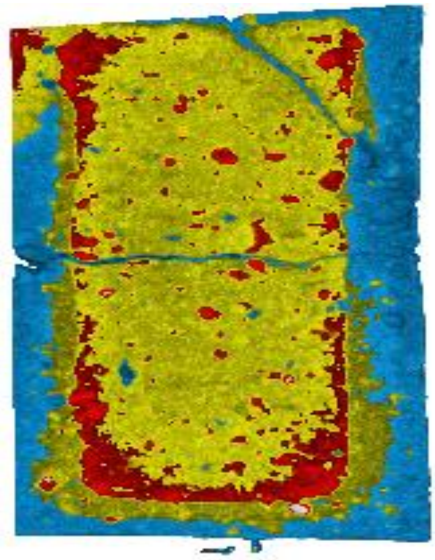
POSSIBILITIES AND LIMITATIONS

OF THE PRESSURELESS INJECTION METHOD

IN MASONRY BUILDING MATERIALS



Thesis Booklet

of the PhD -Thesis of

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to obtain the academic degree of

Ph.D. in Architectural Engineering

from the University of Pécs

Faculty of Engineering and Information Technology/

Marcell Breuer Doctoral School

November 2018

Prologue

This dissertation was developed as part of a cooperation between the Marcell Breuer Doctoral School of the University of Pécs/Hungary and the Faculty of Engineering at the University of Applied Sciences in Wismar/Germany. Everyone involved in this cooperation is gratefully acknowledged.

I would like to say a special thank you to:

.... first of all my children Lena and Felix - thanks for your understanding and consideration

.... my family and my friends who supported me a lot during this time

.... Mrs Adél Len Ph.D. from Budapest Neutron Centre for the supervision of the PhD-Thesis

.... Mr Zoltan Kis Ph.D. from Budapest Neutron Center for support during the investigation of the samples

dedicated to my father

Outline

Abstract

All over the world, many buildings and in particular cultural monuments are affected by rising damp due to a missing or non-functional horizontal sealing however their preservation would be valuable for future generations.

One possible remedy is the application of a subsequent horizontal sealing by means of a pressureless injection method but the results are often varying or even inadequate so that in consequence the method itself is frequently questioned. This phenomenon prompted the following research on the possibilities and limitations of the pressureless injection method on common building materials.

As a result of the investigations mentioned before, several factors have a limiting effect on the spreading of an injection agent, in which case the prevailing factor is the existing degree of moisture penetration of the building material.
Based on the results obtained, it is possible to derive a model of the spreading of an injection agent in building materials and therefore it is possible to make a prediction regarding the effect of the sealing. It was also found that the combination of the injection agent used and the building material produces specific results that cannot be transferred to other building material/injection agent combinations.

In addition to this, it is possible to present the distribution of an injection agent in the building material three-dimensionally with the help of neutron imaging. By means of methods such as Neutron Radiography and Neutron Tomography it can be proven that the distribution of an injection agent in the inner part of a building material is not homogenous: the concentration is higher at the edges of the impregnated samples, caused by variations in moisture content.

In summary, the results provide valuable information regarding the widely differing sealing results in construction practice and show possibilities for optimizing the planning and execution of the method.

1 Introduction and problem definition

Water can damage buildings in various ways: in the form of driving rain, leachate, condensation or (even) hygroscopicity e.g. [1]. The resulting damage varies from rising damp, the rough solving of composite material to finally a cross-sectional weakening [2].

Among others, many historic, architecturally significant buildings (eg. cultural monuments) are affected by these patterns of damage and many are worth preserving for future generations. Moreover, as this damage pattern is not limited to specific regions of the world a productive refurbishment is of high relevance.

Figure 1: Rising humidity in masonry buildings in Venice
(source: www.passengeronearth.com)

In Germany there are no legal standards how to obtain a functional subsequent horizontal seal but there is a certification 4-10 of WTA (Wissenschaftlich-Technische Arbeitsgemeinschaft für Bauwerkserhaltung und Denkmalpflege e.V.) which deals with this topic [3]. The results of this certification refers to laboratory experiments but it does not describe the workmanship on the building. It should be noted that the statements made in the WTA certification regarding the used injection agent (IM), refer exclusively to WTA-tested injection agents, and one type of the bricks to build the proof of effectiveness; the borehole distance to be used is stated to be between 10 cm and 12,5 cm. There is no further information regarding other types of building materials or non-certified injection agents.
In Austria there is a certification called ÖNORM [4] which states the corresponding bore hole distance to be about 10 cm. In addition, missing preliminary investigations are blamed for failure.

Two further test procedures are available in Germany, No. 01/2010 and 02/2012 of the Dahlberg Institute e.V. [5, 6], which quantify the effectiveness of a subsequent seal by determining reduction factors. It should be noted here, that the following results refer to investigations using on the test procedures from Dahlberg Institute.
One possible means to create a subsequent horizontal seal is the pressureless injection method, whereby an injection agent is brought into the masonry [3] with the aid of suction angles or cartridges.

In practice, however, it can be seen that many failures are produced [7], since the applied injection agent does not appear to spread sufficiently to form a flat sealing level. As a result, rising humidity and a reduced or inadequate drying process are still to be expected in these areas.

This PhD-Thesis addresses the aforementioned problems and shows the possibilities and limitations of a subsequent horizontal seal in masonry. The factors mentioned above as well as the varying results of this method, prompted the research into the spread of an injection agent in different mineral building materials such as samples of brick, calicium silicate brick and cement-lime mortar. Due to the large range of variation in the achieved sealing results, the following remarks relate to the pressureless application of injection agents (IM) to masonry building materials.
The model of injection agent spreading [8, 9, 10] co-developed by the author should be used to determine the dependency of the spread of an injection agent on limiting factors, and make statements regarding the application limits.

2 Theoretical background

The transport of water, which often turns out to be the main reason of damage to buildings, as well as the transport of an applied injection agent are both affected by the pore system of the building material by means of capillarity and gravity. From this, it can be deduced that the number, the distribution and the arrangement of the capillary pores are relevant for water and injection agent (IM) transport and therefore decisive with regard to the efficiency of a subsequent seal.
With regard to the presence of the capillary pores in the building material, it should be noted that a fundamental problem with high degrees of moisture penetration is that the pore space of the capillary pores is already filled with water [8]. This means, that with increased degree of moisture penetration D(g) and thus increased filling of capillary pores with water, it can be assumed that less IM can be taken up by the pore system [9] and the probability of a successful seal decreases [8, 9, 10, 11].

The ability of a building material to absorb water and to store it in the pore system can be determined using the water absorption coefficient w in accordance with EN ISO 15148. To determine this, a dried building material test specimen was water applied to it at certain time intervals, and the change in mass in measured in function of time t.

In addition to mechanical methods, another possibility to obtain a subsequent horizontal seal is the injection method using pressureless injection. The effectiveness of this method is based on influencing the moisture transport processes in the building material itself.
This is achieved by the introduction of an injection agent (IM), which modifies the existing pore spaces in the building material by means of various active principles (hydrophobic, constricting, occluding or in a combination of them) in order to reduce or completely prevent the water transported.

After application, the injection agent is distributed by the existing pore system (these agents are called hereafter “classic”, Fig. 2) by means of cartridges or suction edges, whereas creamy agents are also available. Both kinds of injection agents were used in the following studies. The main ingredients in classic as well as in creamy injection agents are Silanes and Siloxanes with a similar reaction mechanism.

Figure 2: Pressureless injection of injection agent in masonry
(source: Dahlberg Institute)

It can be assumed that after application the pore system of the building material becomes hydrophobic due to the reaction mechanism (e.g. hydrophobing, pore constricting, see also Fig. 2 and 3) of the agent.
One method to proove a hydrophobic effect on the surface of the sample is the droplet test. After setting a water droplet on the surface of the building material the droplet remains on the surface, due to the change of the contact angle to over 90°. On untreated areas of the building material, the droplet is passed into the pore structure by capillarity and gravity.
This effect is recognizable only on the surface of the test specimen and it is not known how the spread of an injection agent is distributed in the inner part of the sample.

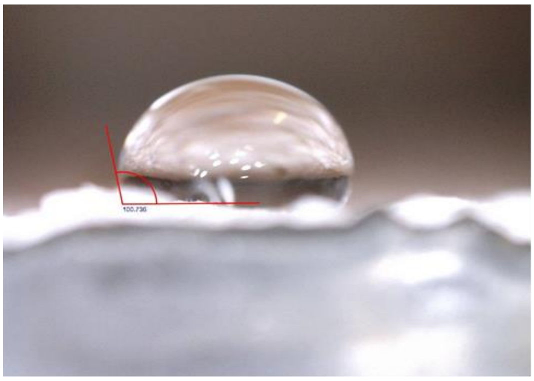


Fig. 3: Contact angle >90° due to hydrophobicity [21]

Fig. 4: Remaining droplets on the surface due to hydrophobicity after application of the IM

Subsequently, the samples need to be split with a hammer and chisel to measure the spreading of the injection agent in the inner part of the material.

3 Experimental studies

The following studies [18] were carried out on three types of building materials: bricks, calcium silicate bricks and cement lime mortar samples. “Classic” IM and creamy injection agents were used for the experiments. The experimental setup and its implementation is described briefly.

3.1 Application of the injection agent

Different moisture levels were set on the samples and various IM (“classic” and creamy) were applied into the test specimen. Afterwards the samples were manually split by means of a hammer and chisel and the spread of the injection agent was observed as the darker coloured region around the borehole on the failure plane (Fig. 5). Using the method of droplet test the spread of an agent could be rendered visibly and therefore be measured (Fig. 6)

Fig. 5: Failure plan of the sample after splitting.
The darker areas are due to the spreading of the IM

Fig. 6: Measurement of the spread of the IM [18]

3.2 Neutron imaging investigations

To show the spreading of an IM in the building material another testing method was used: Neutron imaging [12, 13, 14]. The advantage of imaging compared to other methods is that neutrons can " look into the interior" of the material. Two-dimensional imaging or three-dimensional imaging is possible [14]. Another advantage is that it is a non-destructive process, i.e. after examination it is possible to carry out further investigations on the same sample [13].

X-ray examinations are also suitable for carrying out material tests. However, X-rays have lower penetration of certain materials than neutrons and can produce only weak contrast in elements such as hydrogen, carbon, oxygen and nitrogen [15, 16].
The two methods should not to be considered as competing, but rather as complementary.
Neutrons are generated in nuclear fission processes in reactors, or in nuclear spallation processes in spallation sources. The used facility was the 10 MW Budapest Research Reactor. The produced neutrons are passed through a collimator, where a parallel beam is generated, which subsequently hits the examined object.

The sample is placed on an adjustable rotatable sample plate, where either the entire test body or individual regions of a larger test body to be aligned with respect to the incident neutron beam. After passing through the examination object, the neutron beam strikes the detector (consisting of films, semiconductors or neutron counter tubes), where a two-dimensional representation of the radiation intensity is made. [13].

The following figure illustrates the aforementioned measuring procedure:

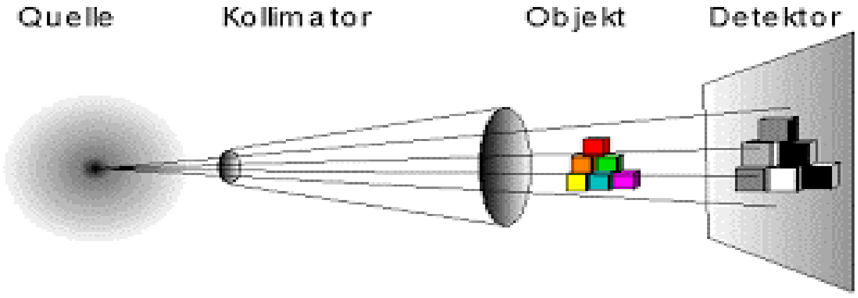


Fig. 7: Experimental setup of neutron imaging (source: sni-portal.de)

The attenuation of the intensity as a function of the layer thickness and concentration of the absorbing substance can be described as in Lambert-Beer´s law [17]:

$$E_\lambda = \log_{10} \frac{I_0}{I_1} = \varepsilon_\lambda \, cd$$

with the following abbreviations:

E	extinction (absorbance, non-dimensional)
I_0	intensity of irradiated radiation (W/m²)
I_1	intensity of the transmitted radiation (W/m²)
c	molar concentration of the absorbing substance (mol/l)
ε_λ	extinction coefficient at wavelength λ (specific value for the absorbing substance)
d	layer thickness of the irradiated body (m)

Based on the neutron intensity images, the concentration of the hydrogen protons of the IM can be determined from the weakening of the neutron beam measured after passing through the test specimen. This is represented by so-called gray values, to which, depending on the corresponding value, a color can be assigned.

Due to the possibility of rotating the sample and recording radiographs in short time intervals, a three-dimensional image, the neutron tomography, can be generated after a 360 ° rotation of the sample tray (one by one degree) from the many individual images.
The software Fiji and VG Studio (Volumegraphics) were used to present the results below.

4 Thesis on the spread of injection agents

On the basis of the previously described methods, four theses have been prepared, which will be shortly presented as the consequences of the investigations carried out.

4.1 Thesis 1

The spread of an injection agent in a building material depends on the existing degree of moisture penetration D(g) and decreases with increasing moisture penetration in the building material.

Starting with the assumption that the capillary pores are the main transport system for water as well as for the injection agent, it seems reasonable that with increased filling of the pores with water (and therefore an increased degree of moisture penetration) less injection agent can be taken up by the pore system [11].

Consequently, at higher degrees of moisture penetration > 80%, the amount of injection agent taken up by the pore system is very small, as is the spreading of the agent. As a conclusion there is a dependency between the existing degree of moisture penetration and the spreading of an injection agent.
Since most of the injection agents used for pressureless injection method are based on similar ingredients, this effect should occur in the same way for varying combinations of injection agent and building material although the correlation between the two parameters may differ.

4.1.1 Results thesis 1

For the above thesis, 7 studies of the spread of injection agents were carried out, of which only two are presented here as examples.

Study 3: cement-lime mortar with IM-cream I

Tab. 1: characteristics study 3 [18]

Material:	cement-lime mortar (1) time of setting 2 days (2) time of setting 28 days	Bulk density: 1,73 g/cm³ Porosity: 0,12 Factory-adjusted hydro-phobic
Injection agent:	IM-cream, active ingredient 80 Gew.-%	Active principle: hydro-phobing
Application:	pressureless	
Surrounding temperature:	12,6 ° C	relative humidity 71%

The spread of the agent can be presented by using linear regression as follows:

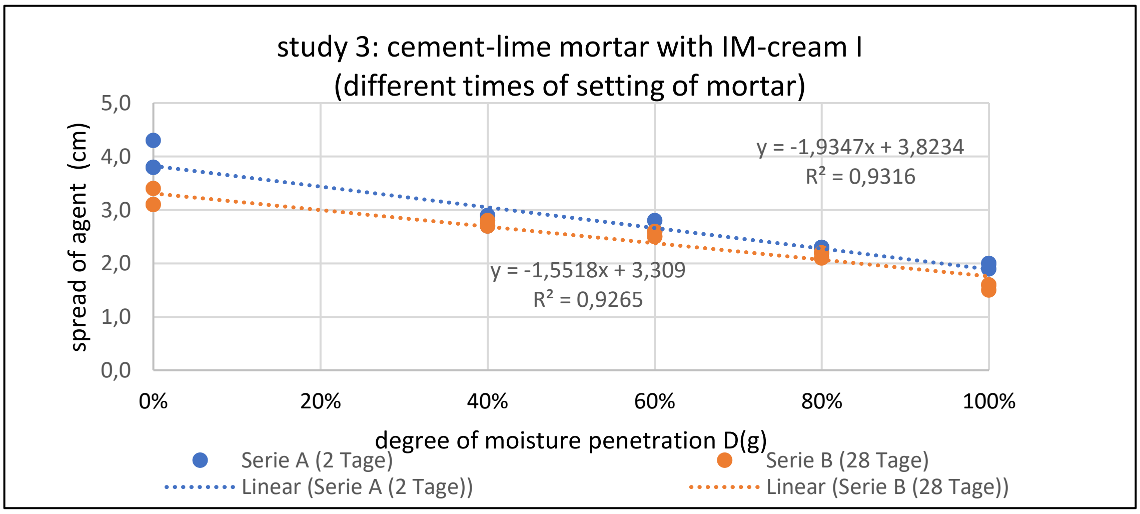


Fig. 8: Linear regression study 3

The mortar test specimens of the two rows of tests used different setting times; a significant difference in the extent of the effects is not evident. A moisture-dependent spread in the building material is clearly shown, where even at high throughput levels there is still a slight spread.

Study 7: bricks and calcium sillicate bricks with IM cream

Tab. 2: characteristics study 7 [18]

Material:	(1) Brick (2) Calciuim silicate brick (KS-stone)	Bulk density (1): 2,12 g/cm³ Bulk density (2): 1,88 g/cm³ Porosity (1): 0,09 Porosity (2): 0,21
Injection agent:	IM-cream	Active principle: hydrophobing
Application:	pressureless	
Surrounding temperature:	13° C	relative humidity 45%

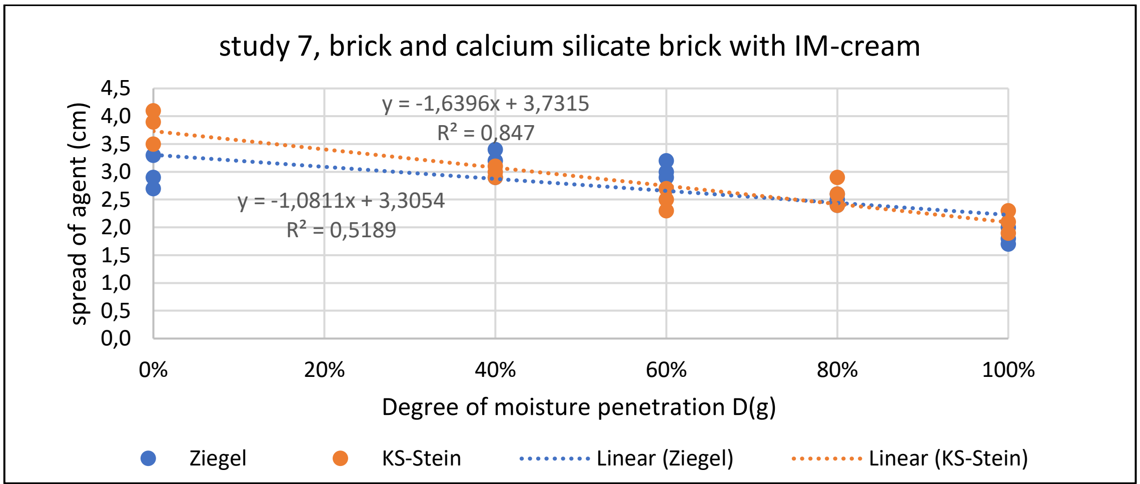


Fig. 9 Linear regression study 7

In the case of the brick samples, high correlation values were also determined. There correlation is somewhat lower for the calcium silicate brick sample. A moisture-dependent spread of the IM was likewise detectable on one side.

The performed neutron imaging studies are presented here. Test series with different degrees of moisture penetration were examined by neutron radiography and tomography. The tomography results are presented here.

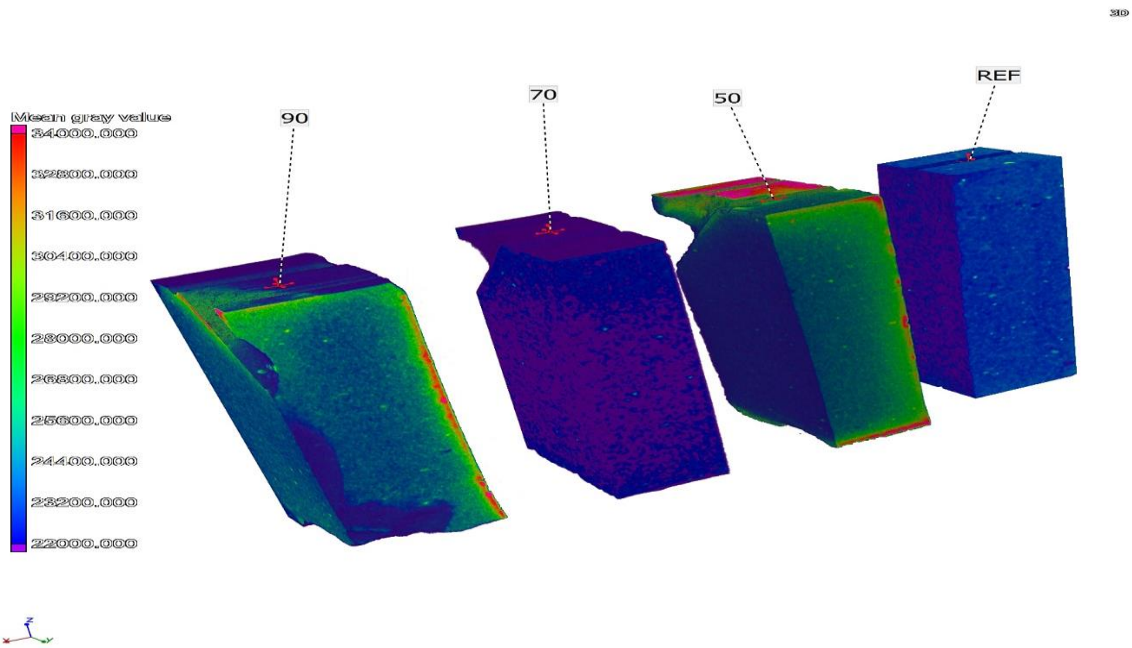


Fig. 10: Moisture-dependent spread of injection agents, presented by neutron tomography.

On the right side (Fig. 9) we can see the reference sample of the neutron tomography. The sample with D(g) 70% is not plausible and therefore not rated.
A decrease of the content of the IM is recognizable in values of D(g) 50% (green colour) compared to the lower values of the test piece at D g) 90% with bluish colour.

4.1.2 Summary assessment of thesis 1

I have proven by several experimental methods such as application of injection agents in different building materials by means of pressureless injection method, implementation of droplet test, measuring of the spread of injection agent in the building material [18] and neutron radiography and -tomography [19] that the spread of the agent in building materials is highly dependent on the existing degree of moisture penetration in the building materials. I worked out that the spread of an injection agent decreases with increasing degree of moisture penetration of the building material, i.e. it is inversely proportional [8, 9, 20].

4.2 Thesis 2

I supplemented and developed a model that I designed as a co-author regarding the spread of injection agents in building materials by using linear regression. The spread of an injection agent as well as the appropriate borehole distance, which is necessary to obtain a functional subsequent horizontal seal can be represented not only visually, but also by means of physical parameters.

From a graphical representation of the examination values of the spread versus the respective existing degree of moisture penetration, a linear relationship can be identified that can be represented as a linear function.
From the test results obtained, a specific IM characteristic curve can be calculated, from which, on the basis of which extrapolation, it is possible to read off those degrees of moisture penetration in which there is still sufficient spreading of the IM to produce a functional seal.

In addition, statements regarding the necessary borehole spacing, which is likewise moisture-dependent, provide valuable information for execution in construction practice.

4.2.1 Results Thesis 2

For this purpose, the linear regression obtained from the experimental values was used as a model.

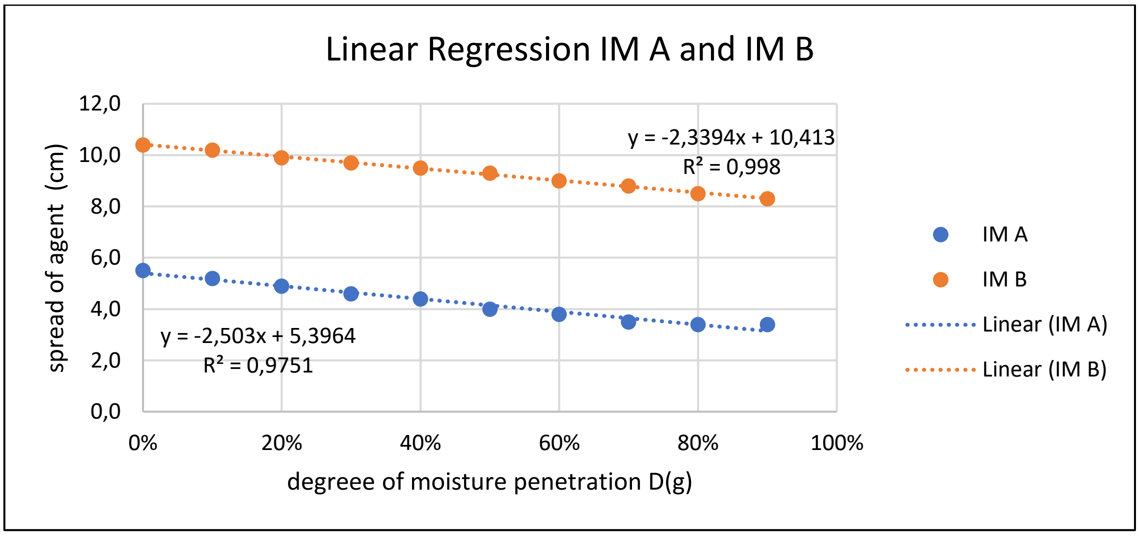


Fig: 11: Linear Regression IM A and IM B

The following modelling was derived from the graphical presentation:

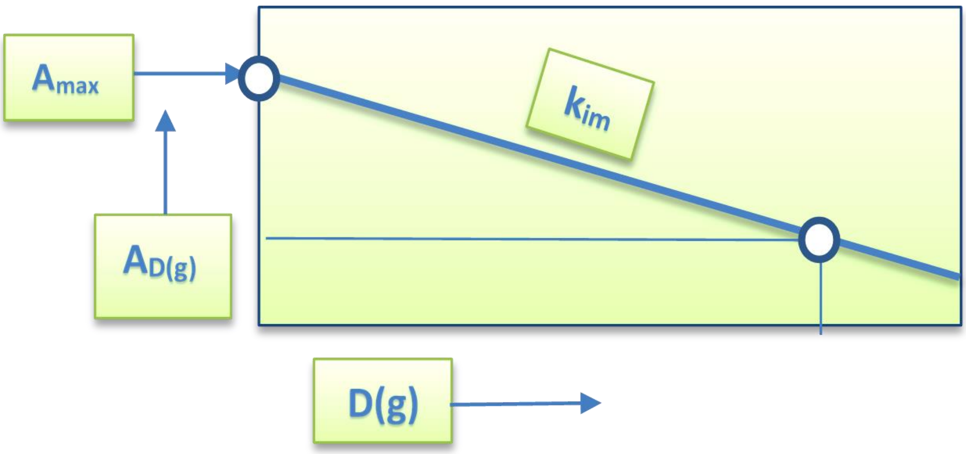


Fig. 12: Modelling of the spread of the injection agent [8]

with following abbreviations:

A_D moisture-dependent spread of IM

A_{max} maximum spread of IM

D(g) degree of moisture penetration

k_{im} injection agent permability (cm/%), describes the decrease of an agent in relation to the degree of moisture penetration

The dependency mentioned above between the spread of an agent and the degree of moisture penetration can be represented as an equation of function due to the linearity:

$$\mathbf{A_D = A_{max} - A_k = A_{max} - k_{im} \cdot D(g)}$$

The parameter k_{im} can be determined by the gradient of the characteristic curve as follows:

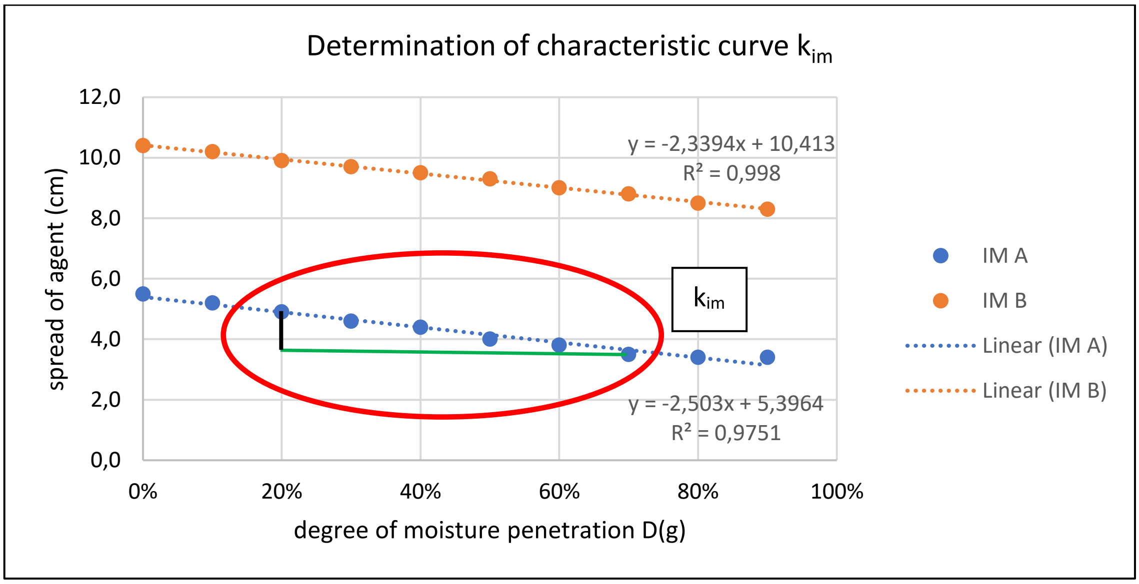


Fig. 13: Graphic determination of the characteristic curve k_{im}

In this case, the parameter can be determined from the quotient of the spread of an IM at a certain degree of moisture penetration in relation to a checkpoint:

$$\mathbf{k_{im}} = \frac{\mathbf{A_{D1} - A_{D2}}}{\mathbf{D_2 - D_1}}$$

The application area of an IM can be described from the above explanation. It can be seen from the graphs up to which degree of moisture penetration a sufficient spreading of the IM is given. The reference line is the 6cm-line according to WTA [3], which corresponds to half the distance between the boreholes.

In the case of spreads with smaller values than the WTA-line, it can be concluded that there is not sufficient spreading of the IM to achieve a functional seal.

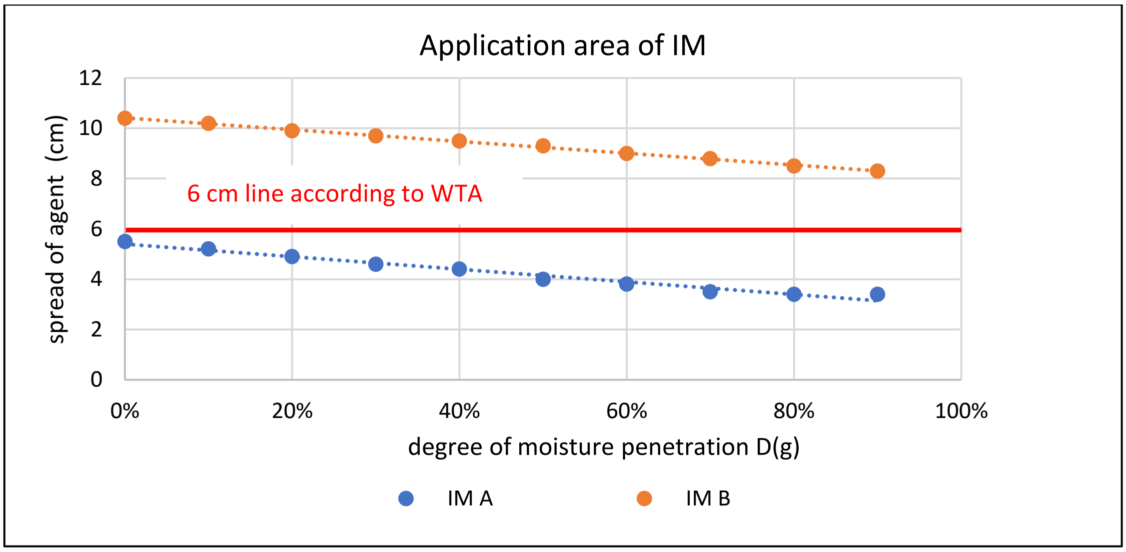


Fig. 14: Graphic representation of application area of an injection agent

Two important statements can be made:

- the spread of IM A is too low, so that even at a degree of moisture penetration of 0% (where it can be assumed that the whole pore space is available for the IM uptake) no functional seal can be achieved
- regarding the major spreading of IM B a misperformance of the seal according to the 6 cm-line is not expected

Depending on the degree of moisture penetration, it is also necessary to determine the bore hole distance in accordance with the preceding explanation. According to WTA specification, a consistent bore distance has to be implemented, stated to be between 10 cm and 12,5 cm.

Following considerations, have to be made with regard to the distance between the boreholes:

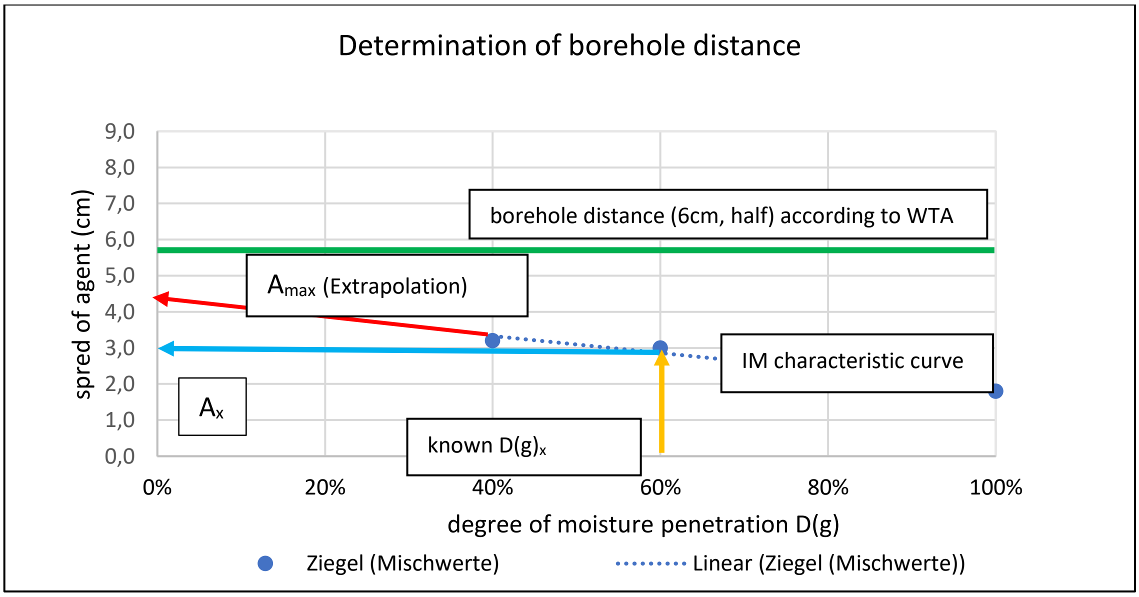


Fig. 15: Determination of borehole distance

Explanation:

- The IM characteristic curve (dotted here in blue) is assumed to be known; in the case of missing values, the value A_{max} can be determined graphically by extrapolation (red line, corresponds to the point of intersection of the IM characteristic curve with the y-axis at D (g) 0%)
- Assuming, for example, a degree of moisture penetration of 60%, a point of intersection with the IM characteristic curve can be read in the vertical direction (orange straight line)
- This intersection, when read on the y-axis (horizontal intersection, marked by the turquoise line), represents the spread of the IM at the selected D (g) 60%, in this case 3 cm.

For the borehole distance to be applied, however, a further distinction must be made:

- Theoretical borehole distance $B_{theor.}$
  The theoretical borehole distance B_{theor}. is to be considered a double propagation of an IM at the respective degree of moisture penetration, in the above example of D(g) g 60% it would be assumed that a value of 2 x 3 cm = 6 cm.

  $B_{theor} = 2\ A_D$

- Practical borehole distance B_{prakt}.
  With regard to an overlap of the spreading radii, the corresponding borehole distance should be selected such that a further subsequent rising of moisture in the building material can be avoided. The size of the overlap of the propagation radii, which is to be understood in the sense of a "safety area", is to be selected technically meaningful and economically viable. An overlapping range of 20 % seems to make sense for the aforementioned reasons.

  $B_{prakt} = B_{theor.} \cdot 0{,}8$

The new characteristic values are listed again in the following table:

Tab. 3: Compilation of new parameters

Parameter/Formula		Example
		Example: $D(g)_1$: 40 %, A_1: 5,0 cm $D(g)_2$: 80 %, A_2: 2,0 cm
	$A_{max} = A_D – k_{im}\ D(g)$	• graphical presentation of IM-line with P_1 (40%/5,0 cm) und P_2 (80%/2,0 cm) • intersection by extrapolating the straight line at a D(g) of 0% (with the y-axis), A_{max} can be determined graphically A_{max} = 7,9 cm
k_{im}	**IM permeability** $k_{im} = \frac{A_{D1} - A_{D2}}{D_2 - D_1}$	$k_{im} = \frac{(5-2)\ cm}{(80-40)\ \%}$ = 0,075 cm/% k_{im} (IM permeability) indicates how many cm the IM propagation reduces as the D (g) increases by 1% $A_k = k_{im}\ D(g) = \frac{2}{5}$ cm/% D(g)

		example 1: D(g) = 60% correction: A_k = 60 x 0,075 cm = 4,5 cm **example 2**: D(g) = 40% correction: A_k = 40 x 0,075 cm = 3,0 cm **example 3**: D(g) = 20% correction: A_k = 20 x 0,075 cm = 1,5 cm
A_D	**Moisture dependent spread of agent A_D** $A_D = A_{max}-A_k=A_{max}-k_{im}$ D(g)	**example 1**: D(g) = 60% -> $A_D = A_{max} – A_k$ = 5 cm – 4,5 cm = 0,5 cm **example 2:** D(g) = 40% -> $A_D = A_{max} – A_k$ = 5 cm – 3,0 cm = 2,0 cm **example 3:** D(g) = 20% ➔ $A_D = A_{max} – A_k$ = 5 cm – 1,5 cm = 3,5 cm
$B_{theor.}$	**theoret.** **borehole distance** (without „safety area“) $B_{theor} = 2 A_D$ $B_{theor} = 2 [A_{max} – k_{im} D(g)]$	$B_{theor} = 2 A_D$ example 1: 1,0 cm example: 2: 4,0 cm example 3: 7,0 cm
$B_{prakt.}$	**pract. borehole distance** $B_{prakt} = B_{theor.} \cdot 0,8 A_D$ (with „safety area“)	$B_{prakt} = 0,8 B_{theor.}$ example 1: 0,8 cm example 2: 3,2 cm example 3: 5,6 cm

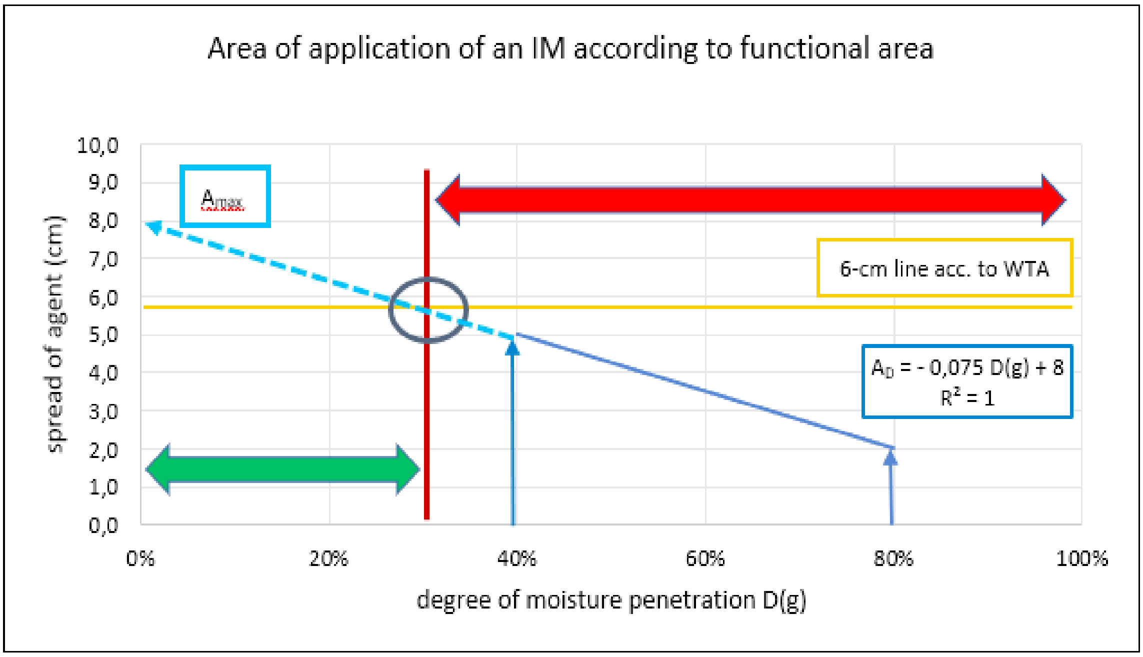


Fig. 16 Area of application of an IM according to functional area

Result:
Based on the intersection point of the two straight lines (IM-line and 6 cm-line according to WTA), a conclusion can be made up to which degree of moisture penetration an IM can be used.

4.2.2 Summary assessment of thesis 2

Based on the above mentioned model I have built the graphical representation of the spreading in function of the existing degree of moisture penetration of the building material [18].
The graphical representation allows to predict the spread, therefore the efficiency and the result of the sealing process; it determines the maximum degrees of moisture penetration to up which the use of an injection agent is useful.
I have validated the graphical representation of the spreading of the injection agent by experiments [9, 8, 10,11, 18, 20].

4.3 Thesis 3

The combination of building material and injection agent produces different results, depending on the materials which cannot generally transferred to other building material/injection agent-combinations.
Different studies on the spread of IM are intended to prove that the results obtained are not suitable for general portability due to their different characteristics, despite the same tendencies of the decreasing uptake of an IM with increasing moisture penetration.
Commercially available injection agents and common building materials such as lime-cement mortar, bricks, clinker and calcium silicate bricks form the basis of the investigations carried out.

4.3.1 Results thesis 3

In the following, two studies are presented as examples in which different combinations of building materials with varying injection agents produce diverse results. The results of the study are presented by using linear regression.

Tab. 3 Characteristics study 2 [18]

Material:	(1) Cement-lime mortar MG II (2) Cement-lime mortar MG II (different manufacturers)	(1) Bulk density: 1,76 g/cm³ Porosity: 0,2 (2) Bulk density: 1,78 g/cm³ Porosity: 0,15
Injection agent:	Kaliummethlysilantriolat und -silikat	Active principle: pore occluding, hydrophobing
Application:	(1) Time of length 21 days	(2) Time of length 14 days
Surrounding temperature:		(1) 17° C, 28%/40% rel. humidity (2) 12° C, rel. humidity: --

Regarding the mortar samples it should be noted that it they are the same type of mortar, but from different manufacturers while the IM used is the same.

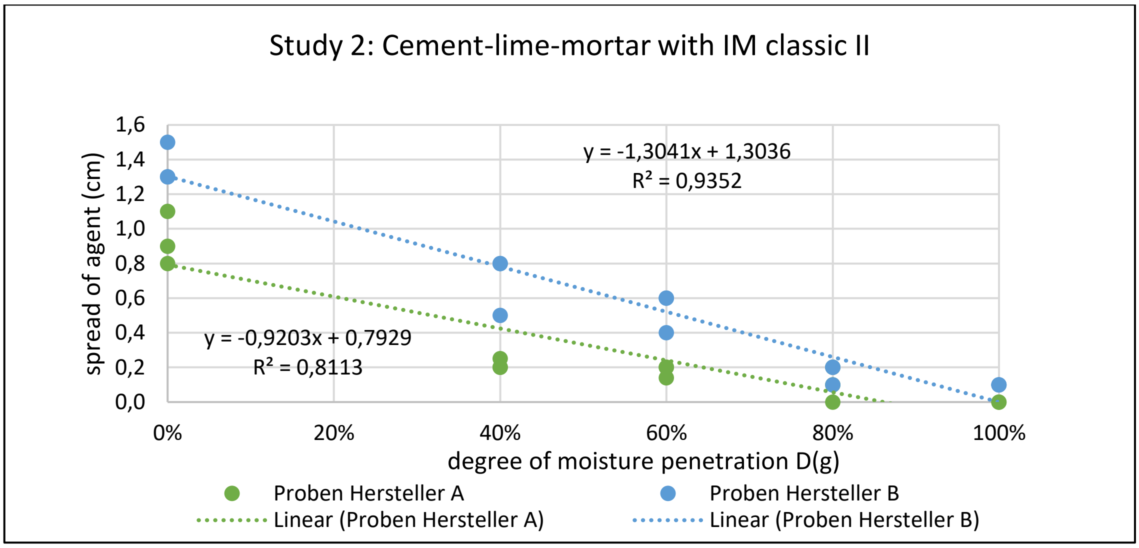


Fig. 17: Linear regression study 2

Although the same mortar groups were used and the same IM, it seems that there are differences in the raw materials and therefore in the composition of the products of different manufacturers which obviously have an effect on the spreading of the IM. The tendency of decreasing spread with increasing moisture penetration of the building material is present.

Tab. 4: characteristics study 6 [18]

Material:	(1) clinker (2) calcium silicate brick (KS-Stein)	Bulk density (1): 2,3 g/cm³ Bulk density (2): 2,06 g/cm³ Porosity (1): 0,03 Porosity (2): 0,08
Injection agent:	1-K silification	Active principle: pore constricting, solidifying
Application:	length of time: 7 days	
Surrounding temperature:	11,5-12,7 ° C	51-55 % relative humidity

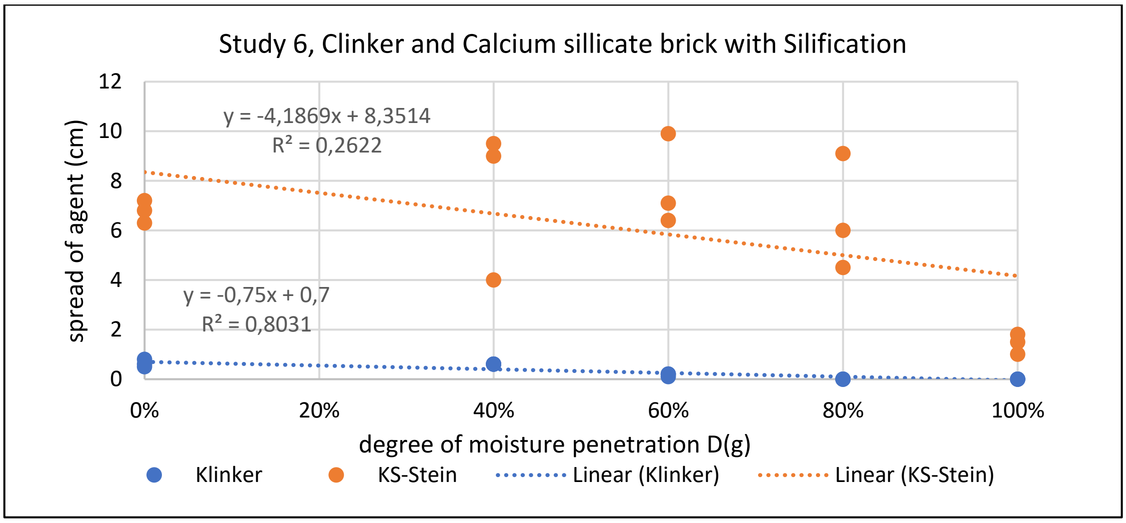


Fig. 18: Linear Regression Study 6

In the treated calcium silicate bricks there are considerable fluctuations in the determined spreading of the agent detectable, which is reflected also in a low linear relationship and thus a low coefficient of determination.
With clinker, the spread is generally very low; however, both materials show - as well as most of other studies - the same tendency of lower spreading of the agent with increasing moisture penetration.
Similarly, for both building materials, the maximum IM propagation at D (g) is 0%. The fluctuations in calcium silicate bricks may be due to moisture inhomogeneities; but in the end, despite the same agents used, there are strong differences in the spreading values of the IM.

The main results of the studies are summarized in a table below.

Tab. : Compliation of results

	study 1	study 2	study 3	study 4	study 5	study 6	study 7
building material	mortar	mortar	mortar	mortar	clinker	brick/ calc.silic. brick	brick/ calc.sili. brik
IM	1-K, fl.	1-K, fl.	Creme	Creme	1-K, fl.	1-K, fl.	Creme
A_{max} at D(g)	53%*	0%	0%	0%	40%	40%-60%	0%
A_{min} at D(g)	0%/100%	80%-100%	100%*	>88%	0%	100%	100%
A_{max} (cm)	4,5	1,5	1,8	0,8	12	10	4
Nota					Temp. !		

The two studies presented and the tabular compilation reveal the differences in the spread of the IM depending on the materials used and from this it can be concluded that the results cannot be transferred. Although some of the injection agents used have a small spreading at higher degrees of moisture penetration, it is not possible to deduce a functionality of the seal.

4.3.2 Summary assessment of thesis 3

I have proven by various experimental techniques such as the application of different injection agents in varying building materials that one of the most important factors that influences the efficiency of the usage of different injection agents is the combination of the applied injection agent and the building material. [9, 11, 18, 20].
I have tested different combinations of injection agents [18] and building materials. The differences indicated that without a proper pre-testing procedure for each combination of used agent/building material, the results and the efficiency prediction became very limited or impossible [11]. The main characteristics that influence the efficiency are the type and composition of the building material, its bulk density, the existing degree of moisture penetration and the injection agent used.

4.4 Thesis 4

The distribution of an injection agent in the building material is not uniform, but there are zones of different levels of the injection agent, which consequently also effect the effectiveness of the seal. Probably there are differences between the spreading limit and the effective limit of an injection agent.

In addition to a visually recognizable spreading of an IM on the surface of a building material, a "look into the interior" of it is necessary in order to be able to make statements regarding a spatial distribution of the IM. On the basis of the previously carried out droplet test on the surface of the building material, a hydrophobization can be detected only locally on the surface. However, regarding the distribution in the interior of the specimen, no statement is possible. Additionally, there is no information whether the distribution of an IM after application - depending on the distance to the borehole - runs evenly or must be reckoned with isolated defects or zones of higher concentration of the IM, which in turn can affect the sealing success.

4.4.1 Results Thesis 4

Neutron imaging can be very helpful in order to get “a look inside” the body of a test specimen. Due to the acquisition of the gray values during the measurement, these can also be color-coded therefore colourgraded imaging is possible depending on the intensity of the gray values. Neutron radiography basically shows a stationary uptake of the inside of a test specimen, while neutron tomography makes it possible to take three-dimensional images by turning the sample plate.
The neutron radiography provides a basic overview of the presence of a in the test body. For a better presentation, only the "raw shot" is shown, for better illustration, the relevant areas of the test body are subsequently highlighted in color.

Neutron radiography:

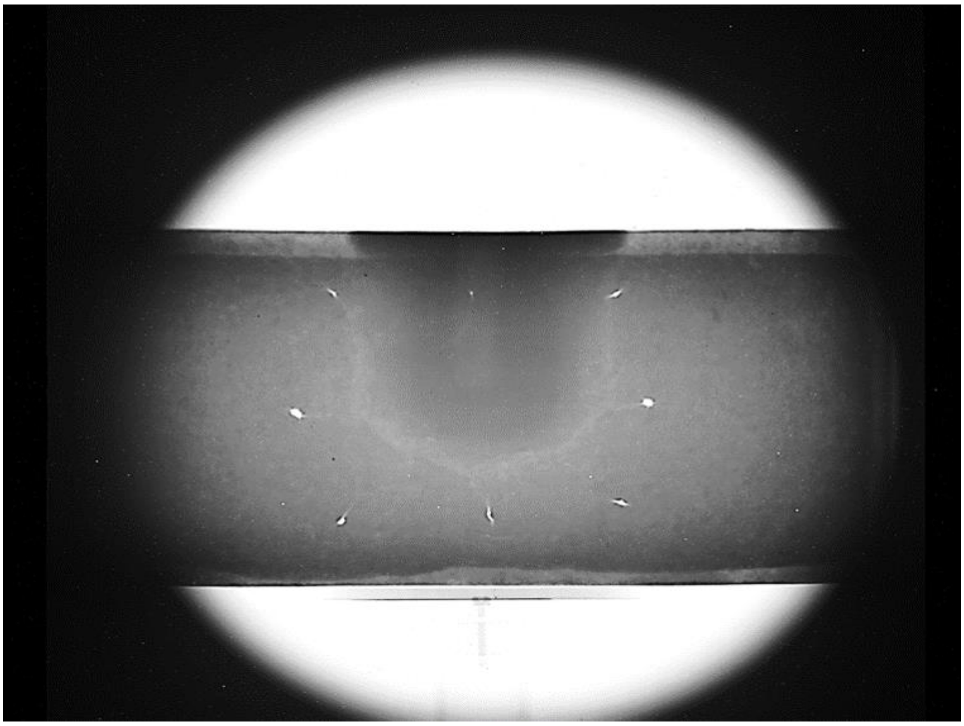


Fig. 19 Neutron radiography on brick

The physical image is a brick test specimen in which the IM was applied via a horizontal borehole. On the radiography image there is clearly visible is an area of increased IM contents in the immediate neighborhood of the borehole, represented by the dark grey coloration.

The star-shaped arrangement of small elliptical white discoloration may be due to microcracks in the creation of the borehole.

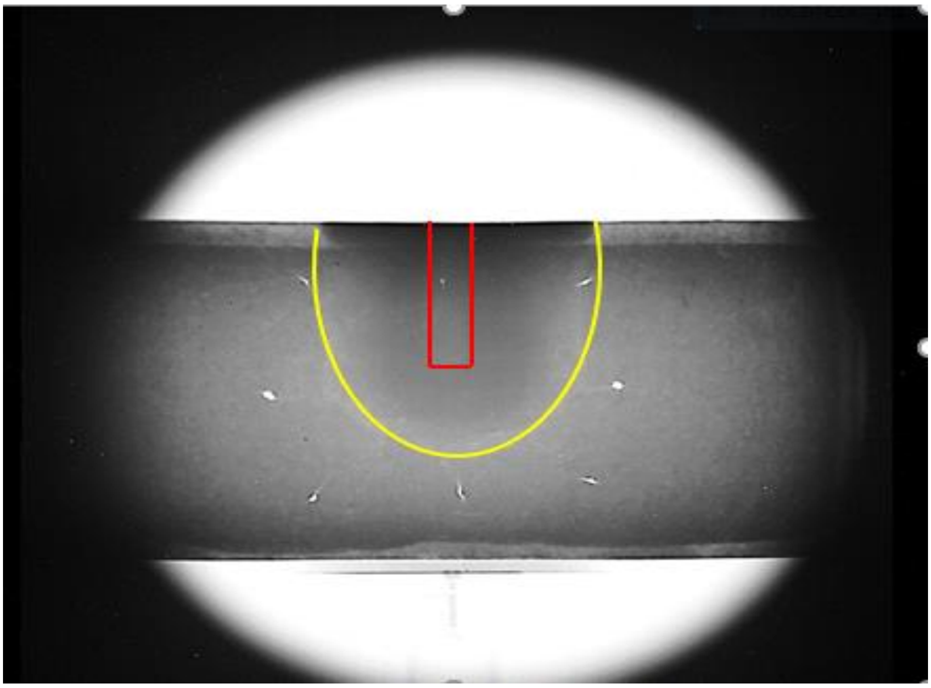


Fig. 20 Neutronradiography on brick (coloured)

Neutron tomography:
It should be noted that the specimen was split due to previous examinations; this can still be recognized by the occurrence of cracking in the central area of the test specimen as well as in the upper right area. However, there is no influence on the validity of the subject investigation method.
Due to the type of application, on the test specimen presented below, the borehole was located as it is presented on the figure [21].

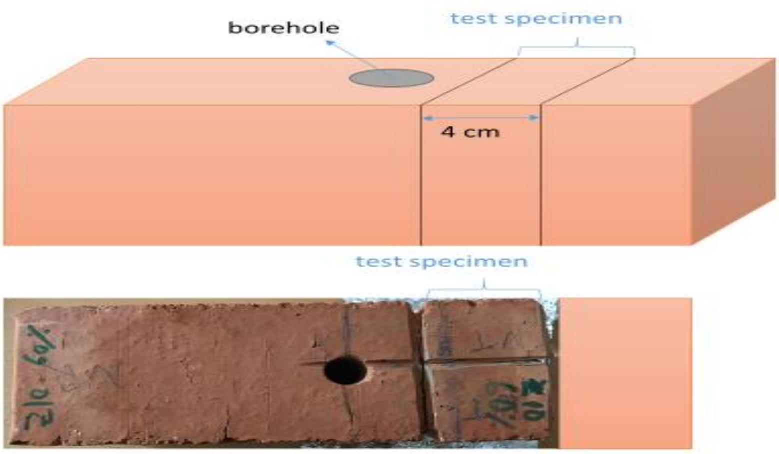


Fig. 21 Original brick and sample

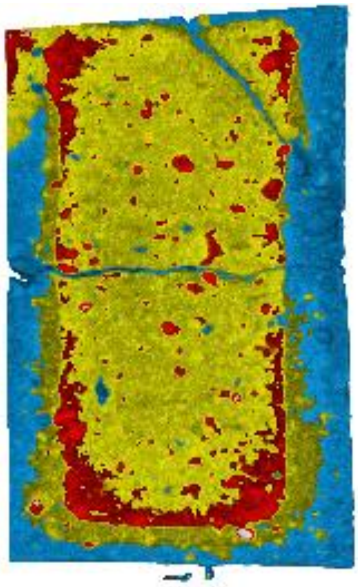


Fig. 22: Front view sample

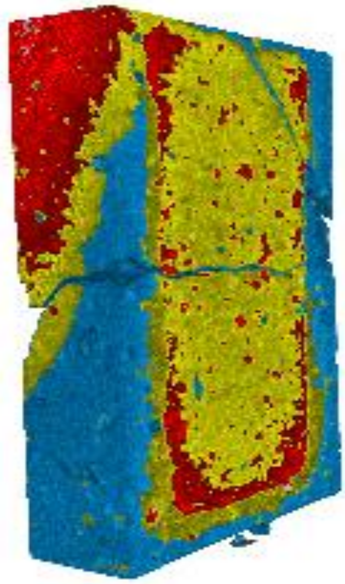


Fig. 23: Partly lateral view of sample

The color schemes respectively match the measured gray values and thus the content of the IM, the colors on picture 22 and 23 are scale parts and correspond to the concentration of the hydrogen from the IM.

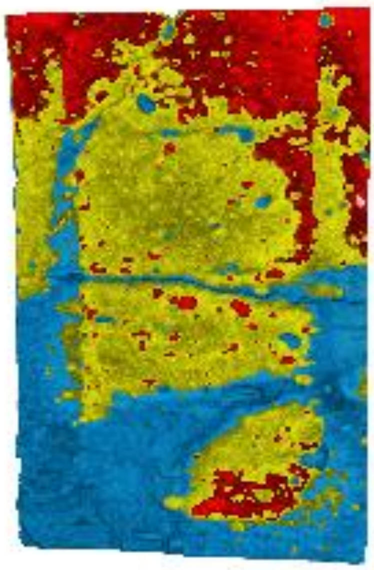
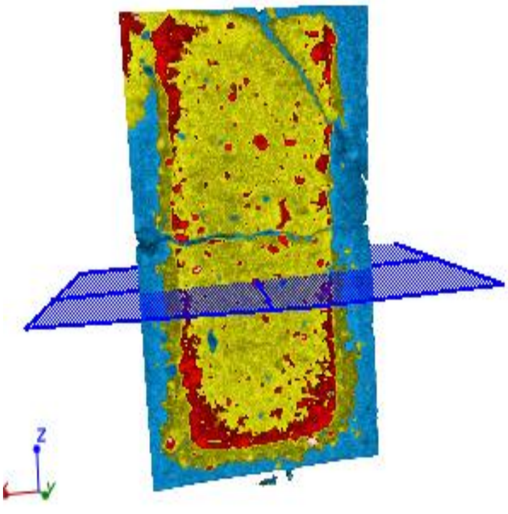


Fig. 24: Rear view sample

Areas of high grey values (red coloration) are to be found primarily in the upper area of the test specimen, i.e. the area which first comes into contact with the IM after the beginning of the application. In the partial side view it can also be seen that the increased grey values are not homogeneous in the upper region of the test specimen, but are distributed on one side.

This may be due to the arrangement of the test specimens in the IM application; so it is possible that when positioning the specimen on the wide side, the IM spreads unilaterally after application. This is also recognizable on the back of the test specimen, which has lower grey values than the front side.
Evidently, the propagation of the IM here is not circular, but the gradient of the gray values indicates a course of the IM, which takes place approximately parallel to the contours of the specimen. Also noteworthy here are areas of increased grey values (red colour) towards the edge areas of the specimen, which follow a range of medium gray values (yellow color) and assume a hemispherical spread. These hemispherical values are again followed by a zone with lower grey values (yellow colour) at the edge of the test specimen.
With the aid of the corresponding software, an average value of approx. 1.6 cm can be read for the hem-shaped course of increased gray values.
Apparently, there is a kind of transition zone, after the application, the IM spreads with decreasing concentration (recognizable by the decreasing grey values), but before the propagation ends a zone with higher gray values appears in the parallel spreading.

With the aid of suitable software (VGStudio by Volumegraphics), it is also possible to display shots in various levels over the cross section of the measured specimen. In the aforementioned test specimen, two levels were exemplified. In the left picture the complete test piece is visible with the examined cutting plane, on the right picture the corresponding cut plane is shown as a cross section.



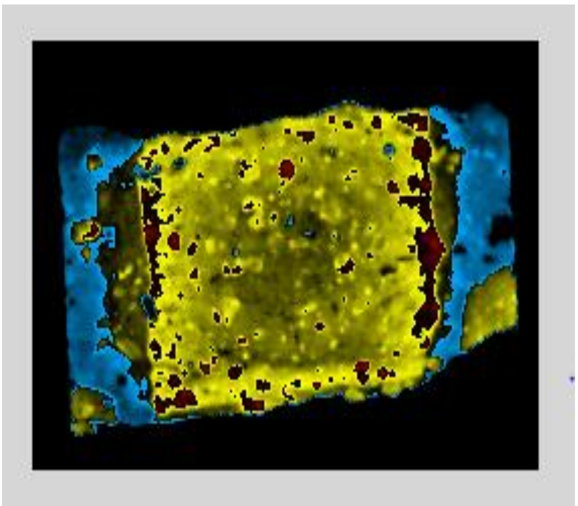


Fig. 25 and 26: Location upper section plane and tomography cross section

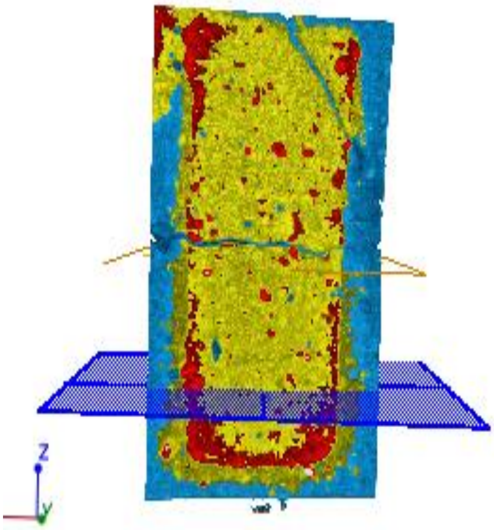
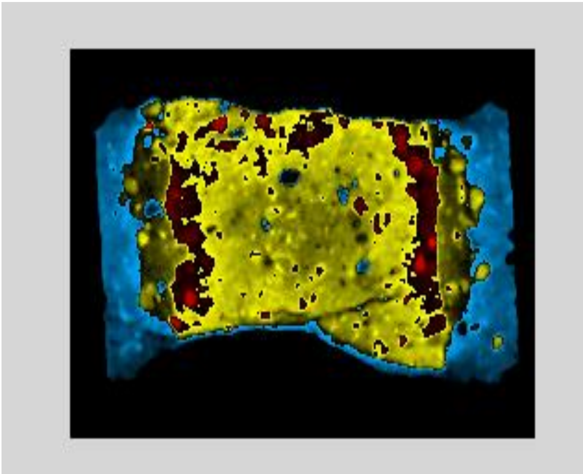



Fig. 27 und 28: Location lower section plane and tomography cross section

4.4.2 Summary assessment of thesis 4

With the aid of the Neutron Radiography and Tomography methods I have proven that the concentration of the spread of the injection agent is non-uniform inside the impregnated material volume [19]. I have detected a concentration increase at the edge of the impregnates volume which was influenced by the moisture content: at higher moisture content the higher concentration was more pronounced. The different levels and the injection concentration influence the effectiveness of the seal. I assume that there is a certain amount of injection agent necessary to develop a hydrophobic effect.

5 Effects of the test results on the execution of the subsequent horizontal sealing by means of a pressureless IM application

In the studies presented, a traceable decrease in the IM spread with increasing degree of moisture penetration, irrespective of the building material used and the IM applied, is evident with regard to the course of the IM spread. With degrees of moisture penetration of approx. 60%, a declining decrease of the IM is already to be expected, with high degrees of moisture content of 80% -100% there is often no further intake of IM.

Under these conditions, in most cases, a functional seal could not have been created in the case of an application on the building, especially as the bore hole distances to be drilled out according to the manufacturer's instructions would have been too large. The possibility of continuous rising damp and a subsequent inadequate drying of the masonry would have been the result. It is doubtful to what extent a double-row drill chain would have been able to "catch" any moisture still rising between two drilled holes. In the case of low-absorbent building materials or as the here presented, water-moderately mortar, and from a D(g) > 50% moisture content on, it is even more important to consider the limitations of the IM. On the one hand, absorbent materials such as brick / sand-lime brick are achieved by the IM (e.g. by a tilted borehole, where multiple levels of joint / brick are detected) or flanking measures such as convective pre-drying.

Although mortar results are very low, it should be noted that when using the above method on masonry structures, the inadequate results are due to the presence of a more absorbent material such as bricks. It remains important that this can be achieved by choosing the borehole in the bearing joint for the IM. In the investigations carried out, the maximum propagation of the IM takes place at 0%, so that no moisture requirement for a transport of the IM seems to be necessary.

From the model of IM propagation it can be seen that the well spreading must be adjusted, depending on the existing D (g), the spacing must be adjusted to accomplish the seal, i.e. with increasing moisture penetration of masonry smaller and smaller borehole distances should be used.

However, neither the decreasing spread nor the borehole spacing to be adjusted are sufficiently taken into account in the respective guidelines or the respective IM manufacturer specifications, so that the user inevitably gets the opinion, with a degree of permeability of 100% and a borehole distance of 10-12 cm a functional seal can be created. This also explains the failures that lead to the process being critically discussed in the professional world. The transferability of results as well as generalized details regarding the execution, such as the borehole distance, are therefore extremely critical. The basic requirement to achieve a functional subsequent, pressureless IM horizontal seal are, preliminary investigations of the building materials themselves (degree of moisture penetration) and knowledge of the material properties of the masonry (water absorption properties); and finally, the proper IM has to be chosen.

6 Summary and assessment as well as further research

Based on the presented test results, it can be seen that several factors can have a limiting effect on the propagation of an IM in a building material:

- the existing degree of moisture penetration of the building material
- the nature of the building material itself (including porosity, capillarity, hydrophobic / hydrophilic properties)
- the choice of IM (principles of action)
- the chosen combination of building material and IM

The tendency of the decreasing spread of an IM with increasing moisture penetration of a building material is equally pronounced in all investigated materials (mortar, clinker, calcium silicate brick), but in different intensities, depending on the material (study 1) and the trial (study 6). Due to the recognizable relationship between the spread of an IM and the respective existing degree of moisture penetration, the obtained examination results show a linearity, which can also be graphically represented by means of linear regression.
The resulting, partly high correlations also reflect the dependence of the two parameters in this sense. The two parameters of the moisture penetration degree as well as the spreading of an IM behave as a result indirectly proportional to each other, regardless of the examined building material / IM combination.

Based on the available results, a model developed by the author in community for the injection of injectable has been further developed and adapted taking into account the new findings. To this end, it is now possible to represent the aforementioned dependencies not only graphically but also by means of physical parameters.

On the basis of this modelling, it is also possible as a novelty to make statements with regard to the borehole distance to be applied and thus contribute decisively to the functionality of the method. The experiments presented on an experimental basis can also be presented in an impressive way using neutron imaging methods.

On the basis of the performed procedures of the neutron radiography it is possible to draw conclusions about the distribution of an IM inside a building material. The experimentally determined indirect proportionality of the two parameters moisture penetration of the building material and propagation of an IM can thus be detected by means of analytical methods and confirm the statements made. As a further key statement, enrichment zones of IM in the edge region of the test specimen, which are evidently moisture-dependent, can be detected by means of neutron tomography.
In general, in the three-dimensional representation of the specimen individual "IM islands" can be seen, which may be due to inhomogeneities in the building material. The above-mentioned neutron methods also create the possibility, with the help of the appropriate software, to image-depict a three-dimensional distribution of an IM in the building material and thus to make further statements regarding possible propagation and action limits of an IM. Since both methods are non-destructive examination methods, further investigations can be carried out on the same test piece, which in turn eliminates material-related fluctuations which could complicate the statements to be made.

In summary the process of subsequent horizontal sealing by means of pressure-free injection offers a good opportunity to generate a functional seal. However, in this context, the present PhD thesis indicates that there are several factors that may limit the propagation of an IM and, as such, the success of a functional seal. Consequently, it remains indispensable to carry out various preliminary investigations in advance of a planned sealing and then to coordinate the procedure; therefore sample injections are recommended. Information from the manufacturer as well as the processor must be checked on the basis of the local conditions or adapted to the sealing.

To this end, a valuable approach has been developed to avoid errors in the physical sealing procedure, which can be transferred to construction practice. From the results of these investigations, detailed questions regarding the spreading as well as the effective measure of injectables are not fully clarified. For this purpose, further investigations are planned, including quantification of the test results obtained. An influence of the examination results in a test specification for subsequent horizontal seals by means of pressure-free injection is on the part of the author.

7 Statutory declaration

I hereby declare on my honour that I have prepared the present work independently. The ideas taken directly or indirectly from external sources are identified as such. No sources other than the ones indicated were used.
The present work has not been submitted to any other examination authority and has not yet been published.

Ottobrunn, __________________

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