Gypsum efflorescence on clay brick masonry: Analysis of potential efflorescence origins

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Abstract

Gypsum efflorescence on clay brick masonry is a growing problem, leading to a persistent grey-white staining of masonry facades. Gypsum efflorescence has been reported in the United Kingdom, the Netherlands and Belgium, with a specific occurrence on masonry facades erected over the last few decades. This article investigates the origin of this recent occurrence of gypsum efflorescence, with accelerated testing of the gypsum efflorescence sensitivity of separate and combined masonry components. It is demonstrated that both brick and mortar may provide a gypsum source, respectively, via the dissolution of anhydrite and the carbonation of ettringite. Neither does however directly result in gypsum efflorescence, as the released gypsum commonly subfloresces below the brick surface. The efflorescence is instead triggered by mortar admixtures, the application of which has indeed risen strongly in recent decades. Avoiding gypsum efflorescence on clay brick masonry hence requires an inert alternative for the mortar admixtures.

Keywords

Gypsum wick test, efflorescence quantification, drying rate evolution, gypsum sources, mortar admixtures

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Figure 1. (a, b) Belgian examples of gypsum efflorescence on clay brick masonry walls, and (c, d) close-ups of efflorescence deposits, at magnifications 125% (c) and 500% (d).

Introduction

Salt efflorescence on exterior wall surfaces, caused by the evaporation of salt-laden pore water, is a familiar sight on masonry and concrete facades. Most frequently, these are whitish deposits of soluble salts, like alkali sulphates and sodium chloride, which generally appear and disappear soon after the construction of the facade. Because of their high solubility, these salts are easily transported to the facade surface with pore moisture flow, after which they equally easily disappear by reabsorption or run-off draining during driving-rain events. Since the 1980s however, a persistent grey-white efflorescence has started developing more and more often on clay brick masonry, see Figure 1, in the United Kingdom, in the Netherlands and in Belgium (Bowler and Winter, 1996; Brocken and Nijland, 2004; Chwast et al., 2015).

Field studies on this new type of efflorescence (Bowler and Winter, 1996; Brocken and Nijland, 2004; Chwast et al., 2015) reveal that the surface deposits mostly contain gypsum, whose low water solubility explains their persistence at the facade surface. These field studies also show that gypsum efflorescence is a recent development, appearing since the 1980s only, exclusively on newly erected facades. Furthermore, gypsum efflorescence is typically only noticed after a number of years, contrary to the primary efflorescence of more soluble salts. In addition, gypsum efflorescence mainly appears on facades with high wind-driven rain loads.

There is no clear relation with the brick properties though: gypsum efflorescence is noted on bricks with low or high sulphate contents and with low or high water sorptivities.

Its exclusive occurrence on clay brick masonry facades suggests that the masonry constituents themselves are the gypsum source, with the subsequent gypsum efflorescence involving source dissolution, moisture transport and surface crystallisation. Its recent appearance furthermore implies that gypsum efflorescence is most likely triggered by modern changes in these masonry constituents (Bowler and Winter, 1996; Chwast, 2017; Chwast et al., 2015), for example, the rising application of mortar admixtures. Regrettably, until recently, all further analyses and/or future solutions of the problem were hindered by the lack of a tailored experimental method to judge the specific sensitivity of masonry for gypsum efflorescence. That matter has however recently been solved by Chwast's (2017) methodology for the accelerated assessment of gypsum efflorescence sensitivity of clay brick masonry.

While gypsum efflorescence on clay brick masonry solely affects the facade's appearance (none of the present field studies (Bowler and Winter, 1996; Brocken and Nijland, 2004; Chwast et al., 2015) report on material decay caused by gypsum efflorescence), it nevertheless creates a crucial threat for the brick manufacturing industry. Nowadays, clients often chose the facade product for its appealing appearance, but owing to the increasing complaints on gypsum efflorescence, brick manufacturers are facing a potential loss of market share and business revenue. As the gypsum effloresces mainly on the brick surfaces, the brick producers are being blamed for delivering a deficient product, and the burden of explaining and resolving the gypsum efflorescence is put on their shoulders. Through experiments with the tailored testing protocol presented by Chwast (2017), this article targets such explanations and solutions.

This study therefore aims at clarifying the current occurrence as well as at avoiding the future incidence of gypsum efflorescence on clay brick masonry. In the ensuing 'Efflorescence assessment' and 'Masonry constituents' sections, a short digest of the accelerated assessment protocol for gypsum efflorescence sensitivity and a summary of the materials employed in this study, with focus on their selection and preparation, is brought. The main section on 'Gypsum efflorescence' collects the outcomes of all assessments performed, revealing that primarily mortar admixtures are to blame for gypsum efflorescence. Possible solutions to avoid gypsum efflorescence in the future are finally brought forward in the 'Discussion' section.

Efflorescence assessment

The testing method to assess the particular sensitivity of clay brick masonry facades for gypsum efflorescence, introduced and developed by Chwast (2017), is based on the common methods for ceramic brick efflorescence testing (Chin and Behie, 2010; Hennetier et al., 2001). A wicking method is used, wherein a brick sample is in constant bottom contact with a test solution, which is transported to the top surface of

the sample, where evaporation occurs and efflorescence may ensue. That efflorescence is then quantified by image processing (Hennetier et al., 2001), contrary to the visual appraisal that is used in most other methodologies (Chin and Behie, 2010). However, numerous features of the usual methods need to be tailored explicitly towards the particular assessment of sensitivity for gypsum efflorescence.

First, it is undecided still which (combination) of the masonry constituents – brick, mortar, mortar admixtures – forms the source of the gypsum efflorescence. Therefore, separate evaluation of these constituents should be possible. All potential gypsum sources are therefore always inserted through the test solution, which is drawn from the masonry constituents directly. This demands that the brick sample applied in the wicking test does not affect the test outcome, hence solely serving as an inert gypsum transport medium and gypsum efflorescence surface. This, in turn, necessitates that its moisture transport properties do not impact the wicking or the efflorescence. In addition, salts present in the brick sample are to be removed as much as possible, to avoid their disturbing the wicking and/or efflorescence. Finally, on a similar note, inert adhesives for sealing the samples in the setups (see below) are required as well (Chwast, 2017).

Second, gypsum efflorescence takes some years to develop in the field (Bowler and Winter, 1996; Brocken and Nijland, 2004; Chwast et al., 2015), but such intervals are unacceptable for applied scientific research and industrial quality control. This interval may be attributed to the low solubility of gypsum and/or the slow carbonation of cement mortar (Brocken and Nijland, 2004; Chwast et al., 2015). The low solubility is countered by modifying the drying environment at the top surface such that evaporation is promoted, with high temperature, low humidity and strong surface air flow. In addition, frequent ‘wetting events’ – applying a small amount of distilled water to the top surface – are integrated, a feature imitating the regular wetting of masonry facades by driving rain, which has been shown to promote gypsum efflorescence (Chwast, 2017). Finally, the slow carbonation is countered with the accelerated carbonation of small mortar chunks, prior to their insertion in the test solution.

Third, gypsum has a natural propensity to subfloresce instead of effloresce (Bowler and Winter, 1997; Charola et al., 2006; Franke and Grabau, 1994; among others), which infers that a lack of gypsum efflorescence on the sample cannot directly be interpreted as a lack of gypsum formation in the solution. When subflorescing however, the gypsum crystals yield pore clogging (Todorović and Janssen, 2018), reducing the permeability of the sample and thus the wicking through the sample. Frequent weighing hence becomes a crucial part of the protocol to monitor the formation of gypsum in the test solution independent of the deposition of gypsum at the top surface.

Preparation of setups

Brick samples. Contrary to most common efflorescence tests (Chin and Behie, 2010), where the efflorescence sensitivity of the used sample is typically evaluated,

the brick sample in our protocol only serves as inert transport medium and efflorescence surface. This implies first that its moisture transport properties are not to impede the wicking and/or efflorescence process. In Chwast (2017), a number of bricks identified in the field survey (Chwast et al., 2015) were judged on that front, and the impact of their different moisture transport properties was found to be insignificant. That suggests that a single brick material can be applied in all tests, the choice being governed by the visual appearance of gypsum efflorescence on its surface. From the spectrum of bricks in the field survey, the Vandersanden Robusta brick is preferred, since its dark colour contrasts well with the grey-white gypsum efflorescence.

Cylindrical samples, with diameter 30 mm and height 62 mm, are drilled out of bricks, randomly selected from a brick pallet. Three core samples per brick are drilled perpendicular to the brick's stretcher, which serve as the exposed brick core side during the test. To exclude all disturbance by salts naturally present in the brick (Chwast, 2017), after drilling all samples are leached, by keeping them in a tank with demineralised water at 40°C. Each 24 h, the leachate's conductivity is measured, after which the samples are submerged in fresh demineralised water. This procedure is repeated until the leachate conductivity reaches a constant background level, after which samples are oven-dried at 105°C.

Test solutions. Given that the applied brick samples only serve as an inert transport medium and efflorescence surface, the potential gypsum efflorescence sources are brought in via test solutions in the containers, drawn from (combinations of) masonry constituents. Depending on the actual research question, this test solution can be pure water, gypsum solution or water mixed with the masonry constituents being judged as gypsum efflorescence source, that is, powdered brick, carbonated cement paste, mortar admixtures, and so on. Where applied, the gypsum solutions are prepared from pro-analysis-quality calcium sulphate dihydrate (gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) at a concentration of 2.2 g/L, equivalent with 85% of gypsum saturation at 20°C (Chwast, 2017). More information on the other test solutions follows in section 'Masonry constituents'.

Container setups. The brick sample and the container's lid are sealed together with an inert hot melt adhesive (Figure 2(a) and (b)). To facilitate the wetting events, the lid is enriched with a 'wetting ring' (diameter 37 mm, height 10 mm), to guarantee a repeatable and complete wetting of the sample surface. The ring moreover reduces the variation of the evaporation over the surface and hence promotes an even efflorescence growth (Chwast, 2017). During the course of the experiment, the setups are frequently moved between the climate cabinet at 35°C and the lab room at 20°C. It was noted that, upon return to the climate cabinet, solution droplets formed on the samples' surfaces (Chwast, 2017). Moving setups from the cold lab room to the warm climate cabinet probably generated an excess air pressure in the containers, which, in turn, pushed test solution to the sample's surface. This problem is avoided by drilling an inlet in the lid, enabling pressure levelling, which is finally covered with a perforated scotch tape to limit evaporation.

The containers are then placed in a climate cabinet Weiss SB22 1000, set at $35^{\circ}\text{C} \pm 2^{\circ}\text{C}$ and $21\% \pm 4\%$ RH, see Figure 2(c). The latter is the lower limit for the climate cabinet applied, and the former is chosen to avoid gypsum dehydrating to hemihydrate. The high temperature, low relative humidity and strong air velocity in the cabinet are the crucial accelerating factors in this protocol (Chwast, 2017), increasing the wicking rate to about 20 times the rate at standard laboratory conditions. Use of a climate cabinet has the added advantage that multiple setups can be tested simultaneously, in our case up to 108 setups spread over two levels. Potential effects of the setups' location in the cabinet were investigated in Chwast (2017), but no statistically significant impact was found.

Execution of protocol

While the protocol is based on a standard wicking approach, frequent wetting events have also been integrated in the method, that is, applying 3 mL distilled water to the top surface. The final experimental protocol is shown in Figure 3: the entire test takes 4 weeks, and runs on a weekly routine. In the first 5 days, wicking phases and wetting events are alternated, taking about 16 and 8 h, respectively, with weighing of the setup before and after each wicking phase. The procedure is repeated until Friday evening and then the lids with the samples are detached and dried during the weekend. On Monday morning, the dry samples are photographed, the lids are returned to their respective setups and the wick-wetting cycling is restarted.

Processing of results

Image analysis. The sample surface is frequently photographed, see Figure 3, to monitor the occurrence and development of gypsum efflorescence. Gypsum efflorescence shows less clearly on a wet surface (Chwast, 2017), therefore the samples are dried prior to photographing. Constant and uniform lighting conditions are imposed via a photography stand in a room with no daylight ingress, wherein the working area is illuminated by room lighting and two side lamps, see Figure 4. The JPG photographs are taken with a Canon G10 mounted on a tripod, with these fixed settings: white balance calibrated with a grey card, resolution 4416×3312 , F-stop f/8, exposure 1/5 s, ISO 80, small AF frame, centre-weighted average metering mode, macro mode and 2 s shutter delay.

The resulting photographs (Figure 4(b)) are treated with ImageJ software, to determine the efflorescence coverage %E (–) on the top sample surface. They are thus first transformed to an 8-bit grey scale, and subsequently to black and white by applying a threshold of 130–255 (Figure 4(c)), yielding an image where black and white pixels correspond to, respectively, unaffected brick and gypsum efflorescence. The threshold spectrum is determined based on several trials (by visual assessment), aiming at maximising the agreement between the actual efflorescence

Figure 2. (a) Scheme and (b) photo of the setup, and (c) climate cabinet with setups.

Figure 3. The experimental schedule for the accelerated wick-wetting protocol. The wicking phases (dark boxes) and wetting events (light boxes) are separately numbered. The photographing and weighing moments are indicated by hollow and full dots, respectively.

coverages on original photographs with the white pixel coverages in transformed images.

Calculation of the non-normalised efflorescence coverage IA (–) requires (1) activating the ‘Area fraction’ setting, (2) selecting the brick surface only and (3) applying the ‘Measure’ tool. The efflorescence coverage IA is finally normalised via the raw sample surface appearance IA_{raw} (–) to come to the normalised efflorescence coverage $\%E$ (%) = $(IA - IA_{raw}) / (100 - IA_{raw})$.

Drying rate. The target of the frequent weighing, with a Mettler Toledo PB3002-L balance with ± 10 mg precision, is to monitor the wicking rate evolution, which allows us to pinpoint the gypsum formation in the test solution independent of the gypsum deposition at the top surface. The setup mass varies constantly during the experiment, due to the frequent wetting events followed by wicking phases, as exemplified in Figure 3. The setups are typically weighed before the wetting event, after the wetting event and after the wicking phase, at corresponding times t_1 , t_2 and t_3 (s), with respective weights m_1 , m_2 and m_3 (kg), see Figure 5. Wetting event starts with a wetting of the surface with 3 mL of water, which is mostly absorbed by the sample, and partially lost due to evaporation to the environment. The setup mass after the wetting event hence is

$$m_2 = m_1 + \Delta m_{abs} \quad (1)$$

where Δm_{abs} is the mass of water absorbed by a brick sample. During the wicking phase, water evaporates at the brick surface, first the absorbed wetting water Δm_{abs} (kg) and successively the test solution water Δm_{TS} (kg). The mass after the wicking phase can thus be expressed as

$$m_3 = m_2 - \Delta m_{abs} - \Delta m_{TS} = m_1 + \Delta m_{abs} - \Delta m_{abs} - \Delta m_{TS} = m_1 - \Delta m_{TS} \quad (2)$$

The amount of evaporated test solution hence becomes

$$\Delta m_{TS} = m_1 - m_3 \quad (3)$$

Figure 4. (a) Photography stand, (b) original photograph and (c) processed photograph.

Figure 5. Mass evolution during the wetting events and wicking phases.

while the duration of the test solution wicking phase is equal to

$$\Delta t_{TS} = \Delta t_{wick} - \Delta t_{absor} = t_3 - t_2 - \Delta t_{absor} \quad (4)$$

where Δt_{wick} and Δt_{absor} (s) are the durations of the total wicking phase and of the wicking of the absorbed water, respectively. Δt_{abs} is unknown and is thus estimated from the average wick rate of setups tested with pure water: $\Delta t_{abs} = 0.01$ days, thus having negligible impact.

The drying rate, DR (kg/(m² day)), for the wicking phase can then be expressed as

$$DR = \frac{\Delta m_{TS}}{(A \cdot \Delta t_{TS})} \quad (5)$$

where A (m²) is the surface area of the exposed brick surface.

Efflorescence composition. Salt deposits are gently scraped from brick samples and ground. The samples are analysed via the powder X-ray diffraction (XRD) method (Philips PW1830 diffractometer) with the following settings: CuK α radiation (45 kV, 30 mA), 2 h scan, angle range of 5°–70° with step size 0.02° and counting time 1 s. Other samples are analysed for the presence of calcium carbonates by placing a drop of 1M hydrochloric acid (HCl) on the sample's efflorescence.

Masonry constituents

In the following 'Gypsum efflorescence' section, the gypsum efflorescence sensitivity of different masonry constituents is investigated: clay brick, cement paste and mortar admixtures (and their combinations) are tested with the protocol described in the preceding 'Efflorescence assessment' section. The selection and preparation of these masonry constituents are discussed here.

Clay brick

Bricks contain water soluble sulphates, whose source can be anhydrite and/or alkali sulphate(s). Dissolution tests in Chwast (2017) on bricks from the field survey (Chwast et al., 2015) revealed the dominant presence of anhydrite, which may hydrate to gypsum upon contact with water. Clay brick is hence to be tested as a potential source for gypsum efflorescence. To that aim, two bricks from the field survey are selected: the Vandersanden Robusta (BR1) and Parma (BR2). For their use as a test solution, the sampling and crushing methodology from BS 3921:1985 (1985) is applied. Six bricks are taken from different locations in the brick palette and are then crushed with a jaw crusher to a powder fraction of <1 cm. A representative 1 kg subsample is taken by coning and quartering, which is finally ground with mortar and pestle until the powder passes a 500- μ m sieve.

Given that masonry is composed of a volume of brick and mortar, while gypsum efflorescence is a surface phenomenon, the gypsum efflorescence potential of clay brick depends on the ratio of brick surface to brick volume. For the typical Waalformat brick ($21 \times 10 \times 5$ cm³), there is 10 cm³ of volume for each cm² of surface. For our samples with a surface area of 7.07 cm², 70.7 cm³ of brick is needed, translating to 119 g for BR1 and 115 g for BR2. Such amounts of brick powder are finally topped up with 100 mL of distilled water to obtain the test solution.

Cement paste

Mortar equally is a potential gypsum efflorescence source, since calcium sulphate is deliberately added to and ground with Portland cement clinker to provide better control on setting properties. Its contribution to gypsum efflorescence is commonly neglected, as it is mostly bound to virtually insoluble ettringite and monosulphate phases quickly after cement hydration (MacGregor and Melander, 2003). Synthetic

ettringite and monosulphate do however decompose back to gypsum upon carbonation (Nishikawa et al., 1992; Xiantuo et al., 1994; among others). The risk of a gypsum source arising in cement mortar masonry joints may hence be high, as it is reported that 2 years of exposure suffice for their full carbonation (Brocken et al., 2000). Cement mortar is therefore to be tested as potential source for gypsum efflorescence. Since sand is considered to be irrelevant in relation to gypsum efflorescence, cement paste is tested instead of cement mortar.

Four cements are selected because of the substantial differences in their compositions:

- B1: ordinary Portland cement (CEM I SPEED 52.5 HES), as a reference (95%–100% clinker).
- B2: blended cement (CEM II/B-M (S-V) 32.5 N), as a cement commonly used for masonry construction (65%–79% clinker).
- B3: sulphate resistant cement (CEM I 42.5 SR0), due to its distinctly low content of aluminate phases (95%–100% clinker).
- B4: pozzolanic cement (CEM IV/B-P 32.5), due to its markedly high replacement of cement clinker by pozzolana (45%–64% clinker).

These cements are made into cement paste by addition of water, with an intended water/cement ratio of 0.5. Significant bleeding is observed for cement B2 though: the excess water is weighed and discarded, and its corrected water/cement ratio is 0.44. The hardened pastes are crushed into chunks of 0.5–2 mm, to subsequently undergo accelerated carbonation (Chwast, 2017). Finally then, the carbonated cement paste is further ground to a powder of $<500\text{ }\mu\text{m}$ and the needed amount of paste is placed in the container and topped off with 100 mL of distilled water.

When testing cement pastes in the test solution, the required amounts need to be adjusted to (1) the top surface area of the samples and to (2) the use of cement paste instead of mortar. This is realised by determining the amount of anhydrous binder per brick in masonry, then rescaling it to a sample, and finally calculating the amount of cement paste to be tested given its water/cement ratio. The brick-to-mortar ratio in masonry is determined by assuming a standard facing brick of Waalformat embedded in horizontal and vertical mortar joints of 10 mm, complying to the C300 masonry mortar designation (CSTC, 2009), see Table 1. The C300 mortar density and its anhydrous cement content are calculated from a commercial recommendation for dosages of masonry mortar components (Holcim, 2010), see Table 2.

Table 3 illustrates the calculation steps needed to determine a representative amount of cement paste to be tested in a setup with a brick core. First, the mortar joint volume per brick is calculated from the known dimensions of bricks and mortar joints. Next, its mass is determined from the determined mortar density, while the amount of anhydrous cement required for its preparation is estimated from the calculated anhydrous cement content (Table 2). These values are rescaled to a brick

Table 1. Specification of the C300 mortar designation according to CSTC technical note (CSTC, 2009).

Mortar designation	C300
Binder (kg) per 1 m ³ sand	300
Cement/sand ratio (vol.) ^a	1:4

^aAssuming a sand density of 1500 kg/m³.

Table 2. Dosage recommendation for C300 mortar preparation according to (Holcim, 2010) and the calculated properties of mortar after mixing with water.

The dosage recommendation for C300 mortar preparation	
Anhydrous cement mass (kg)	25
Sand (L)	90
Water (L)	20
Volume of the prepared mortar (L)	85
The calculated C300 properties after mixing with water	
Mortar density (kg/m ³) ^a	2100
Anhydrous cement per 1 L mortar (kg/L)	0.29

^aAssuming a sand density of 1500 kg/m³.

Table 3. Amounts of mortar, anhydrous cement and cement paste calculated per single Waalformat brick, and rescaled to a brick core sample.

Parameter	Single brick	Brick core
Stretcher surface area (cm ²)	105	7.07
Mortar volume (cm ³)	270	—
Mortar mass (g)	572	—
Anhydrous cement (g)	79.4	5.3
Binder type	w/c	Cement paste/brick core (g)
B1/2/4	0.50	8.0
B2	0.44	7.7

core sample according to the ratio of the surface area of the Waalformat brick's stretcher and the brick core's top surface. Finally, the necessary amount of cement paste is calculated from the anhydrous cement mass per brick core and from the water/cement ratio used for the paste preparation.

Table 4. List of admixtures used for benchmarking. The chemical composition is declared by producers.

Code	Admixture type	Chemical composition
A1	Common washing up liquid	15%–30% anionic surfactant 5%–15% non-anionic surfactant
A2	Mortar plasticiser and air entrainer	Not available
A3	Mortar plasticiser and air entrainer	Not available
A4	Mortar plasticiser and air entrainer	8% detergent
A5	Concrete superplasticiser	Sulphonated melamine formaldehyde condensate

Mortar admixtures

More and more often, admixtures are added to masonry mortar, in order to improve the mortar's workability and/or the joints' performance. These mortar admixtures are available as solution, to add to the liquid mortar mix, or as solids, to add to the dry mortar mix. In both cases, the admixtures are water soluble, and in a wet mortar mix, they are therefore present in the liquid phase, which renders them mobile during bricklaying. Upon contact with fresh mortar, bricks absorb a part of the admixtures via the pore water, and this way, the admixtures can get distributed over both mortar and brick. Given that the increasing use of mortar admixtures is one of the leading evolutions for current masonry facades, they may play a role in the recent occurrence of gypsum efflorescence (Bowler and Sharp, 1998; Bowler and Winter, 1997). Mortar admixtures are therefore to be tested as a potential source for gypsum efflorescence.

Their impact is assessed in three consecutive steps. First, (1) the common products are benchmarked in setups where a gypsum solution provides a direct and unlimited gypsum source. In the next step, two products are selected to separately assess their influence on gypsum efflorescence from (2) cement paste and from (3) brick powder.

Admixtures benchmarking. Three commercial mortar admixture products A2–A4 (representing admixture types commonly applied in masonry mortars) are selected, based on a survey of building material distributors in the area of Leuven (Belgium), see Table 4. These three admixtures are surfactant-based plasticiser and air entrainer products, which enhance the workability of the fresh mortar and promote the formation of air microbubbles (having a beneficial effect on the freeze-thaw performance of cement mortars). Similar surfactant-based products are suspected to be possible triggers of the recent gypsum efflorescence cases (Bowler and Sharp, 1998; Bowler and Winter, 1997).

In addition to the three commercial mortar admixtures, a common detergent A1 is also included, as such are reportedly also applied, instead of air entrainers. Finally, superplasticisers may also improve the workability of a fresh mortar, but potentially without inducing gypsum efflorescence formation. While they are

Table 5. Dosage of admixtures to gypsum solution calculated from the recommendation given by the admixture producer and for the C300 mortar formulation.

Code	Admixture dosage		Benchmarking dosage	
	Recommended by producer	Average	g per L	mL per L
A1	3–6 g per l L water ^a	4.5 g per l L water	13.5	–
A2	50–100 mL per 50 kg cement	75 mL per 50 kg cement	–	5.6
A3	50 mL per 50 kg cement	50 mL per 50 kg cement	–	3.8
A4	40 mL per 50 kg cement	40 mL per 50 kg cement	–	3.0
A5	0.2%–3.4% by cement weight	1.8% by cement weight	67.5	–

^aNo official dosage recommendation available, dosage suggested by a mason.

widely applied in concrete, they do not find their way into masonry mortars yet though. A commercial sulphonate-type superplasticiser A5 is included in the tests, as this type is usually not surface-active (Pagé, 2003). However, as a consequence, these products do not induce air entrainment (Mosquet, 2003).

For benchmarking the five admixtures, the brick samples are saturated with a gypsum (2.2 g/L) and admixture solution prior to assembling them in a setup with a gypsum solution. The admixture dosage, see Table 5, is calculated to reflect its concentration in a fresh C300 mortar, based on the known C300 mortar composition and the recommended admixture dosage. To our knowledge though, it is common practice to overdose these admixtures and thus a three times higher dosage is applied instead. This ‘three times overdose’ is equally maintained when testing admixtures in combination with cement mortar and clay brick.

Based on the benchmarking results, two admixtures are selected for further evaluation. An additional experiment is carried out to determine whether the selected admixtures modify the wick process. This is realised by following the procedure explained above, but using distilled water instead of gypsum solution both for preparation of the admixture solution and as test solution.

Cement and admixture. Mortars used for residential construction in Belgium are mostly prepared on site from separately purchased components, or are prepared from dry premixed commercial formulations. The two selected admixtures are tested in combination with the B1 and B2 cements, see Table 6. In the cement paste preparation, the admixtures are added to the cement powder together with water.

In addition, a commercial premixed mortar (B5), containing unknown solid admixtures, is tested as well. This mortar formulation is a common product according to building material distributors in the area of Leuven (Belgium). The admixture-enriched cement pastes are prepared, carbonated and tested similar to the original pure cement pastes.

Brick and admixture. The selected admixtures are also tested in combination with the BR1 brick powder, see Table 7. The test solution is in this case composed of distilled water mixed with brick powder and admixture, to allow for the interaction

Table 6. List of cement paste and admixture formulations. Some pastes show bleeding after 28 days curing, hence their w/c ratio and sample masses are corrected accordingly.

Cement paste composition	w/c	Admixture dosage (3× surplus)		Cement paste/setup (g)
		(g/kg cement)	(mL/kg cement)	
B1 + A3	0.50	–	3	8.0
B2 + A3	0.50	–	3	8.0
B1 + A5	0.39	54	–	7.4
B2 + A5	0.35	54	–	7.2
B5	0.50	–	–	8.0

Table 7. List of brick and admixture compositions.

Brick and admixture composition	Admixture dosage (3× surplus)		Brick powder used in test (g)
	(g/setup)	(mL/setup)	
BR1 + A3	–	0.016	119
BR1 + A5	0.286	–	119

between the gypsum source (brick powder) and the used admixture. The dosage of the latter is calculated to reflect the amount of admixture used relative to the surface area of the brick sample. The recommended dosage of A3 and A5 admixtures is relative to the used amount of anhydrous cement, see Table 5, which equals 5.3 g for a single sample, see Table 3. The dosage is thus calculated proportionally to the latter and increased to a threefold overdosage, as for the other admixture tests. The setups are further prepared and tested similar to the original pure brick powders.

Gypsum efflorescence

In the prior ‘Masonry constituents’ section, the different possible sources of gypsum efflorescence have been introduced. In this section, the results of the accelerated assessments of their sensitivity for gypsum efflorescence are compiled. These are presented with (1) brick surface photographs, serving as evidence for gypsum efflorescence, and (2) drying rate evolutions, wherein a strong drop is a sign of gypsum subflorescence. The drying rates are presented in function of the number of wick phases, since these best represent the progression of the experiments. The error bars indicate the spread for the multiple duplicate setups that are applied.

Figure 6. Drying rate evolutions for pure water (W) and gypsum solution (G) setups.

Table 8. Efflorescence photographs for water and gypsum setups; the additional three columns contain pictures at similar magnitude from selected cases from the field survey (Chwast et al., 2015).

W	G	FS16	FS24	FS29

Water and gypsum

Introductorily though, prior to and as a reference for the masonry constituent results, the efflorescence photographs and drying rate evolutions for setups with either pure water or gypsum solution as test solutions are collected in Table 8 and Figure 6. Table 8 also contains efflorescence photographs from the field survey (Chwast et al., 2015), illustrating the common intensity of gypsum efflorescence on clay brick masonry in reality.

Figure 6 shows a constant drying rate for the water setups, demonstrating that the wicking and evaporation processes proceed steadily throughout the test, unhindered by any sizable sub- or efflorescence. HCl testing of the slight efflorescence on

the water setups, see Table 8, signals calcite, which must derive from the brick samples, implying an imperfect leaching hence.

The gypsum setups, on the contrary, give a swift and sizable drop in the drying rate, showing that the wicking and/or the evaporation are gradually being obstructed. A minor efflorescence is noted again and XRD analysis exclusively reveals gypsum. The drying rate drop is thus caused by pore clogging due to gypsum subflorescence (Todorović and Janssen, 2018), as confirmed by Scanning Electron Microscopy (SEM) analyses in Chwast (2017). The pore clogging greatly shrinks the total wicking transfer through the sample, probably eliminating the efflorescence of sample-derived calcite, thus nullifying the imperfect sample leaching.

The water setups show that the absence of gypsum efflorescence and of a drying rate drop signify the lack of a gypsum source. The gypsum setups however highlight that absence of gypsum efflorescence in combination with a drying rate drop indicates the presence of a gypsum source, yielding subflorescence instead of efflorescence though, which is the natural tendency for gypsum (Bowler and Winter, 1997; Charola et al., 2006; Franke and Grabau, 1994; among others). It should finally be noted that the gypsum setups, in spite of their ‘unlimited’ gypsum source, do not result in the abundant gypsum efflorescence as found in the field survey (Chwast et al., 2015), most plausibly owing to the quick gypsum pore clogging, restricting moisture wicking and gypsum efflorescence. It therefore appears that presence of a gypsum source is insufficient and that a certain trigger is required to get gypsum efflorescence on clay brick masonry.

Clay brick

Table 9 shows the efflorescence photographs for the brick powder setups, and reveals the presence of both gypsum and calcite. One could argue that the efflorescence coverage is sizeably stronger than for the gypsum setups shown above. This presumably stems from the sustained evaporation in the brick powder setups, see Figure 7, which brings sample-derived calcium to the surface. Both observations are evidence for the low availability of gypsum in the brick powder test solutions. Chemical analysis in Chwast (2017) results in gypsum contents of 0.42 g/brick and 0.61 g/brick for BR1 and BR2, respectively, present in the brick as anhydrite. Assuming the immediate dissolution of all anhydrite – neglecting its very low dissolution rate (Jeschke and Dreybrodt, 2002) hence – would result in a gypsum concentration in the test solution of 0.28 and 0.41 g/L, respectively.

These maximal concentrations are far below the 2.2 g/L in standard gypsum setups, and the actual concentrations are probably much lower still, given the very slow dissolution of anhydrite.

This observation does however not rule out brick as potential source for gypsum efflorescence. First, there are commercial bricks that contain much more gypsum, going up to 7 g/brick (Chwast, 2017; Chwast et al., 2015). Second, the mobility – related to dissolution, transport and crystallisation – of the brick’s gypsum may be

Table 9. Efflorescence outcomes for brick powder setups. The rows contain the following (1) setup code; (2) efflorescence coverage %E as average $\pm$ standard deviation, the value between brackets is valid for the given photograph; (3) composition of efflorescence; (4) amount of gypsum per brick; (5) full and (6) detailed photograph of the efflorescence coverage on one of the four duplicates.

BR1	BR2
41 $\pm$ 10 (28) % Gypsum and calcite 0.42 g gypsum	37 $\pm$ 2 (37) % Gypsum and calcite 0.61 g gypsum

Figure 7. Drying rate evolutions for brick powder setups.

enhanced through certain triggers. Bowler and Winter (1997) performed water impregnation and drying tests on anhydrite-rich brick types, lasting more than 1 year. These did not yield any gypsum efflorescence. When mortar admixtures were

Table 10. Efflorescence findings for brick powder setups; see Table 9 for the contents.

B1	B2	B3	B4
7 ± 6 (6) % Gypsum 1.20 g gypsum	6 ± 1 (8) % Gypsum 1.41 g gypsum	6 ± 3 (3) % Gypsum 1.97 g gypsum	2 ± 0 (1) % Gypsum 2.94 g gypsum

integrated into the test protocol however, the same bricks gave significant gypsum efflorescence. That suggests that anhydrite in brick, given correct triggers, can be suitably dissolved and transported, to effloresce as gypsum. And actually, bricks BR1 and BR2 are evidence of that theory as well. While there is no gypsum efflorescence in the accelerated assessment of their brick powders, they are among the gypsum efflorescence cases of the field survey (Chwast et al., 2015). Despite their low gypsum amounts, they clearly form a sufficient source for gypsum efflorescence, when the correct triggers are present. These triggers could be present in the mortar cement and/or in the mortar admixtures.

Cement paste

Table 10 and Figure 8, respectively, gather the efflorescence photographs and drying rate evolutions for the four carbonated cement pastes. The drying rates all drop quite swiftly, similar to the gypsum setups in Figure 6, establishing a significant gypsum pore clogging. The efflorescence coverage is somewhat lower than the gypsum setups in Table 8, which is most probably due to the relatively lower gypsum availability. For our cement pastes, the gypsum per brick amounts vary from 1.20 to 2.94 g/brick, which translate to maximal gypsum concentrations from 1.62 g/L to the saturation limit for gypsum. That gypsum is furthermore fairly easily available, as the carbonation of ettringite directly results in gypsum rather than anhydrite. The gypsum availability is sufficient to cause significant pore clogging, hence

Figure 8. Drying rate evolutions for carbonated cement paste powder setups.

Table 11. Surface tension (average $\pm$ standard deviation) of water, gypsum solution (G), gypsum and admixture solutions (G + A1 to G + A5).

Solution	Surface tension (m N/m ²)
Water	70.0 $\pm$ 0.1
G	70.7 $\pm$ 0.7
G + A1	24.0 $\pm$ 0.0
G + A2	28.9 $\pm$ 0.2
G + A3	29.2 $\pm$ 0.4
G + A4	25.8 $\pm$ 0.0
G + A5	69.4 $\pm$ 0.2

hindering the further evaporation of test solution and the accumulation of gypsum efflorescence, as demonstrated by the low efflorescence coverages in Table 10. Cement B4 gives a remarkably low coverage, compared to the three others. This cement has the highest amount of gypsum per brick though, which apparently result in the largest impact of pore clogging, illustrated by its globally lower drying rate, which hence transport less gypsum through the sample for potential efflorescence.

While the absence of gypsum efflorescence for the brick powders can be attributed to the limited availability of gypsum in the test solution, for the cement pastes the abundant availability of gypsum in the test solution is the explanation for the absence of gypsum efflorescence. It appears therefore that the occurrence of gypsum efflorescence is not readily related to the level of availability of gypsum in masonry. This may explain the overall absence of gypsum efflorescence on less recent masonry facades. It also reiterates the need for a trigger for gypsum efflorescence, which can perhaps be found in the mortar admixtures.

Mortar admixtures

The experiments with the gypsum and cement paste powder setups establish the typical subflorescing property of gypsum (Bowler and Winter, 1997; Charola et al.,

Table 12. Efflorescence findings for gypsum plus admixture setups; see Table 9 for the contents.

G + A1	G + A2	G + A3	G + A4	G + A5
81 ± 6 (77) % Gypsum	88 ± 9 (83) % Gypsum	90 ± 5 (92) % Gypsum	57 ± 20 (72) % Gypsum	1 ± 2 (1) % Gypsum

2006; Franke and Grabau, 1994; among others). That characteristic implies that a mere presence of gypsum is insufficient for gypsum efflorescence and that a certain trigger is required. In the past, the increasingly applied mortar admixtures have been singled out in that respect (Bowler and Winter, 1997). First, common Belgian admixture products are benchmarked with gypsum and admixture setups, and then two selected products are evaluated in more realistic conditions: together with cement paste powder and/or brick powder.

Admixtures benchmarking

Impact on surface tension. The common British mortar admixtures suspected for triggering gypsum efflorescence are reported to be surfactant-based, therefore significantly reducing the surface tension (Bowler and Winter, 1997). Initially hence, it is evaluated whether the selected common Belgian products likewise exert a similar effect, by confronting the surface tension of water, gypsum solution and gypsum and admixture solutions, see Table 11. The surface tension values are obtained via the pendant drop method with a CAM 200 tensiometer from KSV (Chwast, 2017). The interfacial tension is derived by fitting the shape of the drop with the Young–Laplace equation. The outcomes establish that the commonly used admixtures A1–A4 indeed reduce the surface tension, indicating that their active compound is a surfactant. In contrast, the concrete superplasticiser A5 does not alter the surface tension significantly.

Impact on gypsum efflorescence. Table 12 and Figure 9, respectively, gather the efflorescence photographs and drying rate evolutions for the five gypsum plus admixture solutions. It is manifest that introducing the admixtures changes the

Figure 9. Drying rate evolutions for gypsum plus admixture setups.

gypsum efflorescence and drying rate evolution quite drastically. Relative to Table 8 and Figure 6, abundant gypsum efflorescence has appeared while the drying rate drops have disappeared for mortar admixtures A1–A4. The A3 product actually results in higher drying rates than the water setups in Figure 6, owing to the formation of abundant dendritic surface efflorescence, which enlarges the drying surface area and hence the evaporation rate.

The continuously high drying rate translates into an efficient gypsum transport through the sample as well as a significant gypsum precipitation on its surface. The A1–A4 admixtures are based on surfactants, as demonstrated by their crucial reduction of the surface tension. This suggests that the presence of surfactants changes the gypsum propensity from subflorescence into efflorescence. In the absence of surfactants gypsum typically accumulates below the surface, which may be explained by its propensity for crystallisation at a solid–liquid interface, hence also within the brick pores.

On the contrary, surfactants accumulate at a liquid–air interface, where they can prompt nucleation and crystallisation (Canselier, 1993), and in this way promote crystallisation at the brick surface instead, resulting in efflorescence formation. When admixtures are present, gypsum efflorescence first appears as complex dendritic structures, which upon frequent wetting recrystallize to more bulky forms, which preserve aspects of their initial dendritic structure though, as illustrated by the photographs in Table 12. However, in absence of admixtures, gypsum crystallises as densely packed stacks of plates, see Table 8. These different crystal habits may also be explained by the effect of surfactants: their adsorption onto crystalline faces alters the crystal growth process, in turn modifying both habit and size distribution of crystal products (Canselier, 1993). Gypsum efflorescence found on actual constructions is also in form of local thick accumulations, though less abundant and without the dendritic shape aspect, see Table 8. The lack of dendritic aspects on field survey cases is most likely caused by the hundreds of intensive wetting episodes that gypsum efflorescence experiences after its development, which recrystallizes and reshapes the deposits. In the applied testing protocol, the wetting water of the wetting events is completely absorbed by the brick sample within less than 50

Figure 10. Drying rate evolutions for water and water plus admixture setups.

min, which gives only partial recrystallization, in some cases preserving the initial dendritic aspects.

However, the concrete superplasticiser A5 does not interfere with the gypsum crystallisation behaviour, and these setups perform similar to the ones with gypsum solution only, see Tables 8 and 12. Moreover, a drying rate drop is quickly generated by pore clogging, accompanied by a minor intergrain gypsum efflorescence, see Figures 6 and 9. The A5 product is a concrete superplasticiser (sulphonated melamine formaldehyde condensate), which, in contrast to surfactant-based products, does not affect the surface tension, see Table 11. The sulphonated melamine superplasticisers have already been reported to have no substantial effect on gypsum crystallisation (Middendorf and Budelmann, 1995), in line hence with the present results.

Influence on the wick performance. Based on the benchmarking outcomes, the A3 and A5 admixtures are selected for further evaluation. The former triggers the most abundant efflorescence, while the latter is the only one that does not alter gypsum's subflorescing propensity. First, their impact on the wicking behaviour is investigated with water and water plus admixture setups, and the resulting drying rates are compiled in Figure 10. It is evident that the admixtures do not have any beneficial effect on the drying rates, and gypsum efflorescence triggering effect thus appears to work through altering gypsum crystallisation behaviour only.

Cement paste and admixture. Table 13 and Figure 11, respectively, gather the efflorescence photographs and drying rate evolutions for the cement pastes plus admixtures. The outcomes contradict our earlier results. The addition of the A3 admixture to gypsum solutions resulted in high drying rates and clear gypsum efflorescence, see section 'Impact on gypsum efflorescence', whereas its addition to cements B1 and B2 does not change their normal behaviour, see section 'Cement paste', as again the quick drying rate drop and the lack of gypsum efflorescence are obtained. The reasons for the lack of the expected admixture effect are unclear: it may possibly be attributed to its encapsulation in a complex cement paste structure or another type of immobilising interaction.

Table 13. Efflorescence findings for cement paste plus admixture setups; see Table 9 for the contents.

B1 + A3	B2 + A3	B1 + A5	B2 + A5	B5
9 ± 5 (5) % Gypsum	6 ± 2 (6) % Gypsum	10 ± 4 (16) % Calcite	52 ± 20 (47) % Gypsum and Calcite	44 ± 15 (58) % Gypsum
1.51 g gypsum	1.42 g gypsum	0.04 g gypsum	1.32 g gypsum	5.15 g gypsum

Figure 11. Drying rate evolutions for cement paste plus admixture setups.

The addition of superplasticiser A5 to cements B1 and B2 also has an opposing impact: if added to gypsum solutions, it led to a quick drying rate drop and negligible gypsum efflorescence, see section ‘Impact on gypsum efflorescence’, while its addition to cements results in a maintained high drying rate and a pronounced calcite (B1 + A5) or abundant gypsum and calcite efflorescence (B2 + A5), contrary to the normal behaviour of these cements, see section ‘Cement paste’. Carbonation of the B1 + A5 cement paste does not result in gypsum formation (Chwast, 2017), which explains the lack of gypsum in the deposit. The A5 superplasticiser thus appears to retard cement carbonation, which is further supported by the development of calcite efflorescence originating from the uncarbonated

portlandite. No such effect is observed for the B2 + A5 cement paste. A significant amount of gypsum is formed during carbonation, and resultantly abundant gypsum efflorescence is observed. Even though the A5 superplasticiser does not alter gypsum's subflorescing tendency in gypsum setups, it evidently shows specific interaction effects with cement, which lead either to limiting of the gypsum efflorescence or alternatively to its enhancement. While these results demonstrate the complex chemistry of cement systems and its interactions with mortar admixtures and superplasticisers, they do not allow to explain the underlying mechanisms.

Carbonation of the commercial premixed formulation B5 leads to a formation of the most abundant gypsum source, given its 5.15 g of gypsum per brick. All samples are greatly covered with gypsum deposit, reminiscent of gypsum efflorescence cases identified in the field survey (Chwast, 2017). At the same time that gypsum crystallisation does not constrain surface evaporation as reflected by a high drying rate. This shows both that (1) commercial mortar formulations can supply sufficient amount of gypsum after their carbonation and (2) may contain components triggering abundant gypsum efflorescence at the masonry surface. The admixture component of B5 formulation appears to maintain its gypsum efflorescence triggering property after its incorporation in the cement paste, followed by its hydration (28 days) and carbonation (70 days). Bowler and Sharp's (1998) experiments on masonry wallettes demonstrated that this can hold true even after a couple of years after their construction. Moreover, while the admixtures A3 and A5 are overdosed three times (as an attempt to reflect common practice), the B5 mortar is a premixed composition and its admixture content is not increased. That shows that the actual admixture levels in commercial premixed products might be sufficient to trigger gypsum efflorescence formation.

Brick and admixture. Table 14 and Figure 12, respectively, gather the efflorescence photographs and drying rate evolutions for the brick powder plus admixtures. Addition of the A3 admixture to the BR1 brick gives inconsistent outcomes. Three setups perform similarly in relation to drying rates (BR1 + A3 (3 s) in Figure 11) and efflorescence to these with brick powder only, see section 'Clay brick'. In both these tests, the brick powder supplies the same low amount of gypsum and the outcomes show that it is insufficient to either cause pore clogging or accumulate as abundant efflorescence. However, a single setup (BR1 + A3 (1 s) in Figure 11) shows an exceptionally high drying rate, accompanied by abundant gypsum efflorescence, like the gypsum plus A3 admixture setups in section 'Impact on gypsum efflorescence'. The tested brick powder is fine and homogeneous, and it is thus improbable that the brick powder sample in one setup contains more gypsum. Another possibility is that a single brick core is richer in calcium sulphate (e.g. in form of coarser grains) which is not completely extracted during the leaching procedure. Regardless of the origin of the gypsum, this single setup demonstrates that the admixture addition triggers abundant gypsum efflorescence. In contrast, the addition of the A5 superplasticiser did not change the normal behaviour of the brick powder only, see section 'Clay brick'.

Table 14. Efflorescence findings for brick plus admixture setups; see Table 9 for the contents.

BR I + A3	BR I + A5
36 ± 12 (38) % Gypsum and calcite 0.42 g gypsum	12 ± 4 (15) % Calcite and gypsum 0.42 g gypsum

Figure 12. Drying rate evolutions for brick plus admixture setups.

The sensitivity assessment for gypsum efflorescence applied to brick powder, with and without the A3 admixture, always results in no gypsum pore clogging (except for a single case). It demonstrates that these bricks contain insufficient gypsum amounts (0.42–0.61 g per brick), which is not necessarily true for other commercial brick types, which may contain up to 7 g gypsum per brick, see also section ‘Clay brick’.

Discussion

The outcomes reported in the preceding ‘Gypsum efflorescence’ section allow arriving at a number of general findings in relation to the potential origins of and possible solutions for gypsum efflorescence on clay brick masonry facades.

The dissolution and efflorescence experiments on powders of clay brick and carbonated cement paste show that both brick and mortar can form the gypsum source: the brick via the dissolution of anhydrite, and the mortar through the carbonation of ettringite. The tested bricks and cements resulted in a wide spectrum of gypsum amounts, ranging from 0.4 to 3 g per brick. But none of the tested powders from clay brick or carbonated cement paste actually led to the abundant gypsum efflorescence formation that was observed in the field survey (Chwast et al., 2015). For the two tested bricks, both relatively low in anhydrite, this is attributed to an insufficient amount of gypsum to produce significant efflorescence. For the four tested cements, all a lot richer in gypsum, that is accredited to gypsum pore clogging preventing significant efflorescence. It therefore appears that the presence of a gypsum source in masonry is indeed a necessary but not a sufficient condition to yield significant gypsum efflorescence. Instead, gypsum shows a specific propensity for subsurface accumulation as subflorescence, which yields slight intergrain gypsum efflorescence at most.

Moreover, this gypsum subflorescence appears to hinder formation of other efflorescence types as well and hence it may be hypothesised that a sufficient gypsum content in masonry constituents might actually be preferred. This finds confirmation in the British experiences, where thousands of millions of bricks with high anhydrite content were produced and used for construction with no history of considerable surface blemish for more than a century (Bowler and Fisher, 1989; Bowler and Winter, 1996; Butterworth, 1957). Complementarily, gypsum formation in mortars could have taken place as long as cement has been used for their preparation, and in Belgium, pure cement mortars have been often used since the 1950s. In both cases, gypsum sources were present in masonry far earlier than the first alarms on gypsum efflorescence from 1980s in the United Kingdom and 1990s in Belgium. Gypsum’s propensity to subfloresce rather than effloresce may possibly explain the lack of gypsum efflorescence (or other persistent efflorescence types) on masonry over decades, regardless of their sources being present in either brick or mortar. Any effort to get rid of persistent efflorescence by diminishing the gypsum contents in brick or mortar may hence be counterproductive.

Instead, one should look at the mortar admixtures for the cause of and solution to the recent occurrences of gypsum efflorescence on masonry facades. In our assessments, significant gypsum efflorescence is never obtained for the normal masonry constituents, clay brick and cement mortar. Efflorescence coverages that resemble the abundant gypsum efflorescence from the field survey (Chwast et al., 2015) are only obtained when mortar admixtures are brought in. The results are not always consistent though: admixtures may lead to (in)significant gypsum efflorescence when mixed into a gypsum solution, while giving the reverse result when

made part of the cement paste. Nevertheless, it is shown clearly that the admixtures – in added form, like admixtures A1–A5, or in integrated manner, like in cement B5 – are most conceivably the sought ‘trigger’ for gypsum efflorescence. These findings are in line with the results from Bowler and Sharp (1998) and Bowler and Winter (1997), where gypsum efflorescence in their impregnation and drying lab tests and in their wallette field experiments was only found when admixtures were present. The role of admixtures is further supported by the fact that their increasing use, starting from the 1980s, coincides with the onset of gypsum efflorescence in both Belgium and the United Kingdom.

Solutions for the gypsum efflorescence problem should hence be sought in that corner. Unfortunately, there is no easy fix. The assessments above have shown that the impact of the admixture is case-dependent. While the tests with gypsum and admixture solutions clearly pointed towards the decreased surface tension as predictor for significant gypsum efflorescence, once embedded in a mortar, this no longer remains valid. Admixture A3, a surfactant, gives significant efflorescence in combination with a gypsum solution, while not yielding much efflorescence when mixed into the cement paste; the reverse is true for admixture A5, a superplasticiser. This implies that the sensitivity assessment for gypsum efflorescence needs to be performed on a case-by-case basis, wherein an actual cement and admixture are prepared together and tested. Only in this way can masonry mortars without risk for gypsum efflorescence be developed. And while it may be possible that the concrete superplasticisers – of which only a single product was evaluated here – are the way forward, one should keep in mind that sulphonate-based superplasticisers do not induce air entrainment (Mosquet, 2003) and thus cannot be considered as an air entrainer substitute to enhance the frost resistance of the cement mortar.

Conclusion

Over the last few decades, persistent gypsum efflorescence on masonry facades has become a growing problem in the United Kingdom, the Netherlands and Belgium. Since the 1980s, more and more recently erected masonry facades have started suffering from the lasting surface staining, much to the disappointment of building owners and brick producers. In this study, the possible origins of and solutions to this problem have been investigated.

The dissolution and efflorescence experiments on powders of clay brick and carbonated cement paste have shown that both may form a sizable gypsum source, although their gypsum release is probably a protracted process, due to the slow dissolution of anhydrite in brick, or because of the slow carbonation of ettringite in mortar. This may explain why gypsum efflorescence is commonly only observed a few years after facade erection. It has also been demonstrated that the presence of a gypsum source is not a sufficient condition for gypsum efflorescence: the tests on brick and cement paste powders only led to slight intergrain gypsum efflorescence, contrary to the abundant coverage typically observed in the field survey. This is one of the more significant findings of this study, since the efflorescence-free older

masonry facades demonstrate that avoiding the problem of gypsum efflorescence – and possibly other types of persistent efflorescence – in the future is possible. Significant gypsum efflorescence was only obtained when a trigger in the form of mortar admixtures was added. This may expound the more recent nature of gypsum efflorescence, as mortar admixtures have been becoming progressively more common since the 1980s. While their impact has been inconsistent, it has been made clear that they are the most plausible cause for the recent outbreak of gypsum efflorescence on masonry facades. Our study makes it finally clear hence that this problem can possibly be solved without limiting the gypsum sources in masonry, but rather through finding an inert replacement for mortar admixtures, thus nullifying the trigger for gypsum efflorescence on clay brick masonry.

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