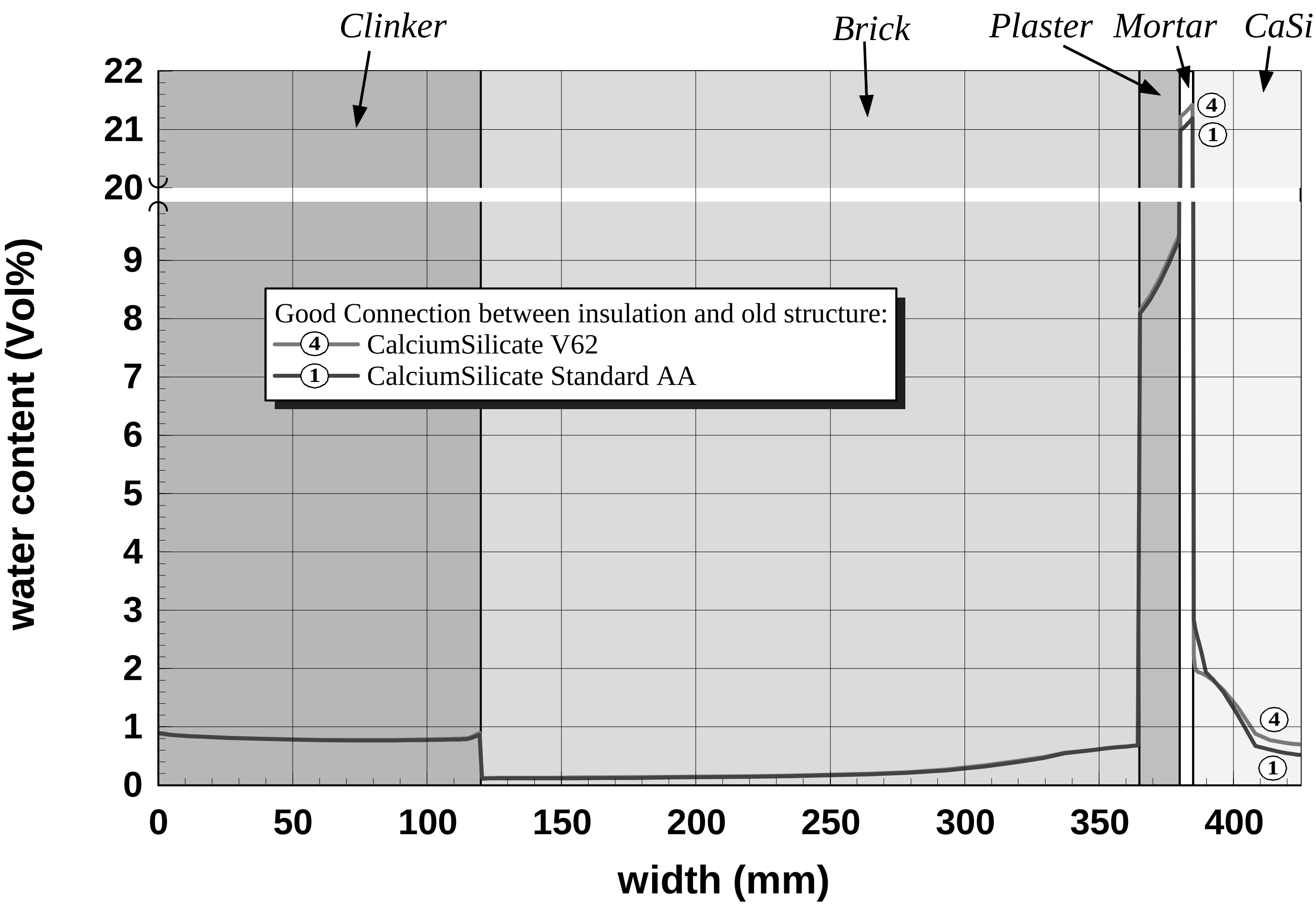


Figure 13. Water content versus location for materials of group 1 after 60 days

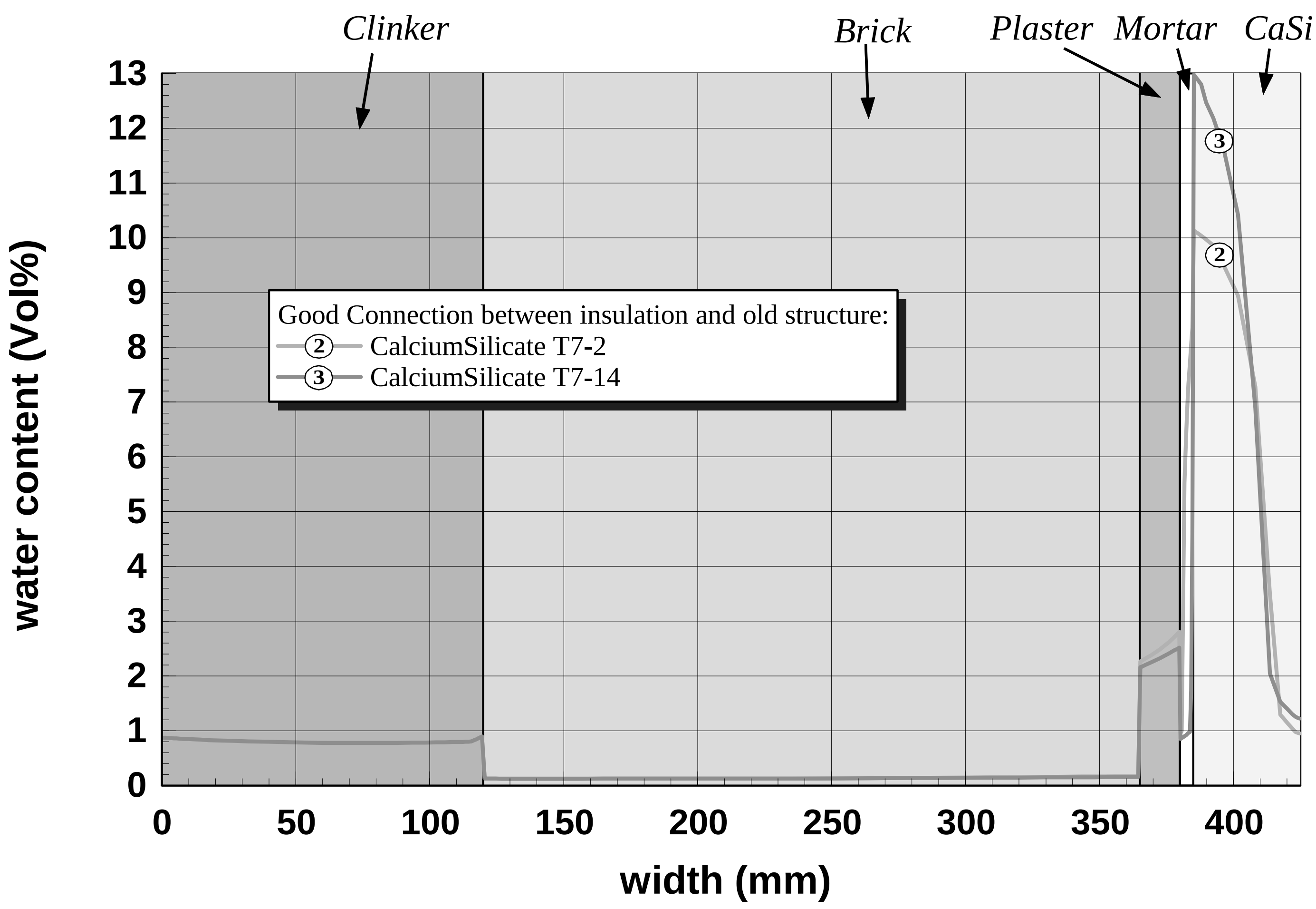


Figure 14. Water content versus location for materials of group 2 after 60 days

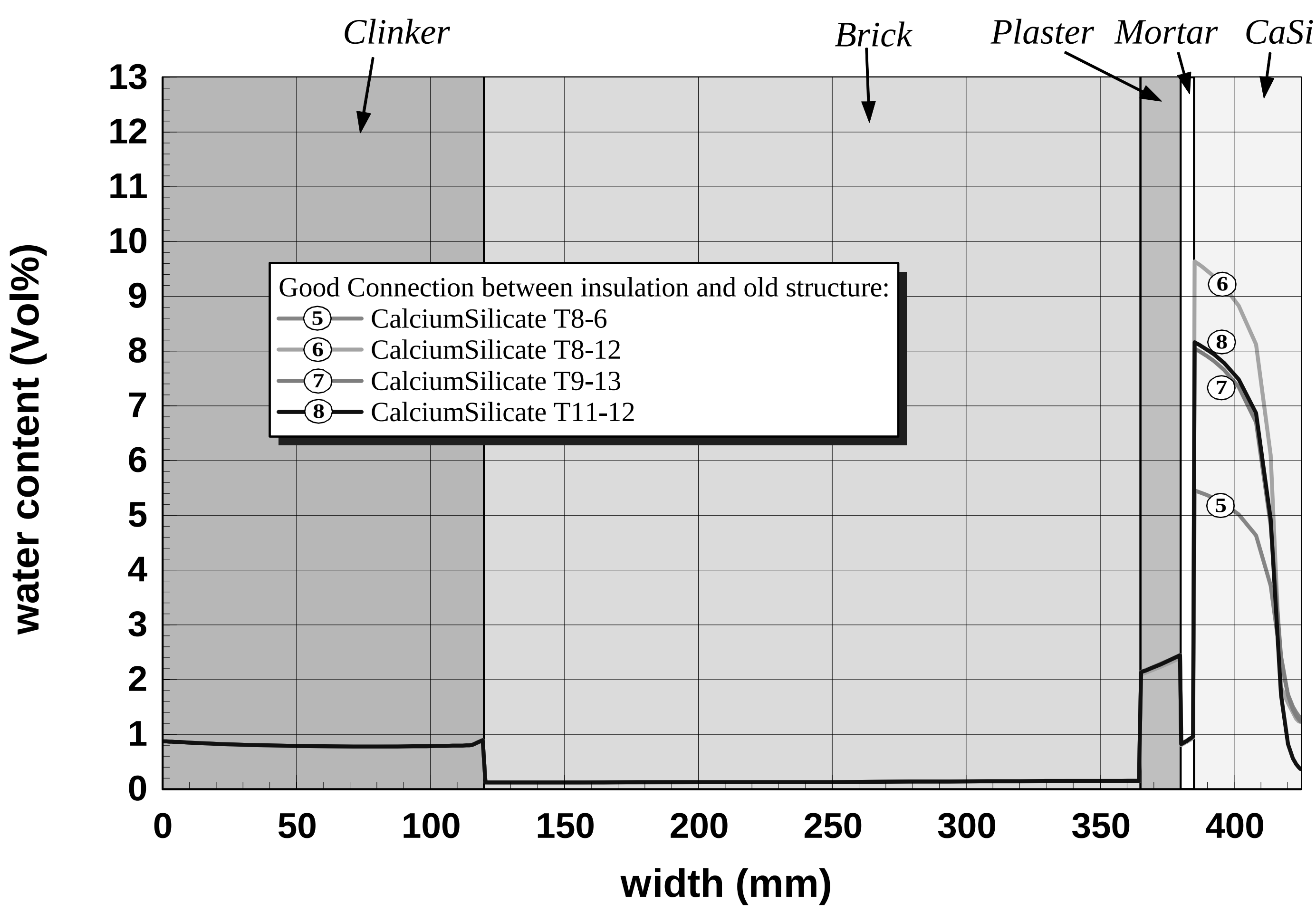


Figure 15. Water content versus location for materials of group 3 after 60 days

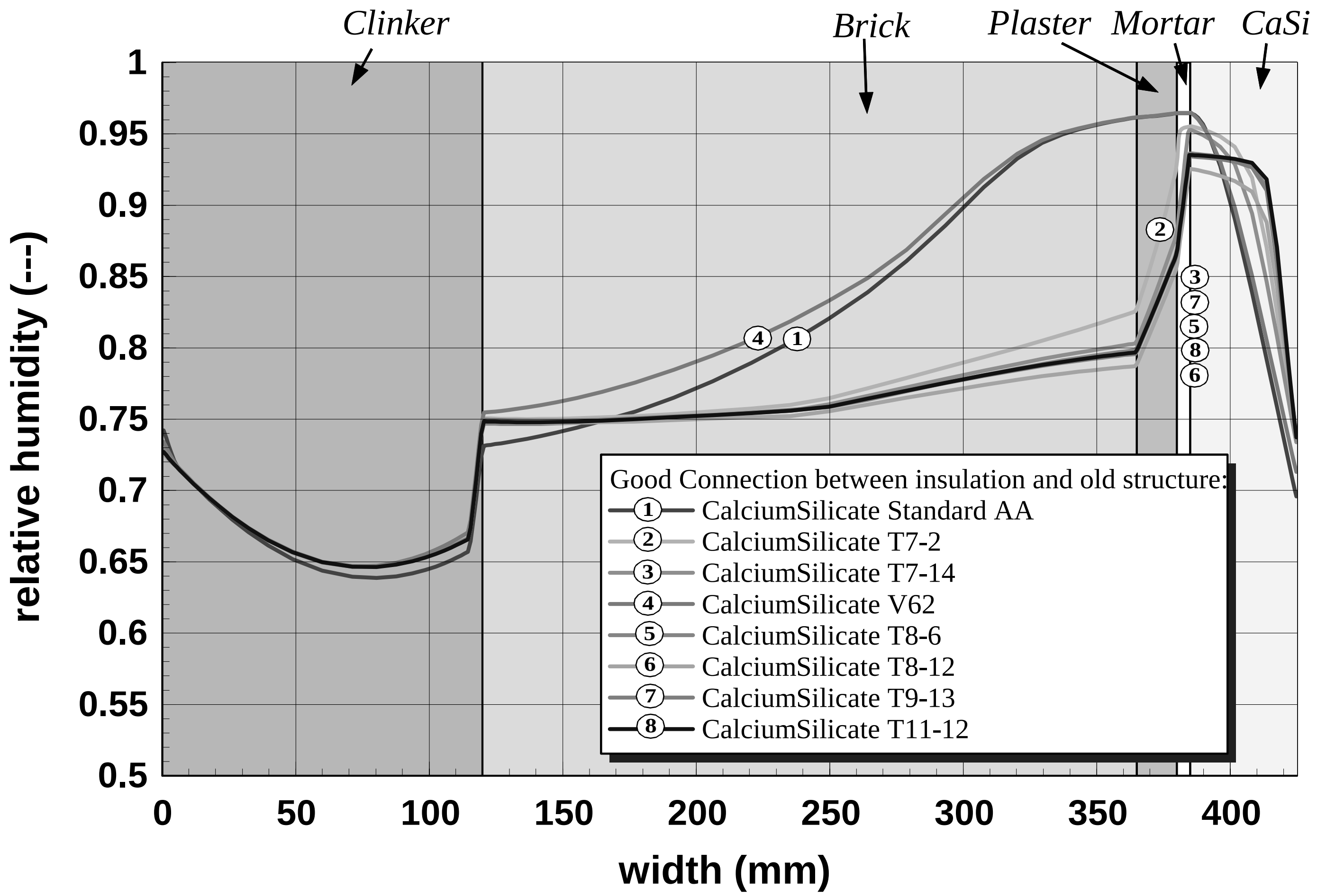


Figure 16. Relative humidity versus location for all 8 materials after 60 days

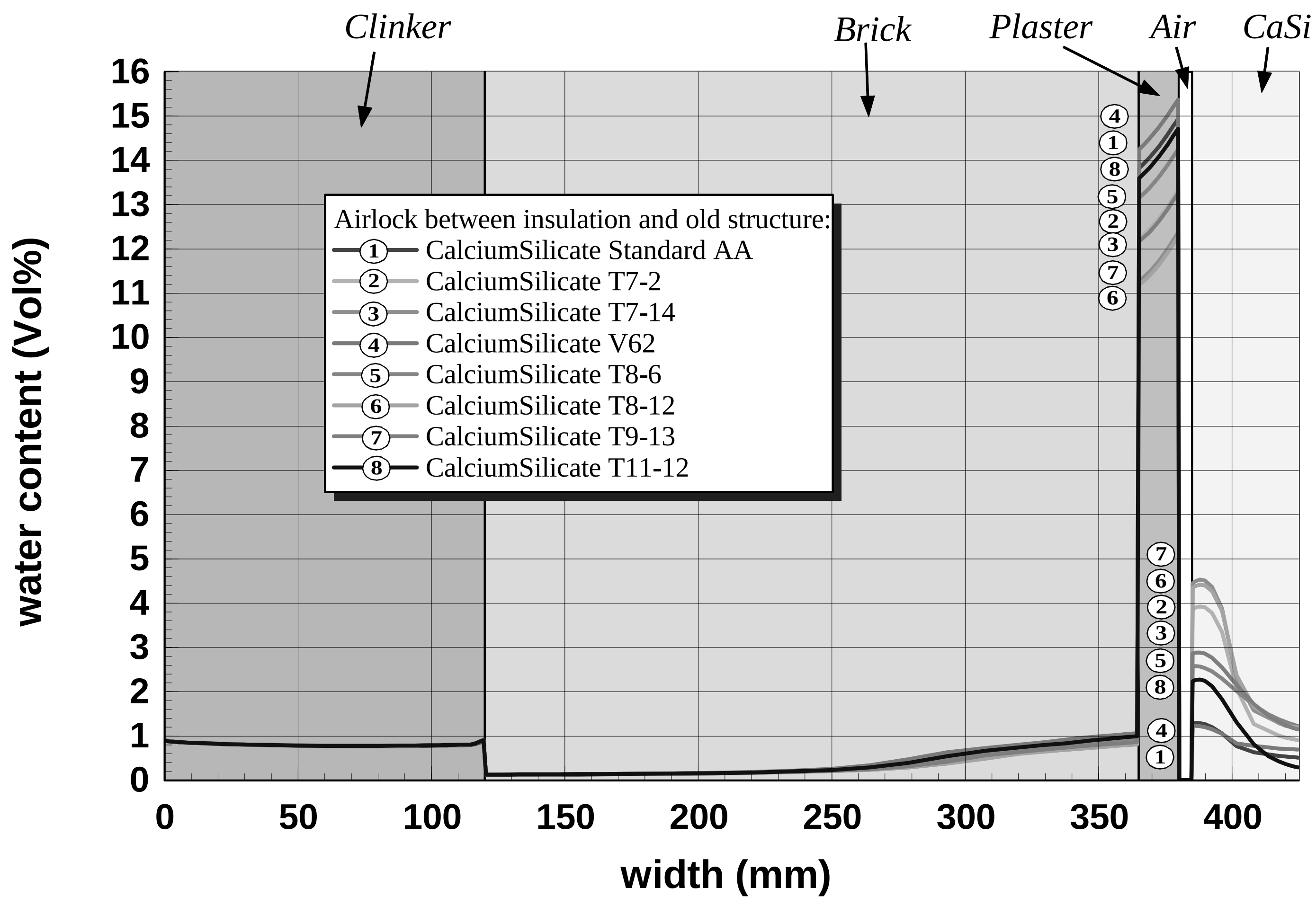


Figure 17. Water content versus location for all 8 materials after 60 days, air gap between calcium silicate and mortar

## 3.4 *Summary*

The two investigated variants of structural accomplishment lead to different predications about the insulation materials. For a good connection between glue mortar and insulation (full contact) the 8 materials can be divided into 3 groups where the second one shows a fair and the third one shows good building physical behaviour. The classification can be made chiefly due to the moisture conducting properties that are essential for a good performance. Calsitherm, who has to take into consideration not only building physical, but also mechanical and optical properties, will continue the development based on materials from group 3 that contains calcium silicate T8-6. T8-12, T9-13 and T11-12.

In contrast for a flawed connection between insulation and old structure containing air locks (bad workmanship) the good performance of the materials is reduced. With a missing retarder layer which causes condensation at the surface of the calcium silicate material, the water vapour penetrates the insulation and condensation can take place at the surface of the old structure. If there is no contact, the advantageous water conducting properties of calcium silicate can not be used and the structure could fail.

Therefore, for a good structural performance a high quality at the construction site must be still guaranteed. Air gaps must be prevented. However, if the connection is unobjectionable, the new materials show a good building physical behaviour.

# 4 CONCLUSIONS

Both simulation studies deliver meaningful results. The idea to design a material by the help of numerical simulation in order to find the best fitting parameters is good, the development of such an insulation system would allow to prevent moisture damages with a high safety level, but it fails because of technological problems in production, yet.

In contrast, the simulation offers also opportunities in optimisation of existing materials. In a very short time clear predications about the building physical behaviour of materials can be made and find their consideration within the production process. The air gap problem does still persist and consequently the requirements for installation at the building site. In this case the optimisation can not solve all physical problems but it can help to make an existing insulation system more capable.

The usage of the capillary activity of insulation materials as de-humification potential is a big innovative step in the building insulation/renovation technology and offers the possibility to develop new solutions for old, long-lasting problems where expensive traditional renovation methods fail. They allow to upgrade the thermal properties of the envelopes of a large group of buildings, where exterior insulation systems are not applicable.

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