The distribution of injection fluids against rising damp in masonry: models and risk factors

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Curriculum Vitae

After his study at the Technical College in Tilburg and Architecture at the university of Eindhoven Kees Snepvangers (1955) worked more than 20 years in the field of maintenance of buildings. Ten years ago he became the external advisor of a company which installs chemical moisture barriers in masonry. Solving the complains gave an in-depth sight of the problems which occur when the masonry is injected with a fluid.

Since 2008 he is working part-time at the Delft University of Technology on his PhD. The subject is the modeling the distribution of injection fluids against rising damp in masonry.

Abstract

The proposed 4-stage model is a qualitative model for analysing the factors that determine the distribution of the injection agent. As it provides an insight into the risk factors, it also lends itself for use as a foundation for development of improved injection methods and/or injection agents. Used in the 4-stage model is the well-known “classic” moisture transfer mechanism.

Four stages can be identified in the distribution of injection fluids. A different transport mechanism is responsible for the distribution in each stage /1/.

1 During the 1st stage, the easily accessible pores are filled with the injection agent by flow under external pressure /2/. This will act as a “holding tank” with injection agent for distribution during the 2nd stage.
2 Further distribution takes place during the 2nd stage by means of capillary transport. An impeding factor is the water that is present in the pores. This doesn’t just allow itself to be “pushed away”. First of all, the capillary forces that “hold” the water in the pores have to be defeated.
3 During the 3rd stage, the further distribution of the injection agent takes place by means of diffusion. This will ensure that the active compound of the injection agent also distributes itself into the water present in all of the pores. This is a process that progresses slowly. In the fast-reacting injection agents, diffusion hardly contributes to the distribution.
4 During the 4th stage, there is a clear distinction between the plugging and narrowing agents on the one hand and the pure hydrophobic injection agents. In the first group

of agents, there is, in principle, so much reacting material that the formation of deposits against the pore walls happens almost of its own accord.
In the hydrophobic agents, a division has to take place between the water and the silicone resin molecules that have formed.

Finally, in the hydrophobic layer, the injected region has to dry before the water repellent layer can have an effect.

Based on the 4-stage model a new work method VDI2F (filling, drying and filling in 2 stages) was developed. The basic idea behind this work method is that the distribution of the injection agent would progress better in dry brickwork than in wet brickwork, and that the injection agent has to be prevented from leaving the intended region.

1. Introduction

Injection agents to interrupt capillary moisture transport in brickwork have been available on the market for more than 40 years. Experience has shown, as has scientific research, that this does not yet guarantee a faultless technology with no hidden secrets. There will always be a significant risk that the desired purpose is not achieved. According to our own estimates, that is a 25 to 40% risk. In Germany in particular, numerous studies have been carried out into the effectiveness of injection agents. These studies confirm the disappointing results (See /3/ and /4/). The cause of these results is chiefly the poor distribution of the injection agent in the brickwork.

In order to be able to improve products and working methods, an explanatory model is required for the poor distribution of injection agents in brickwork. To date, such a model was not available. The 4-stage model described here is an initial impetus towards the creation of a model. It is a qualitative model which uses the classic theories behind moisture transport. A working method for filling has been developed using this model that significantly reduces the risk of a poor result. The 4-stage model can also be helpful when analysing cases of damage where the desired result has not been attained.

2. 4-stage model

2.1 Introduction

Prior to filling, holes are drilled into the brickwork with a mutual distance of 10 to 20 cm. The filling itself usually takes place under pressure or quasi pressure-free.

There are 4 transport mechanisms responsible for the distribution of the injection agent:
1. Flow
2. Capillary transport

3. Diffusion
4. Polymerisation and/or attachment to the pore surface.

During the first stage, distribution is chiefly via the coarser pores. The main transport mechanism involved with this is flow. Afterwards, the finer pores are filled. The driving force behind this is the capillary pressure. This does not depend on the pressure at which filling takes place. Further distribution through the water present in the pores takes place by means of diffusion.

The distribution of injection agents is very similar to moisture transport in brickwork. There are, however, clear differences:

1. Most filling techniques involve external pressure, which results in a flow of the injection agent into the brickwork /5/
2. The distribution of the injection agent must, in principle, be limited to the intended area
3. The distribution has to be homogenous within the intended area (5 to a max. of 10 cm from the drilled hole)
4. The distribution has to take place within a (very) limited period of time
5. The injection agent has to either displace the (salt) water that is present, or to mix with it
6. The properties of the injection agent will change during distribution.

These differences necessitate the distribution of injection agents to be considered differently, as opposed to moisture transport in brickwork.

2.2 first stage of distribution: flow through external pressure

Brick and mortar are porous materials with a relatively high void content. If a hole is drilled into the brickwork, innumerable pores will open into the drilled hole. The drilled hole can thus be seen as a "leaking tank", the walls of which are made from innumerable fine "straws" at right angles to the wall surface (see figure 1). These "straws" have various diameters and lengths. The majority of "straws" have a small diameter and only a few have a larger diameter.

At the ends, the "straws" are:

- Open, or;
- They change to a straw with a larger diameter, or;
- They change to 1 or more straws with a smaller diameter, or;
- They are closed.

The length of the "straws" varies considerably. The lengths can vary so significantly that these discharge outside of the intended injection region.

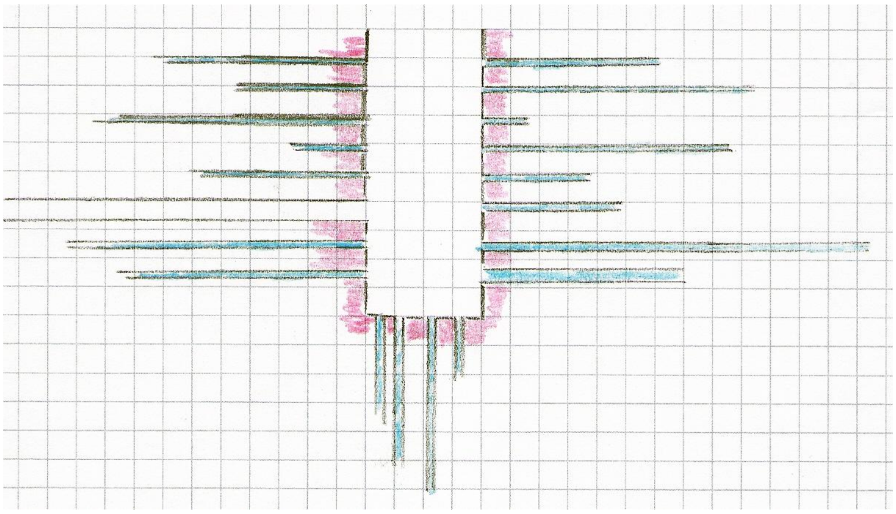

Figure 1: the proposed “leaking tank” model

Most of the “straws” are full of water and some are empty. The empty straws are mainly the “straws” with the largest diameters /6/. If the “tank” is filled under pressure or quasi pressure-free with injection fluid, this will drain via the “straws” that offer the least resistance and of which the ends are “open”. As long as that does not change, the injection fluid will only distribute itself via these “straws”. Only if there is an increase in the flow resistance of the injection fluid the distribution will also take place through other “straws” which have the same flow resistance. The distribution by means of flow will always take place via the path of least resistance. Taking into account the basic assumptions of the “leaking tank” model, the sequence shown below applies to the injection fluid flowing out of the “tank”:

- Cracks;
- Dry pores >100 µm
- Water-filled pores >100 µm
- Dry pores 0.2 – 100 µm
- Water-filled pores 0.2 – 100 µm

It should be noted here that, in practice, the boundaries are not as defined as the overview shown above might suggest.

cracks

(Micro) cracks in brickwork that open into a hole drilled for the filling constitute the highest risk for the injection fluid flowing away in an uncontrolled manner. It makes no difference whether these are full of water or are dry. Micro cracks are often present on the interface between mortar and brick. Generally, only a limited amount of injection fluid remains behind in the crack.

dry and water-filled pores >100 µm

Dry pores with a diameter in excess of 100 µm /7/ offer the least resistance. These are followed by water-filled pores with a diameter >100 µm. Water in pores with a diameter in excess of 100 µm barely impedes the distribution of the injection agent. At the very most, in addition to the flow resistance, there is a very small hydrostatic counterpressure. The amount of injection fluid that can seep out through the pores initially filled with water >100 µm, is then practically just as much as in the dry pores. In brickwork thicker than 40 cm, it is usually no longer possible for the water to “squeeze out” /8/.

dry and water-filled pores <100 µm

The pores with a diameter between 0.2 µm and 100 µm can also be filled by means of flow. The flow resistance does increase exponentially, on account of which the volume flow is negligibly small in the case of a pore diameter of 0.2 µm. In those cases where the injection fluid opts for “the path of least resistance”, logically, there is only a small risk of the smaller pores potentially also being filled with injection fluid by means of flow.

In water-filled pores of <100 µm, the presence of the water has a negative effect on distribution. First of all, the capillary pressure of water has to be “defeated” before the water can be displaced and the injection fluid can flow into the pores. This can only happen if the injection pressure, together with the capillary pressure of the injection fluid, is higher than the capillary pressure of the water. This capillary counterpressure of the water increases significantly with the reduction of the diameter of the pore. It is barely possible for water-filled pores smaller than 0.25 µm to be filled with injection fluid by means of flow.

2.2.1 holding tank

The pores that can be filled with little pressure through flow, can, in theory be seen as a “holding tank” for the second stage of the injection process. If the stone and mortar show no defects in the form of cracks or hollow spaces, the volume of the pores with a diameter in excess of 100 µm is limited to just a small percentage of the total void content. This implies that if the introduction of the injection fluid is ceased, the pores with a diameter in excess of 100 µm barely forms a “holding tank” for further distribution of the injection fluid during the 2nd stage. This implies that an application method where the 1st stage lasts for a long period of time, thus ensuring that the “holding tank” remains filled for longer, has advantages in respect of short-lived injection.

2.2.2 seeping out outside the intended injection region in dry brickwork

In spite of the pores with a diameter >100 µm only having a very limited holding function, after the cracks they constitute the greatest risk for the injection fluid seeping out outside the intended injection region. The speed at which the injection fluid flows through the empty pores, is, in the pores, dependent on the flow resistance, the viscosity of the fluid, the pressure and the length of the path taken. Also of importance is the distribution of the pores in the location of the surface of the drilled hole.

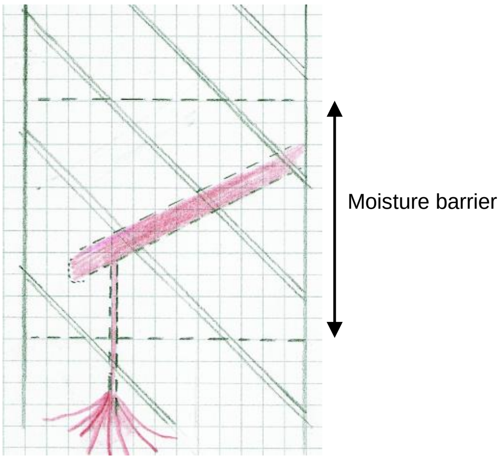

Figure 2: uncontrolled leakage of injection fluid outside the planned moisture barrier

With the Hagen–Poiseuille equation it is possible to calculate the amount of injection fluid, in a certain situation, that flows through a pore. The table below shows calculations that have been made of the amount of injection fluid that “seeps out” of a drilled hole with a 10-cm length and 18-mm diameter in dry brickwork. In these calculations, the assumption is that 0.1% of the wall of the drilled hole consists of the pores for which the calculation has been made. The calculations have been made for slow-reacting injection agents and two injection techniques (under pressure and quasi pressure-free).

Table 1: calculation volume flow from the drilled hole in pores with free leakage

Pore diameter [µm]	Pore length [m]	Injection pressure /9/ [bar]	Injection time /10/	Total volume that seeps out during filling per 10 cm drilled hole [l]
100	0,05	5	5 min	1.06
		0.02	1 day	1.22
	0,1	5	5 min	0.53
		0.02	1 day	0.61
	0,2	5	5 min	0.27
		0.02	1 day	0.31
50	0,05	5	5 min	0.26
		0.02	1 day	0.31
	0,1	5	5 min	0.13
		0.02	1 day	0.15
	0,2	5	5 min	0.07
		0.02	1 day	0.09
20	0,05	5	5 min	0.04
		0.02	1 day	0.05

The calculations show that the amounts of injection fluid that can seep out outside the intended injection region are not negligible. It should be noted that the aforementioned theoretical calculations provide a representation of actuality that is (too) negative. In practice, a high percentage of the pores with a diameter of 100 µm would connect to pores with a much smaller diameter. Because of this, the flow resistance would increase to such a degree that the leakage into the brickwork outside of the intended injection region would be much less than calculated.

2.3 second stage distribution: capillary transport

During the second stage, the further distribution of the injection fluid takes place from the "holding tank" – which is formed by the pores >20 µm – filled during the first stage of filling. In this stage, the transport of the injection agent heads towards the finer pores /6/. This means that the large pores are, as it were, drained. This mechanism reduces the more that the reaction of the injection agent leads to larger molecules.

dry pores

The progress of the distribution of the injection agent shows significant differences between when the pores are dry or filled with water. In the dry pores, the "further transport" of the injection agent takes place through capillary transport and surface diffusion. In some agents, distribution can take place through vapour diffusion.

water-filled pores

In water-filled pores, capillary transport depends on the difference between the capillary pressure of the injection fluid and that of the water that is present. The capillary pressure increases the more the diameter of the pore decreases. This implies that, in this case, an injection fluid is always to the detriment of the water present in the pores. The fact of the matter is that the water that is present is mainly present in the smallest pores.

surface tension

For the capillary transport, the surface tension of the injection fluid and the angle of contact between the fluid and the pore wall are of significant importance /11/. In the ideal situation, the capillary pressure of the injection fluid would have to be equal to or higher than that of water. Only then would the injection agent "push" the water out of the pores. If this is not the case, the injection agent will not penetrate as far into the pore structure. This applies in particular to pores smaller than 20 µm. Pores in excess of 20 µm can also be filled under pressure.

speed of the displacement of injection fluid through capillary transport

The speed at which the injection fluid is displaced through capillary transport also depends on the viscosity of the injection fluid. As the viscosity of most injection fluids is often a factor 5 or more higher than that of water, the capillary transport of the injection fluid will be slower than that of water. This is both advantageous and disadvantageous:

- A slow distribution helps to prevent the injection agent being distributed outside of the intended injection region before the injection agent has reacted;
- A high viscosity impedes the penetration of the injection fluid into the smallest pores.

2.4 third stage: diffusion

Of the three mechanisms that are responsible for the distribution of the injection fluid in brickwork, diffusion is the least known. It is also the final one in the sequence. Distribution will only continue through diffusion once flow and capillary transport have come to a halt. There are three types of diffusion in the distribution of injection fluids in brickwork. The main type is the diffusion of the active compound from the injection fluid into the water present in the pores. In injection agents with a limited molecular length, such as silane, vapour diffusion can also occur. In addition, surface diffusion takes place.

The end of the diffusion process is determined by the progress of the formation of large molecular chains resulting from the chemical reaction of the injection fluid. In fast-reacting injection agents, almost no diffusion would then occur.

diffusion of active compound from the injection fluid into the water that is present

In the 1^{st} and 2^{nd} stages of the distribution of the injection fluid, first of all the larger, then the smaller pores are filled with the injection agent. The “direction” of the transport can roughly be summarised as being “from coarse to fine”. This “direction effect” also happens in the 3^{rd} stage – the diffusion process. As diffusion is a slow process, this happens much more slowly than in stages 1 and 2.

vapour diffusion

In most injection fluids, vapour diffusion does not play a meaningful role as a distribution mechanism, as it is barely volatile. An exception to this are the silanes. These are able to vaporise well. Besides the fact that the vapour diffusion takes place within the dry pores of the brickwork, a vapour flow of silane from the brickwork also occurs. Because of this, active compound is released into the air of the space. This results in active compound being lost. The risk of this happening increases at higher temperatures such as in outside walls that are warmed up considerably by the sun during the summer months.

2.5 fourth stage: polymerisation /12/

As the final step in the process, the reaction product has to be created in the “correct place”. In the plugging agents, this is the formation of a sealing plug in the pore. In the hydrophobic and narrowing agents, this is the formation of a layer on the walls of the pores with the required properties. During studies, insufficient attention is generally paid to this stage in terms of the effectiveness of injection agents. Even so, there are indications that this does not always take place as it should. A percentage of polymerisation that has progressed poorly or that is incorrect can be explained by the conditions – acid content, temperature, etc. –not meeting the conditions. Pollutants in the pores can also disrupt polymerisation.

plugging agents

In plugging agents with an active compound level of 100%, the reaction of the injection agent will ensure that a plug will be formed in the pore that closes the “passage”. In most of these injection agents, this “plug” will attach properly to the walls of the pores, so that movement is no longer possible.

In agents that do not or that barely bind water, the formation of the “plug” in the pore can be disrupted if, when filling, too much water has got into the injection agent. This results in many small “plugs” of injection agent which float in the water. Because of this, there is a significant risk that the dimensions of these are too small to close off a pore. Because of this, the effect of the injection agent can partially be lost. The risk of this happening seems to be the highest when filling at very high pressure.

In the gel-forming agents, the mixture of the injection agent with the water already present in the pores is, to a certain degree, not a problem. Because of this, the gel does become increasingly “watery”. Provided that the volume of this is sufficient, the “discharge” will also have a plugging effect.

hydrophobic agents

The pure hydrophobic agents all belong to the organic silicone compounds that form a hydrophobic silicone resin. The formation of the silicone resin does not take place against the wall of the pore, but in the water /13/ in the pore.

The silicone resin resulting from this is a substance that is not, in principle, water soluble. In essence, because of the formation of the silicone resin, an emulsion is created. This emulsion is not stable and a separation of the silicone resin and the water will occur. The way in which this happens depends on the properties of the particles of silicone resin that float in the water. The desired result is a total separation of silicone resin and water. However, the occurrence of another mechanism cannot be ruled out (see figure 3).

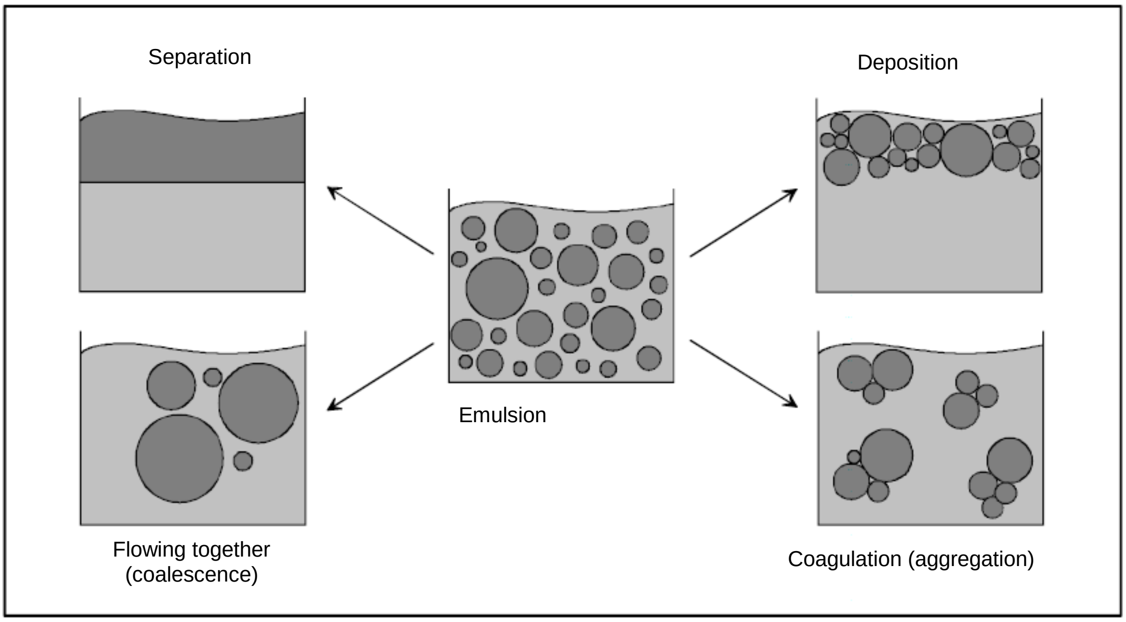

Figure 3: the possible reactions of an emulsion if this is not (sufficiently) stable
Source: /14/

If total “separation” takes place between silicone resin and water, this can be defined by the *Stokes Law* proposed by Wirringa /15/. This would mean that the silicone resin will either float on the water, in the pore or will sediment. The practical implication is that the silicone resin would only form a deposit on part of the pore wall – either the bottom or the top. Because of this, the pore would only become partially water repellent. According to Rose /16/, it can be concluded from the simplified fluid transport model that the only partial hydrophobic pore wall will have almost no effect.

other “separation mechanisms”

Existing literature does not describe any other “separation mechanisms”. From the way in which the silicone resin attaches itself to the base, it can be concluded that dipole effects potentially also contribute to the deposit of the silicone resin to the surface of the pores. Another possibility is that a molecule of the active compound attaches to the surface of the pore and that, as a result of this, the polymerisation can continue. In such a way, in a manner of speaking, “trees” are created on the surface. This mechanism can only work if the concentration of the active compound in the water is sufficiently high.

Furthermore, drying – the vaporisation of the solvent – can enable the deposit of the silicone resin on the walls of the pores. This is comparable to applying a hydrophobic agent to the outer wall.

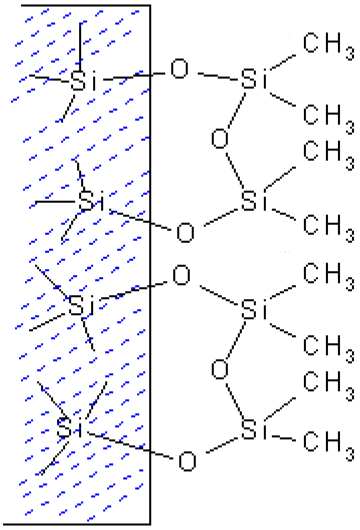

figure 4: attachment of silicone resin to the base, source: /17/

narrowing agents

All narrowing agents are based on the formation of a gel on the surface of the pore. As, in these agents, these layers are much thicker than in the hydrophobic agents, the deposition mechanism is of less importance.

2.5 comments about the 4-stage model

The proposed 4-stage model is based on the "classic" theories for moisture transport in brickwork. This is possible because the physical properties of injection fluids for polymerisation demonstrate significant similarities to those of water.

The effect of the various stages of the model is based on the assumption that the pores are cylindrical and that the finer pores are filled from the coarser pores. It can be concluded from the aforementioned that the distribution process can be sketched by means of a tree structure that branches out ever further.

The actual distribution of the injection agent will be different to that described in the 4-stage model. That is because the pore structure of brick and mortar do not meet the assumption that the pores are cylindrical and that there is evidence of any arrangement in the pores. Furthermore, the water present in the pores impedes the distribution. This will result in the distribution of the injection agent in the brickwork progressing very inconsistently. For that reason, the proposed 4-stage model is only suited to defining the risk factors.

2.6 conclusion

The proposed 4-stage model makes it clear that there is only a small chance that the injection agent will homogenously distribute itself around the injection hole. The differences in the structure of the pores are the main parameter which determines the distribution. Not only are there differences between brick and mortar, but there are also significant differences within the material itself. In older-type bricks, the differences are greater than in bricks from modern brick factories.

These differences in structure will result in unequal distribution of the injection agent. During the 1st and 2nd stage of the distribution, the injection agent will chiefly opt for the path of least resistance and those are the pores with the largest diameters that are preferably dry /18/. This unequal distribution is known as *viscous fingering*. The result of this is that the intended moisture barrier will show “holes”.

Injection techniques

The 4-stage model will also set out clearly what the consequences are as regards the distribution between the quasi pressure-free filling and filling under pressure. Clear differences are evident. These differences are of particular importance for the fast reacting agents. In this group of agents, filling under pressure has a clear advantage. In slow reacting agents, there are much smaller differences between the 2 techniques. In that case, there are no advantages of one technique over the other.

Contrary to the reports of the majority of manufacturers, the properties of the injection agent are not the determining factor for the result. In particular the pore structure is the determining factor. When distributing injection agents, a distinction has to be made between the injection fluids and the injection creams and injection gels. Applicable to the creams and gels is that no distribution takes place through flow and capillary transport. The main transport mechanism in these products is diffusion (see par. 2.4).

It should be noted that the 4 stages of the distribution start almost simultaneously. This does not apply to the time at which a stage terminates. First of all, the first stage – the filling of the pores – will terminate and the 4th stage – the polymerisation – will mark the end of the distribution.

3. The VDI2F working method

The research by manufacturers into the improvement of the treatments against capillary moisture transport mainly focuses on the injection agents themselves. Other compositions of the injection agent have given better results. Only a few manufacturers (also) focus on the improvement of the injection technique. As during development, models are not used in which the process of filling – the distribution, the polymerisation and the drying – and the accompanying risk factors are defined comprehensively, there is a significant risk that the focus during the development of new products and techniques has an incorrect emphasis.

In current practice, the basic assumption when developing injection agents is that the injection agent has to reach places where water is present in the pores. After all, these are the pores responsible for the moisture problems. However logical this choice might be, unfortunately experience has shown that this approach does not result in products that function correctly under a wide range of different conditions. And this is despite the claim of many manufacturers that their product is suitable for almost all conditions.

The proposed 4-stage model offers the opportunity of looking at the development of new injection agents and injection methods from a different starting point. One of the outcomes of this model is that the material properties – distribution of the pore diameter and the variation in that, the presence of cracks and hollow spaces – are determining factors for the distribution of the injection agent in the initial stages of the injection process. The properties of the injection agent only have a limited effect on that. During the initial stages of the distribution, the injection agent will chiefly follow the path of least resistance. These are the pores with a large diameter and the dry pores. The dry pores are, however, those that do *not* contribute to the moisture problems. The pores with a large diameter constitute the highest risk for the injection agent seeping out from the intended injection region. This implies that during the first stage of the injection process, the agent will go chiefly to those places where it is not needed.

Based on the aforementioned risk factors and using the 4-stage model and the many years of experience with cases of damage, the work method VDI2F (filling, drying and filling in 2 stages) was developed. The basic idea behind this work method is that the distribution of the injection agent would progress better in dry brickwork than in wet brickwork, and that the injection agent has to be prevented from leaving the intended region.

Two recent developments have been applied to the proposed work method VDI2F. The first is the drying of the brickwork through thermal convection /19/. Furthermore, other drying techniques are also usable. By drying the brickwork, the void content that can easily be filled, is increased considerably as the water no longer constitutes an inhibiting factor during distribution. The second development is the consecutive injection of 2 injection agents with different working principles /20/. The first agent that is used is a plugging agent such as a gel. This will prevent the second agent being distributed too far. The second agent enables the hydrophobation of the small pores that cannot be reached using a plugging agent.

3.1 effect of VDI2F work method

Four process steps are identified as part of the proposed VDI2F work method:

1. The filling /21/ of the hollow spaces and cracks with a very fine mortar such as trass chalk (particularly of importance in brickwork with a thickness of 40 cm or more)
2. The drying of the injection region in the brickwork after the mortar from stage 1 has hardened sufficiently
3. The filling of the coarser pores with a fast-reacting plugging injection agent;
4. The filling of the smaller pores with a hydrophobic injection agent;
5. The drying of the injected region so that the water evaporates, in which the hydrophobic injection agent is dissolved.

Stages 1 and 3 are mainly intended to prevent, in stage 4, the injection agent from seeping out from the intended injection region. For stage 3, a gel-forming injection agent seems to be the most appropriate product.

The drying in stage 2 simplifies the filling. Because of this, much lower pressures can be used during stage 3. The disadvantage of “blocking” the coarser pores in stage 3 is that the drying of the brickwork in stage 5 will progress slowly. This drying is a condition that is required in order for the hydrophobic effect to happen. Stage 2 may not be exchanged with stage 1 as the extraction of water from the mortar has to be avoided until this has hardened sufficiently.

The required drying after completion of the filling can be accelerated artificially. Based on the experiences with hydrophobic agents on outer walls, it is very unlikely that artificial drying through an increase in temperature will result in damage to the hydrophobic layer in the pores. That does not apply to the gel that is injected during the 3rd stage. This would display considerable contraction. If the gel again comes into contact with moisture, this would once again expand. For the time-being, it is assumed that the contraction of the gel does not cause direct problems for the effectiveness of the treatment.

Acknowledgement

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Notes, literature and sources

1. Applicable to the creams and gels is that no distribution takes place through flow and capilliary transport. The main transport mechanism in these products is diffusion (see par. 2.4).
2. This can also be the gravitational force, such as in the bottle method.
3. Balak Michael; Injektionsverfahren zur nachträglichen Abdichting von Mauerwerk – neueste Erkenntnisse; Berlin 2007
4. Simlinger C.; Erfolgskontrolle nachträglicher Maβnahmen gegen aufsteigende Feuchtigkeit und damit verbundene baupraktische Erfahrungen; in Alberts D.,

Venzmer R. (red); Europäischer Sanierungskalender 2006 für Holz, Bautenschutz und Denkmalpflege; Berlin 2006

5. Convection (flow) does not form part of the injection gels and creams. This also applies to the filling through capiliary absorption.
6. Hens H.; Bouwfysica 1, Warmte en massatransport; Antwerpen
7. For purposes of readability, a clear-cut transition between pores is assumed, in which there may and may not be capiliary moisture transport. In reality, this boundary is not as clear-cut.
8. Adamini R., Protz A.; Praktische Erfahrungen bei Abdichtungen mit Injektionsverfahren; in Kots L., Werder J. von (red); Aktuelle Entwicklungen der Bauwerkstrockenlegung; Wismar 2003
9. For the filling under pressure, 5 bar has been adhered to and for the quasi press-free techniques, a fluid pressure of 20 cm that corresponds with 0.02 bar.
10. For the filling under pressure, 5 minutes has been adhered to. For the quasi pressure-free, 1 day.
11. This information is not provided by the manufacturers of the injection agents, so it is not possible to find out whether the capiliary pressure of a injection agent is higher or lower than that of water.
12. Polymerisation is used here as the common meaning of the word: the formation of long molecule chains as a result of a chemical reaction.
13. As the current generation of injection agents with organic silicone compounds hold water as an active compound, water is assumed in this case. Instead of water, this can also be taken to mean an aromatic or aliphatic solvent.
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17. Glatthor A.; Hintergrundwissen zu Hydrophobierungsmitteln; Baustoffchemie http://www.baustoffchemie.de/hydrophobierung/ consulted on 5 January 2008
18. It follows from this that the distribution of the injection agent progresses more consistently if the brickwork is dried beforehand.
19. Friese P, Protz A; Thermische und konvektive Trocknung von Mauerwerk mit hohen Durchfeuchtungsgraden; Berlin 1999
20. Witteman A.J.M.; Een nieuwe injectietechniek tegen vocht- en zouttransport; Praktijkboek Instandhouding Monumenten The Hague 2002
21. Water in hollow spaces and cracks rarely impedes the filling.

Appendix: moisture transport after filling

It is often assumed for injection agents with a hydrophobic effect, that because of the interruption of the capillary moisture transport, no further moisture transport can take place through the injected region. This is an incorrect assumption. Just like in hydrophobised walls, vapour transport takes places through the hydrophobised injection region. A lot of research has been and is being carried out into the vapour transport in hydrophobised walls. It is evident from this research that there is a high risk of moisture transport through a hydrophobised outer wall construction. In light of this, it is striking that no research has been carried out into the risks of vapour transport through the injected region. Consideration was not even given to this aspect in the literature that was examined about filling brickwork.

In order to find out whether the vapour transport through the injected region can lead to damage, the “linked tanks” model was drawn up. It is evident from the model that this vapour transport constitutes a real risk for the reoccurrence of damage.

the connected tanks

Of the three working mechanisms of injection agents – plugging, narrowing or hydrophobic – there is only one that can prevent **all** of the moisture transport through the injection region (see figure 1). These are the plugging agents /1/. The fact is that, in the hydrophobic agents, vapour transport can still take place by means of diffusion through the pore. The narrowing agents prevent neither water nor water vapour.

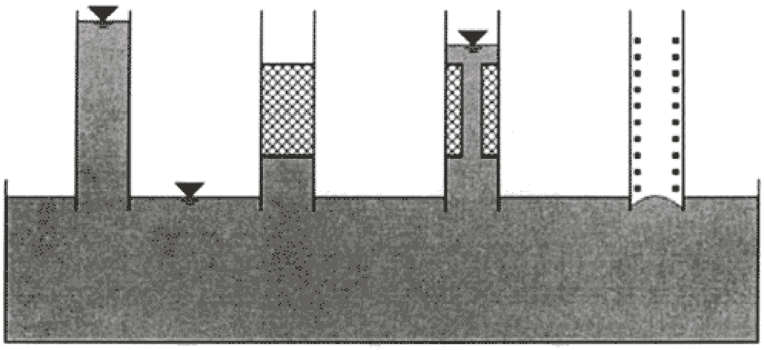

Figure 1: the working mechanism of injection agents, source: /2/

the “connected tanks” model

In the hydrophobic injection agents, the situation after filling can be simplified to the following model. Because of the high porosity of brick and mortar, the brickwork above and below the injected region can be seen as being two closed thanks, connected by a thin channel (see figure 2). The lowermost tank is partially filled with water, with air above. The uppermost tank has been fitted with a tap, through which air can “escape”.

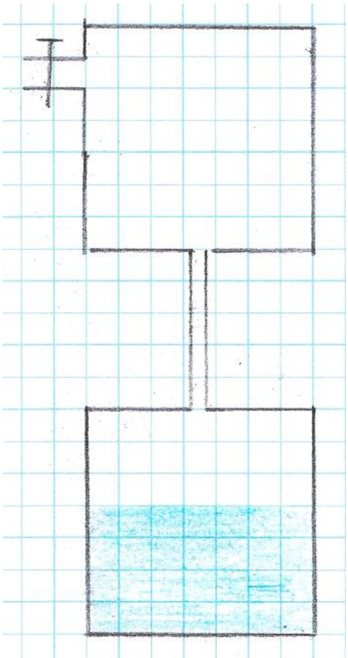

Figure 2: the proposed “connected tanks” model

equilibrium

If the tap in the uppermost tank is closed, the water vapour pressure in both the lowermost and the uppermost tank will, after some time, be equal. This also applies to the connecting channel.

Because of the water in the lowermost tank, after some time, the vapour pressure will have reached a maximum. At a temperature in the lowermost tank /3/ of 12ºC, that corresponds with a vapour pressure of 1,403 Pa /4/. The speed at which the equilibrium is adjusted depends on the vapour diffusion resistance of the connecting channel /5/.

relative humidity and temperature

Once the maximum vapour pressure has been reached in the lowermost tank, the relative humidity in the lowermost tank is 100%. In the uppermost tank, the relative humidity depends on the temperature. In the event that the temperature in the uppermost tank is 1ºC higher, the vapour pressure in the uppermost tank will perhaps remain equal /6/ but the relative humidity will fall to “just” 93.7% /7/. The greater the difference in temperature, the more the relative humidity will fall.

drying

If the tap in the uppermost tank is opened, moisture will be discharged provided that the vapour pressure outside the tank is lower than in the tank. The flow resistance of the tap and the vapour pressure difference over the tap determine the speed at which moisture is discharged. At the same time, moisture is discharged from the lowermost tank through the connecting channel. The speed of this is determined by the vapour diffusion resistance of the connecting channel /8/.

If the amount of moisture that is discharged is greater than the supply (= drying), the vapour pressure in the uppermost tank will fall. The fall in the vapour pressure will result in the relative humidity falling. The effect of the discharge of moisture will have a much more limited effect on the vapour pressure in the lowermost tank. Here, the vapour pressure will not reduce much unless the moisture transport through the connecting channel is significant.

porous material

If the hollow space in the uppermost tank is replaced by a porous material with an open structure, this will not have an effect on the action of the connected tanks model. The processes will, however, progress more slowly. Additionally, capillary condensation can occur in the pores. This depends on the dimensions of the pores and the relative humidity in the uppermost tank.

moisture content above the injected region

It follows from the connected tanks model that, in hydrophobic injection agents (from a practical point of view) the maximum vapour pressure above the injected region in the brickwork prevails unless:

- because of drying, more moisture is discharged than is supplied through the injected region
- the temperature above the injected region is higher than below.

The high relative humidity in the brickwork above the injected region results in capillary condensation. The scope of that is considerable. This can be deduced from the strong increase in the hygroscopic moisture content equilibrium of the brickwork. This increases significantly as from a relative air supply humidity of 90% /9/. From the theory of Philip and De Vries /10/ it follows that the high moisture content in the brickwork above the injected region – as a result of capillary condensation – will result in further distribution of the moisture in the brickwork /11/. This will also progress slowly as the vapour transport through the injected region (=supply) progresses slowly.

damage

This implies that for all injection agents where, in addition to the capillary moisture transport, the vapour transport is *not* inhibited through the injected region, there is a risk that damage will (once again) occur through capillary moisture transport. Unless the temperature gradient in the core of the brickwork between the top and the bottom of the injected region is sufficiently large (> 1 to 2ºC).

temperature difference and drying as success factors

From the “connected tanks” model, it follows that there are two factors that can significantly decrease or even prevent the risk of capillary condensation. These factors are:

- drying
- temperature gradient between the top and the bottom of the injected region.

It follows from this that good ventilation and heating of the space will contribute significantly to the treatment having a durable result against capillary moisture transport. In other words: *flanking measures are necessary for a durable result*.

Notes, literature and sources

1. If the injection agent does not attach itself or attaches itself poorly to the pore wall, there is a risk that moisture transport can still take place between the injection agent and the pore wall. On account of contraction of the injection agent, openings can occur through which vapour transport is possible.
2. Raupach, M.; Wolff, L.; Mauerwerksinjektion bei aufsteigender Feuchtigkeit: Wirkprinzip; Quelle: Internationale Zeitschrift für Bauinstandsetzen, 2002
3. For the sake of this example, a temperature of – 12 °C – has been chosen as this is often the case in practice. This is based on a ground temperature of 10 °C at a depth of three metres and an average room temperature of 18 °C.
4. If salt is present in the water of the lowermost tank, this will result in a decrease of the vapour pressure. The decrease is dependent on both the concentration of the dissolved salt and the type of salt.
5. This is dependent in particular on the diameter of the connecting channel.
6. In a closed tank, an increase in temperature leads to a rise in pressure (The General Gas Law of Boyle-Gay-Lussac). In the uppermost tank, as a result of the rise in temperature from 12ºC to 13ºC, the vapour pressure will initially rise from 1,403 Pa to 1,408 Pa. As the pressure in the lowermost tank can amount to no more than 1,403 Pa – maximum vapour pressure at 12ºC – some condensation will take place until the pressure in the uppermost tank amounts to 1,403 Pa.
7. The relative humidity is calculated by dividing the actual vapour pressure by the maximum vapour pressure. The latter is dependent on the air temperature.
8. In the coarser pores, the vapour transport will be much higher than through the smaller pores.
9. Hens H.; Building Physics – Heat, Air and Moisture; Berlin 2007
10. Brocken H.J.P.; Moisture transport in brick masonry: the grey area between bricks; Eindhoven 1998
11. Based on the “classic” theory about capillary moisture transport the consequences of the high moisture content above the injected region would be limited. As the capillary

condensation takes place in the smaller pores, this would not lead to capillary moisture transport. The high moisture content above the injected region will result in a vapour flow also occurring towards the surface. This is the consequence of the drying that occurs.