

Efflorescence



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Abstract

Efflorescence in cementitious materials such as concrete or mortar is a challenging problem. This technical paper describes how various mechanisms and factors influence the formation of efflorescence, and gives general guidelines for minimising efflorescence, in particular through the use of admixtures. Generally, efflorescence results from the interactions of water migrating through the concrete and subsequently evaporating from its surface, salts within the water, and carbon dioxide and other atmospheric gases. It may create an undesirable appearance but rarely affects the mechanical properties or durability of the concrete. Many different types of efflorescence can be distinguished. However, the most relevant type of concern is efflorescence of calcium carbonate. All are formed by the same general mechanisms.

The formation of efflorescence is affected by many interacting factors, some of which may conflict. Efflorescence certainly can be reduced or even prevented by controlling water ingress, water migration through the concrete and evaporation during concreting and in the completed concrete structure or product, and by minimising its exposure to sources of soluble salts. The mechanisms and key factors for efflorescence formation are numerous and complex, so that complete solutions for specific types of concrete or application need to be discussed case by case with specialists in concrete technology. BASF's concrete specialists are ready to serve the market with latest technological know-how and a systematic approach to customer issues such as efflorescence.

1. General

«Efflorescence» is a surface defect of concrete which has more aesthetic rather than structural consequences. Basically, it is a crystalline deposit of salts (carbonates, sulphates, chlorides), usually white, that forms on or near the surface of concrete products (Figure 1). Efflorescence usually consists of carbonates of calcium, sodium and potassium originating from the cement, but can also consist of salts from the surrounding environment. Iron oxides from the concrete can give the efflorescence a yellow/brown tint.

The bulk of the various efflorescence types is calcium carbonate, also known as «lime bloom» or «lime weeping». Efflorescence forms when soluble salts are dissolved by water migrating through the material and then precipitated at its surface by chemical reaction or by evaporation of the salt solution.

«Primary efflorescence» is the first to appear. It develops as a whitish bloom or colour fade during setting and curing of the concrete. It involves the water used to mix the fresh concrete.

«Secondary efflorescence» develops later, sometimes even months later. It is related largely to outside water, for example from external sources like rain or groundwater travelling through the concrete, and may appear as a uniform discolouration or as localised encrustations where water exits the concrete.

«Cryptoflorescence» or «Subefflorescence» is salt crystallisations within the pore structure of the concrete. It forms below the surface and is not visible unless the crystal growth is sufficient to cause surface scaling.

Concrete producers frequently face this inconvenient topic with a general statement like «All concrete products may, in their early life, appear to lose some intensity of colour and experience a milky-white stain on the face of the product. This is efflorescence staining. It is a temporary phenomenon and is in no way detrimental to the performance of the material and responsibility cannot be accepted for its occurrence». As efflorescence is particularly noticeable on dark or coloured concrete, manufacturers of concrete products with prominent, decorative or architectural surfaces are continuously confronted with and put a lot of effort into solving the problem to increase their products' aesthetic appeal and to satisfy the requirements of their customers.

On dark or coloured concrete the effects of efflorescence are seen as colour modifications, for example in intensity and shade, varying over the surface and changing with time. In addition, dust and dirt from the surrounding environment can be stored in the salt solutions and trapped in efflorescence that subsequently forms from them, creating dirt streaks that highlight drainage patterns and that may be difficult to remove with normal cleaning methods. Efflorescence may also be stained by iron and other metal ions present in the salt solution.

Very small quantities of the salts need to be dissolved from hydrated cement paste to produce visible efflorescence, and in fact, removal of these amounts does not affect its integrity. Consequently efflorescence usually affects only the appearance of the concrete rather than its mechanical performance or durability. EN 1338:2003 «Concrete paving blocks» states «When efflorescence occurs, it is not deleterious to the performance of the blocks in use and is not considered significant.» However, some types of efflorescence can saponify oil-based paints, and large amounts of cryptoflorescence can cause surface spallings.



Figure 1
Concrete paving stones with efflorescence stains after stocking outdoor

Occasionally efflorescence may be a symptom of chemical reactions such as sulphate attack that affect concrete performance. Efflorescence may also indicate leaks in a water-retaining structure or undesirable passage of water through other structures that may lead to moisture problems, corrosion of metal components in the structure and decay of timber components. This paper does not consider efflorescence caused by chemical attack, or consequences of moisture movement through the structure other than the formation of efflorescence.

2. Mechanisms relevant for efflorescence formation

Efflorescence requires the presence of:

- soluble salts,
- water in contact with the salts forming a salt solution, and
- a passage allowing the salt solution to migrate to the surface of the concrete.

Efflorescence will not occur if just one of these components is eliminated. This is rarely possible, so the best approach is to minimise all three.

The mechanisms relevant for efflorescence formation are best described by discussing the chemical reactions and the physical processes involved under favourable conditions.

2.1. Chemical reactions

Efflorescence is mainly caused by carbonates of calcium. These are the products of chemical reactions between atmospheric carbon dioxide and hydroxides of calcium from the cement hydration process that are dissolved in the pore water.

The reaction that produces insoluble calcium carbonate (CaCO_3) is the same as the reaction known as carbonation, whereby carbon dioxide (CO_2) from the atmosphere reacts with calcium hydroxide (Ca(OH)_2), both dissolved in water:



The reaction may happen in the salt solution in the pores of the concrete, but if evaporation rates are fast enough calcium hydroxide precipitates on the concrete surface and subsequently reacts with dissolved carbon dioxide in water when sufficient moisture becomes available. Calcium dioxide reacts only if dissolved in water.

Calcium carbonate appears as a white bloom diffused over particular areas or as a hard white crust. It forms as primary efflorescence when premature drying interrupts cement hydration and the concrete is subsequently wetted. It forms as secondary efflorescence as water from an external source migrates through the concrete and evaporates from its surface. It is almost insoluble in water and can be difficult to remove. It is the cause of most efflorescence problems.

Other salts that may produce efflorescence include sulphates of sodium, potassium, magnesium, calcium and iron; sodium bicarbonate, sodium silicate and indeed almost any other soluble salt such as chloride or nitrate that is found in concrete, masonry or in its surroundings. Sodium and potassium carbonates and bicarbonates are soft, white and fluffy. These salts and chloride salts are highly soluble and may be washed off by rain. Very small amounts of insoluble iron oxide and iron hydroxide cause visible yellow/brown discolouration of the concrete surface, which cannot be washed off.

2.2. Physical processes

Efflorescence involves the transport of water and dissolved salts within, through the pores of the concrete to its exposed surface, and the subsequent precipitation of the solid product formed by the reaction between salts and carbon dioxide dissolved in the pore solution. These processes shall now be described in more detail.

Transport of water and salts: Liquid water movement through the concrete pore structure (Figure 2) or ion transport through the pore solution can be driven by capillary suction, hydrostatic pressure, concentration gradients or gravity.

Gel pores are of nm dimension and occupy approximately 28 % of the gel volume as part of the hardened cement paste. Gel pores show open porosity and are, in normal moisture conditions, filled with water which does not freeze and has a low diffusion coefficient. Capillary pores in contrary are of μm size; their volume depends on the degree of hydration, they show open or close porosity and are empty in normal moisture conditions. They can be filled by capillary raise and water easily diffuses or freezes in them.

Usually more than one driving force influences the migration process through concrete. In a few situations capillary forces dominate drying of a horizontal surface in the absence of an external moisture source. Here, in the partly dry concrete, water (and the salts dissolved within) is drawn towards the exposed surface through open capillary pores less than $10\ \mu\text{m}$ in diameter. The finer these capillaries are, the stronger the surface tension of the water in them, and consequently the rate of moisture transfer by capillary suction will be faster (Figure 3). In contrast, the rate of water transfer through saturated concrete by pressure, concentration gradient, or gravity (i.e. the «permeability» of the concrete) is reduced by finer capillaries. The finer the capillaries the more easily they are blocked by the products of cement hydration or efflorescence.

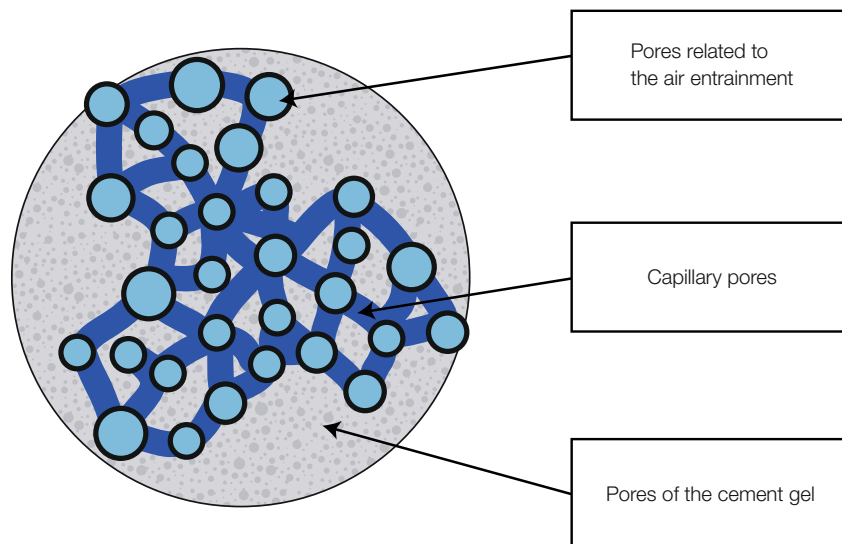


Figure 2
Pore structure in concrete

However, concretes with very fine pores may be more prone to efflorescence at early ages if allowed to dry before the pores become blocked. Water migrates through concrete by a combination of vapour and liquid diffusion. The relative significance of these two mechanisms varies with pore size and moisture content. Movement through large pores is predominantly by vapour diffusion until the concrete is almost saturated (internal relative humidity greater than 95%). In capillaries, liquid diffusion is significant at internal relative humidities as low as 45 %. Salts are not transported by vapour diffusion, so large pores do not necessarily increase the risk of efflorescence unless the concrete is almost saturated.

Evaporation: The position of the water/air interface at which water evaporates and efflorescence forms is called the «evaporation front» (Figure 4). Water movement through capillaries can bring the evaporation front close to the concrete surface, where efflorescence will be highly visible. The free water surface in larger pores tends to be below the surface of the concrete, where efflorescence may be less visible but may cause surface scaling if sufficiently extensive. With fast evaporation rates, the evaporation front may be below the surface of the concrete. When evaporation is slow, the evaporation front is closer to concrete surface, resulting in more visible efflorescence.

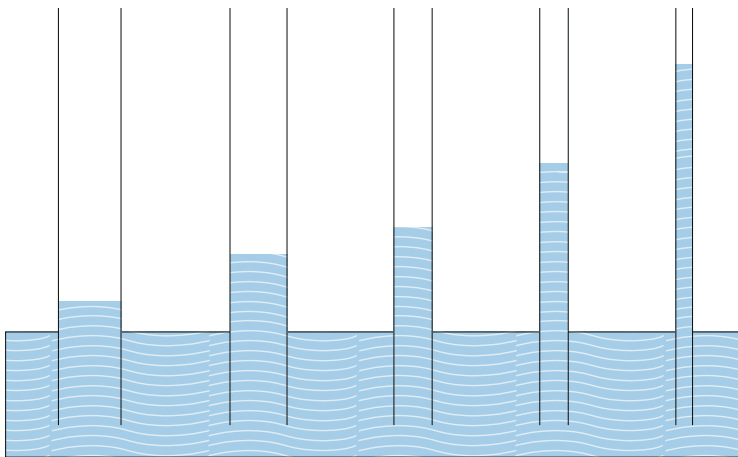


Figure 3

The effect of capillary suction; the finer the tube the stronger the surface tension of water, the faster the moisture transfer. However, the resistance to moisture transfer (permeability) by pressure, diffusion or gravity is increased.

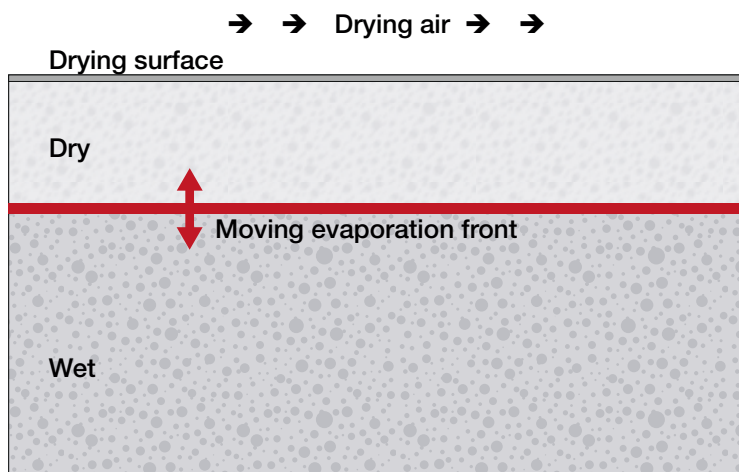


Figure 4

Efflorescence forms at the evaporation front.

Reaction with carbon dioxide: When concrete is water saturated or close to saturated, the dissolved salts react with dissolved carbon dioxide at the exposed surface, producing visible efflorescence. When the concrete is partly dry the efflorescence may develop slightly below the concrete surface. In this way formation of insoluble calcium carbonate below the surface may block pores and reduce subsequent efflorescence. When concrete dries rapidly, calcium hydroxide may precipitate within the pores but lack of water prevents

the formation of calcium carbonate. When the concrete is subsequently wetted, the risk of efflorescence is considerable as the calcium hydroxide redissolves, reacts with the carbon dioxide and precipitates as calcium carbonate at the surface. With decreasing temperatures the solubility of CO_2 in water increases significantly, so efflorescence is likely to be more severe in cold climates.

Salt crystallisation: A salt will only precipitate from solution if the pore water is supersaturated. The concentration of a particular salt depends on temperature and on evaporation rate as well as the supply of water and the salt. Concrete pore water is usually saturated with calcium hydroxide because there is a plentiful supply of it from the cement and it is not highly soluble (typically 1.2 g of CaO per litre; decreasing with increasing temperature – from 1.30 g/l at 0 °C to 1.13 g/l at 25 °C; see also Figure 5).

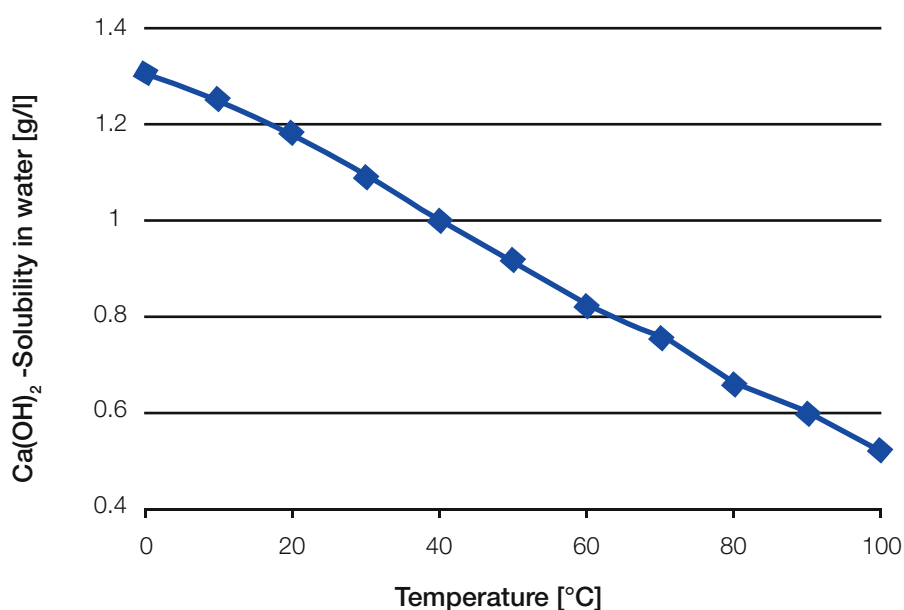


Figure 5

Water solubility of calcium hydroxide Ca(OH)_2 in dependence of temperature. The colder the temperature the more material can be dissolved in the pore solution.

3. Factors affecting efflorescence

Efflorescence usually results from a combination of factors rather than having a single cause. The following section describes how features of [concrete materials](#), [concreting practice](#) and [service environment](#) influence the chemical reactions and physical processes that cause efflorescence.

3.1. Concrete materials

[Cement](#) is the principle source of soluble salts. High alkali cement may increase the risk of efflorescence because the concrete pore solution contains more sodium and potassium hydroxide, which not only increases the amount of salt available but also increases the solubility of carbon dioxide in the pore solution (Figure 6). Rapid hardening cement may also be more prone to efflorescence. White cement is more prone to calcium carbonate efflorescence but its lower alkali content makes it less susceptible to soluble efflorescence, and it contains a little amount of iron to cause iron discolouration. High alumina cement does not produce calcium hydroxide when it hydrates therefore it does not cause efflorescence. Cement composition may contribute to iron discolouration of efflorescence. Despite these effects, overall the brand or type of Portland cement has less effect on efflorescence than the cement content of the concrete.

[Limestone](#) is an extra source of calcium hydroxide and may contain up to 0.7 % soluble salt. Unhydrated and partly hydrated limes are more soluble and therefore present a greater risk of efflorescence.

[Pozzolans](#) in larger quantity consume calcium hydroxide and so reduce efflorescence, providing they do not contain significant amounts of water-soluble alkali or sulphate. They also produce a finer pore structure, which will reduce water permeability but may increase capillary suction, especially at early ages. Slower-reacting pozzolans such as fly ash mitigate against secondary efflorescence. Ground Granulated Blastfurnace Slag (GGBS), while strictly speaking not a pozzolan, has the same effect since its hydration doesn't produce calcium hydroxide. High-reactivity pozzolans such as metakaolin or microsilica will normally not only provide more strength but also prevent primary efflorescence when used at about 15 % cement replacement.

[Pigments](#) may introduce extra salts, increasing the risk of efflorescence. Particulate pigments act as fine fillers, reducing water permeability but possibly increasing capillary suction. Pigments generally create a colour contrast which increases the visual effect of efflorescence.

[Aggregates](#) may increase the risk of efflorescence, for example when contaminated with sea salts or when containing soluble sulphates, such as expanded clay/shale or sulphides, which subsequently oxidise such as GGBS.

[Water](#) complying with standard requirements should not contain significant amounts of soluble salts or other materials that would promote efflorescence. The soluble salt content of recycled wash water is higher than that of potable water, and is not easy to manage. Recycled wash water is therefore not recommended for use in applications where efflorescence appearance is critical.

[Water content](#) of fresh concrete will influence the formation of primary efflorescence because the lower the water content for a given water to cement ratio, the less water there is to migrate to the concrete surface.

[Water to cement ratio \(w/c\)](#) determines the shape, size distribution, volume and continuity of pores in the hardened cement paste (Figure 7), which in turn influences the volume and rate of water and salt transfer. The lower the w/c ratio, the finer and less continuous the pores. If they are continuous their reduced diameter will increase capillary suction. Low water to cement ratio may therefore increase primary efflorescence if the concrete is not cured properly.



Figure 6
Low alkali cement reduces the risk of efflorescence

Low water to cement ratios reduce secondary efflorescence because the pores are finer and can be blocked by products of hydration or primary efflorescence, but the efflorescence that does form will tend to be close to the exposed surface.

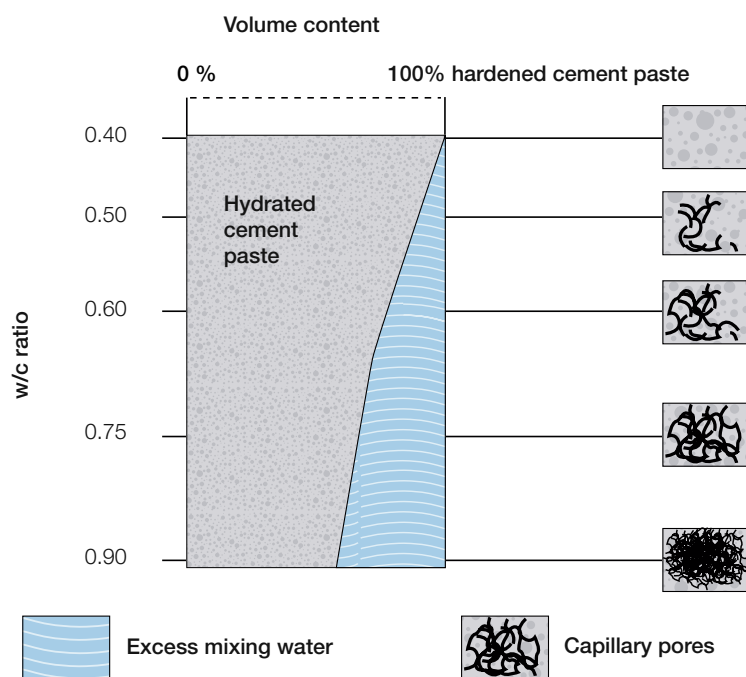


Figure 7
Capillary structure relies heavily on w/c ratio.

[Admixtures](#) may influence efflorescence depending on their composition, how they are used and, of course, the dominant water transport mechanism. Specific efflorescence control admixtures are discussed below.

3.2. Concreting practice

A [concrete mix design](#) that optimises the aggregate grading to allow the minimum binder content for the required workability and hardened concrete performance, and which minimises the water content and water to cement ratio, will minimise efflorescence by reducing capillary suction and the permeability of the concrete.

Variable [concrete quality](#) resulting from incomplete mixing or inconsistent compaction or curing may cause localised areas of efflorescence.

Only the correct [mixing sequence](#) of admixtures, pozzolans and pigments added in concrete batching ensures they are fully dispersed in the cement paste. The sequence will depend on type and form of the admixture, pozzolan or pigment, the type of concrete and the mixing process. If the concrete is not properly mixed the pore structure will not be uniform. Colour and efflorescence may then vary over the finished surface.

Adequate [compaction](#) and [finishing](#) of the concrete must be enabled to dissipate large voids that reduce its strength. Too much compactive effort, however, can increase the water content and water to cement ratio at formed and unformed surfaces, making them more susceptible to primary and secondary efflorescence. Overworking an unformed surface during finishing, or floating it while the concrete might be bleeding, will have the same effect. Permeable formwork liners may help to reduce this effect on formed surfaces by absorbing excess water. It is important therefore that concrete workability, compaction and finishing methods be optimised. For prefabricated concrete products, different materials, mix designs and production equipment will require different operating procedures.

[Curing](#) aims to retain the mixing water in the concrete (Figure 8). This is to ensure that the cement best hydrates to provide adequate strength and resistance to moisture transfer. Young concrete is relatively porous and permeable, and when water evaporates from its surface it is quickly replaced by mixing water from within the concrete, producing a layer of calcium carbonate efflorescence at the surface that can give the concrete a very light colour. This efflorescence blocks surface pores, preventing the subsequent ingress of curing water that is needed to replace the evaporated mixing water used to hydrate the cement. Concrete exposed to such premature drying will not gain strength fully and will remain relatively permeable beneath the layer of efflorescence. In young concrete that has been properly cured, water lost by evaporation can not be replaced by water from deeper within the concrete because the pores are less continuous. Evaporation and formation of efflorescence then takes place below the concrete surface, and the concrete retains a grey colour.

Conditions prior to curing, particularly of semi-dry concrete units, are critical. At this stage the concrete is porous and permeable and so both dries and absorbs water quickly, making it highly prone to efflorescence if allowed to dry. Drying is exacerbated by exposure to sun and wind.

Curing temperature is less important than humidity, although cool temperatures will prolong setting, bleeding and hardening and may therefore increase primary efflorescence, particularly at high humidities where water may condense on the concrete surface. Curing at a humidity of less than 65 % RH increases the risk of efflorescence. Exposure to condensation and runoff during curing increases the risk of localised efflorescence spots, patches and runs. Curing at 80–95 % humidity is believed to be the optimum to protect against efflorescence, although it may not be as effective for the development of strength and water resistance as curing at higher humidity or in water.

Curing in a carbon dioxide-rich atmosphere (more than 5 %) reduces efflorescence by converting calcium hydroxide to calcium carbonate. This blocks the concrete pores at or near the surface, thereby reducing the evaporation of pore water and the ingress of carbon dioxide and producing a uniform surface appearance.

Steam curing can reduce efflorescence, particularly if the concrete contains pozzolan, because the amount of free calcium hydroxide in the hardened cement paste is reduced. Higher temperatures are more effective. The air in steam curing chambers should be kept saturated while concrete units are loaded.



Figure 8

Curing chamber for paving stones. Careful design of the curing conditions has a major impact on the formation of efflorescence.

3.3. Service environment

Moisture: Rain and run-off is the primary source of moisture in concrete above ground. Groundwater is a common source in basements, retaining walls and foundations. Condensation can also provide enough moisture for efflorescence. Early exposure to an external water source increases efflorescence (Figure 9), whereas curing at constant high humidity without condensation maintains internal moisture at a constant level and minimises the permeability of the hydrated cement paste, thereby reducing efflorescence. Defects that direct water and runoff onto the concrete surface and provide a means of ingress into the concrete will increase efflorescence during service. These include inadequate detailing for moisture control; leaky gutters and downpipes; poorly filled mortar joints; cracks and permeable concrete. Efflorescence caused by such defects will tend to be localised where the water touches the concrete surface or evaporates from it.

Weather conditions: At lower temperatures evaporation rates are slow, allowing pore solutions to reach the surface of the concrete before evaporating, and as calcium hydroxide is more soluble the pore solution contains more calcium hydroxide. These features increase visible efflorescence during or immediately after cooler temperatures. At warmer temperatures, evaporation rates are faster and, depending on the rate of water migration, pore solutions may evaporate beneath the concrete surface where the efflorescence formed will be less visible. Higher wind speed will increase evaporation rates for given temperatures and humidities, possibly to the extent, where evaporation occurs below the concrete surface. Still, cold days therefore present the highest risk for visible efflorescence to be produced, particularly if moisture condenses on the concrete surface. As a result, efflorescence may appear as a seasonal or cyclical effect.

External salt: The development of efflorescence will eventually stop unless there is an external source of soluble salts. This may be from a natural source, for example salts in seawater, sea spray or groundwater, or from an industrial source, for example chemicals in contact with the concrete, sulphates from industrial fumes or carbon dioxide from fuel burning. Salts may also be sourced from leaks in piped services, or from infill grout or insulation panels in contact with the concrete and a moisture source such as a leak.

Cleaning materials: Caustic soda, washing soda, soda ash, scouring powders and some detergents used in routine cleaning and maintenance may contribute to efflorescence.



Figure 9

Weathering conditions influence the probability of efflorescence formation. Proper protection during outdoor stocking can reduce weathering effects.

4. Fighting efflorescence (after formation)

To identify an appropriate means of removing efflorescence and preventing its recurrence, its cause must be known. For example, concrete may need to be isolated from soil or groundwater to prevent the crystallisation of sulphate salts, or a leak may need to be repaired. The composition of the efflorescence should be identified if the concrete is in contact with an external source of salts, because it may indicate chemical reactions that affect the concrete's durability. The primary example of this is sodium sulphate, which can attack hydrated cement paste, and can cause surface scaling as its crystal form changes with changes in temperature and humidity.

Efflorescence regularly dissipates in time, in particular calcium carbonate further reacts with carbon dioxide and water to form calcium hydrogen carbonate, which is soluble and easily removed by water (rain, flushing). Primary efflorescence may eventually be dissolved from exposed surfaces by rainwater, which is slightly acidic, and by normal abrasion.

If desired, efflorescence can also be removed (Figure 10) with chemical or mechanical tools.

4.1. Chemical removal

Diluted acid is effective, especially on calcium carbonate, but may alter the surface colour and texture.

Hydrochloric (muriatic) acid diluted 1 part acid to at least 10 parts water is suitable for general concrete cleaning, provided it does not contact any metal components. For coloured concrete a 1 : 50 solution should be used to avoid excess etching that may expose the aggregate and change the concrete's surface colour and texture.

The concrete is wetted with water, the acid is then brushed in and allowed to react for up to five minutes, and rinsed off with plenty of clean water (check the wash water with pH indicator paper to make sure all acid is removed). Surfaces to be painted should be neutralised by washing with 10 % ammonia or potassium hydroxide solutions, or allowed to weather for at least a month before painting. Treatment of a trial area is recommended before treating the entire surface. Only small areas should be treated at a time. Multiple washings with a higher dilution of acid are less likely to etch the surface than one washing with a higher acid concentration. Acetic acid, citric acid, phosphoric acid and acid-based proprietary cleaners are also suitable.

4.2. Mechanical tools

Fresh deposits of water-soluble efflorescence can be removed with a stiff bristle brush. The loosened material from the concrete and surrounding surfaces shall be removed with a vacuum cleaner. Repeated dry brushing as deposits appear is likely to be the most effective treatment. Wet brushing may work if dry brushing is ineffective, but washing with water may result in salt redepositing when the water evaporates.

Efflorescence that is not soluble in water, such as calcium carbonate, may be removed by high pressure water jetting, possibly adding fine sand to the stream. Light sand blasting may also be effective but may alter the surface texture so the whole surface needs to be treated.

If the composition of the efflorescence is unknown, washing with acid as for insoluble efflorescence is usually effective, although it may be preferable to first try dry- or wet-brushing.



Figure 10
Chemical or mechanical removal of efflorescence should be conducted carefully to avoid surface damage.

5. Fighting efflorescence (before formation)

Efflorescence requires the presence of soluble salts, water, and a passage of water through the concrete. The combination of mechanisms and factors influencing efflorescence differs for every combination of concrete age, materials, mix design, application and exposure condition.

It is not possible to provide simple rules that will prevent efflorescence in all circumstances. The following guidelines, however, will help to reduce the risk of efflorescence formation. The general principle is to minimise free soluble salts from raw materials, to minimise concrete permeability and to minimise the concrete's exposure to wetting and drying cycles. The use of specific admixtures can support all three aspects as described at the end of this paper.

Raw materials should contain as few soluble salts as possible. Marine-sourced aggregates should be avoided or washed. Low alkali cement is preferable, above all low alkali sulphate cement. Composite cements containing pozzolanic materials are recommended. Reduce clinker (main Ca(OH)_3 source) as much as possible. Mixing water should be free from significant quantities of salts that may cause efflorescence. Seawater should not be used. Keep tools and equipment clean and free from rust and salt.

Concrete permeability should be as low as possible (Figure 11). This means using aggregates graded to minimise their voids content and sufficient cementitious binder (possibly containing a pozzolan), ensuring low water content and water to cement ratio and effective but not excessive compaction, producing a dense impermeable surface finish, and curing at appropriate temperature and humidity to ensure adequate cement hydration without exposing the concrete surface to uneven moisture conditions, drips or condensation. High binder contents may, however, result in higher water contents, which may increase the risk of shrinkage and affect masonry surface finish. In manufactured concrete products, very low water to cement ratios may reduce primary efflorescence but increase secondary efflorescence unless water content and compaction are optimised to minimise voids.

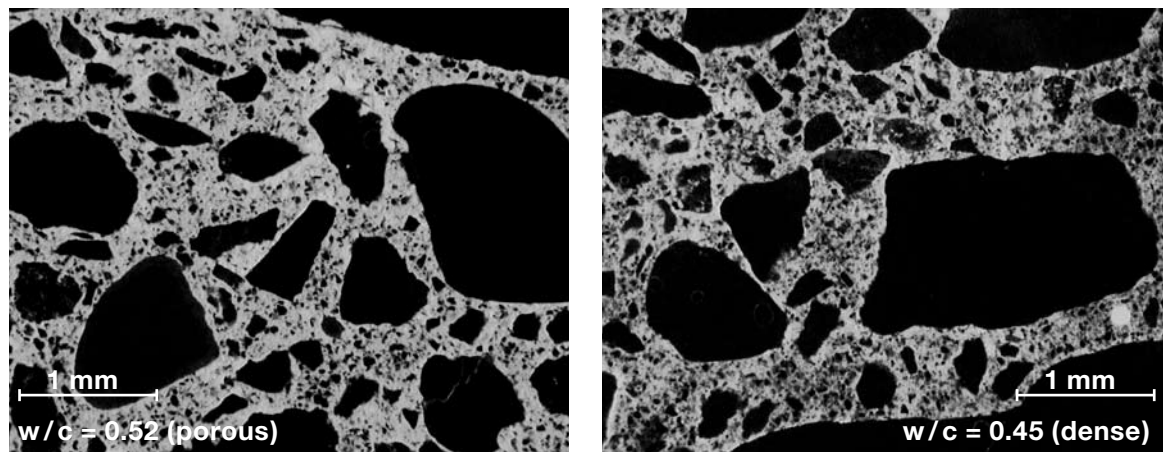


Figure 11

Increased compaction by efflorescence control admixtures. Less porosity means less migration of water (vehicle for salts).

Before curing, concrete should not be allowed to dry, for example by exposure to wind or high temperature. Concrete should be cured for as long as possible using methods appropriate for the application and for the desired quality of surface finish. Curing by plastic covering is not recommended where aesthetics are important because it can produce uneven surface moisture conditions or condensation that result in uneven colouring or efflorescence. Curing at 20 °C and a minimum of 80 % relative humidity (RH) reduces efflorescence. Chambers used for curing, including steam curing chambers, should be designed and operated to avoid condensation and run-off. They should have a means of keeping units damp before curing begins, for example by fog spray. Carbon dioxide curing reduces efflorescence, although it is the most expensive variant.

Storage after curing needs to maintain uniform temperature and humidity inside the concrete to minimise efflorescence. Manufactured concrete products should be stacked on pallets on a well-drained surface after curing, in transit and while stored on site (Figure 12). The stacked units should be protected from rain and rapid drying. Under such waterproof covers air should be able to circulate uniformly between the units as much as possible to prevent localised drying or condensation and runoff.

Surface treatments with a water repellent before exposure to moisture will reduce efflorescence and is recommended for coloured concrete and other architectural finishes where colour change or efflorescence would be unacceptable. If necessary, the surface should be cleaned when curing is completed then the surface treatment applied according to the manufacturer's directions. Effectiveness of the surface treatment will depend on concrete permeability and quality of curing. Surface treatments for surfaces exposed to moisture should be permeable to water vapour to allow water in the concrete to evaporate.

On substrates that contain large amounts of soluble salts or which are subject to significant ingress of moisture from the opposite surface, vapour permeable surface treatments may cause localised salt concentration and crystallisation beneath the treated surface leading to surface flaking or spalling, particularly in porous or soft concrete products. Water-resistant and vapour-proof polyurethane or epoxy could be used on such surfaces.

Moisture control in service is the key to reducing efflorescence. Moisture transfer inside and out of the concrete is essential for efflorescence formation. Therefore, concrete should be protected from wetting and drying during construction. The top of each course of masonry should be covered at the end of each day to protect from rain or dew. Design should include adequate detailing for joint sealants, flashings, waterstops, dampproofing, weepholes, dripformers, copings and sills, and these should be properly installed and maintained. Eaves will protect walls and openings from moisture.

Horizontal surfaces such as floors, roofs and parapets must allow water to drain from them. Pavement sub-bases and bedding layers should be well drained, without drainage being blocked by perimeter strips or mortared-in features. Exterior walls should be designed to equalise internal and external vapour pressures, or be lined with vapour barriers, or the interior surfaces coated with paint that is impermeable to water vapour. Cavity walls should be designed to minimise condensation. Cracked or permeable concrete and damaged moisture control details and appendages must be repaired.



Figure 12

Double layer paving slabs stocked stacked outside after curing; top side faces not in contact with core concrete, air ventilation between slabs enabled while the full palette is protected with a plastic cover from rain and rapid drying.

6. Evaluation of efflorescence

A prerequisite for any quantitative, comparative evaluation of efflorescence is the ability to test reliable specimens, i.e. their quality must be of reasonable reproducibility and close to real plant results. The specimen treatment also requires defined conditions. Last but not least, the evaluation instrument needs to operate repeatedly and with suitable resolution to discriminate relevant changes.

BASF has developed the unique Production Efficiency Method (PEM) for highly reproducible dry concrete specimens with excellent correlation to manufactured concrete products such as paving stones, grey blocks, concrete tiles, instant demoulded pipes, sleepers and hollow core slabs. Based on these specimens, various treatments, e.g. accelerated efflorescence formation, can be applied. Methods to accelerate efflorescence formation are:

- Puddle test
- Wicking test
- Spray test
- Wet-dry cycling
- Weathering test
- Wrapping test

Under these defined conditions property changes of the specimens, especially changes in efflorescence formation, can be compared. Visual inspection of the specimens before and after treatment gives a first indication of how strong their potential is to form efflorescence. Assuming that relative performances of corresponding materials in laboratory testing may be maintained in service, the following quantitative tests are useful for evaluation:

- Measurement of salt content, e.g. by special sample treatment, by X-ray investigations and other analytical methods
- Measurement of concrete density
- Measurement of concrete absorption
- Measurement of concrete permeability
- Measurement of concrete sorptivity
- Measurement of concrete brightness/lightness

The last method is closest to reflecting the human impression of efflorescence. It measures the colour or brightness/lightness change on a concrete surface caused by the formation of efflorescence. A suitable colour spectrophotometer is used for this purpose that allows the relevant parameters to be determined according to the international system CIE $L^*a^*b^*$ (Figure 13).

These tests provide a way of comparing the efflorescence potential of different concretes. They cannot be specified or used as acceptance tests, because the formation of efflorescence on concrete in service will be determined by the conditions it is exposed to rather than the results of a laboratory test, and because the history of samples prior to test cannot be controlled and will influence the test results.

These tests are sensitive to the age of the concrete and to the evaporation rate (temperature, humidity and air flow), so are best suited for comparing materials of the same age at the same time or under tightly controlled laboratory conditions. Measurement of density and absorption are the least favoured methods because they do not account for resistance to water migration, which is a major factor in efflorescence formation.

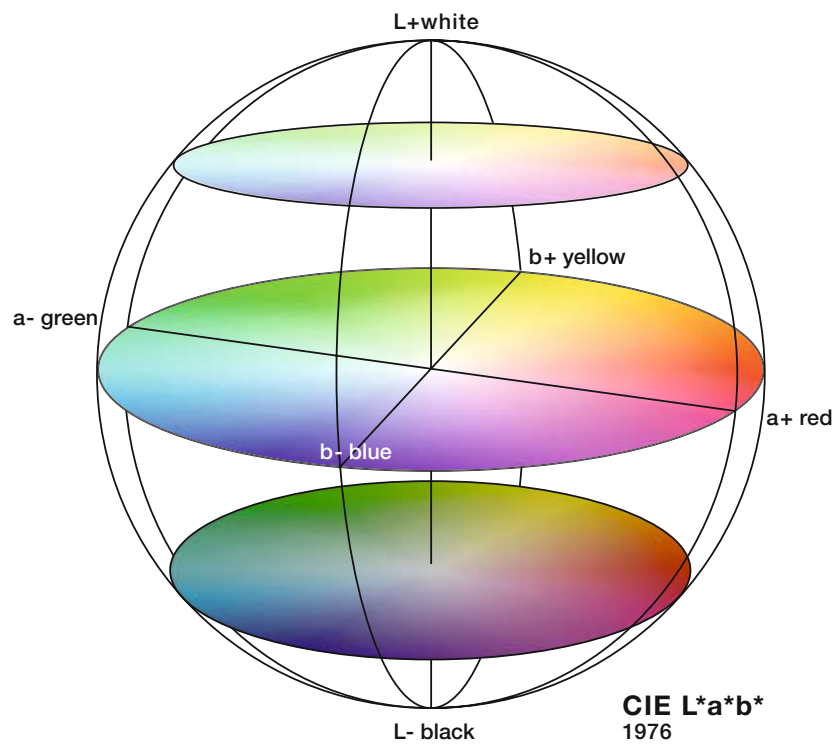


Figure 13

Handheld colour photospectrometer by BYK-Gardner – the appearance of efflorescence can be quantified in terms of brightness/lightness change over time based on the CIE L*a*b* system.

7. Efflorescence control by admixtures

Admixtures for concrete are materials other than water, aggregates and cementitious materials used as an ingredient for concrete, and added to the batch in controlled amounts immediately before or during its mixing to produce some desired modification to the properties of fresh and hardened concrete. Efflorescence control admixtures in particular are designed to fight efflorescence before it forms (Figure 14).

Admixtures may be used to improve concrete compaction, for example by reducing its porosity (capillary pores) and water permeability in general, but also allow the optimisation of the water/cement ratio while maintaining the required processability of the concrete. Water reducers and other admixtures that are able to retain or to release water can act in this way, but should not contain large amounts of highly soluble ions such as sodium, potassium, chloride or sulphate. Surfactants in particular contribute to an improved rheology and compaction in no-slump concretes by positively affecting the tribology between the mix partners. However, during mixing the entrainment of air must be controlled.

Admixtures such as integral curing agents or waterproofing agents may be effective against efflorescence thanks to the hydrophobisation of all surfaces (inside and outside) or capillary stabilisation, provided that their soluble salt content is low and they do not entrain excess air when the concrete is mixed. By avoiding the evaporation of the mixing water and stopping ingress of external water, they strongly affect the relevant material transport mechanisms of concrete.

For example, integral water repellents such as stearates and silicones reduce capillary suction but have little effect on water permeability, so they may reduce primary efflorescence caused by premature drying, but will not reduce efflorescence caused by transfer of water under gravity or pressure. On the other hand, water-reducing admixtures and integral waterproofers (based on cement and other particulates) used to create a finer pore structure may reduce water permeability, but not capillary suction.

Admixtures containing sodium and potassium may increase the risk of soluble efflorescence. Admixtures affect the pore structure of the hardened cement paste, and can make it more or less resistant to the movement of water depending on the concrete mix design.

The most advanced admixture technology has developed specific polymers suitable to chemically stabilise the pore network, for example by ion sequestering. Optimising polymer parameters like trunk chain length, side chain length, side chain and packing density and molecular charging provide new possibilities to actively influence the pore surface of concrete on a nanoscale level.

Once the concrete is optimised for its purpose from a mix design perspective, protecting the product from external influences after concreting is still possible, for example by surface treatment with impregnations, coatings or sealants. Silanes, siloxanes and silicones are suitable water repellents for surfaces exposed to moisture. Siloxanes and silicones are bigger molecules and are more suited for porous materials such as pavers and architectural blocks, especially as they have lower evaporation pressure and are able to penetrate the surface easily and sufficiently to provide long-lasting protection. Film-forming treatments must be impermeable to carbon dioxide. Acrylic emulsions and solvent-based solutions are suitable, too.



Figure 14
Efflorescence control by admixture use

8. BASF – Adding Value to Concrete

The risk of efflorescence can be reduced remarkably, if general principles discussed here are taken in consideration and are optimised for each application. BASF Construction Chemicals approaches the topic from two directions: firstly optimising the mix design and secondly using a suitable efflorescence control admixture (Figure 15). This combination provides the power to prevent efflorescence formation from the start and to minimise its disturbing appearance in a sustainable way.

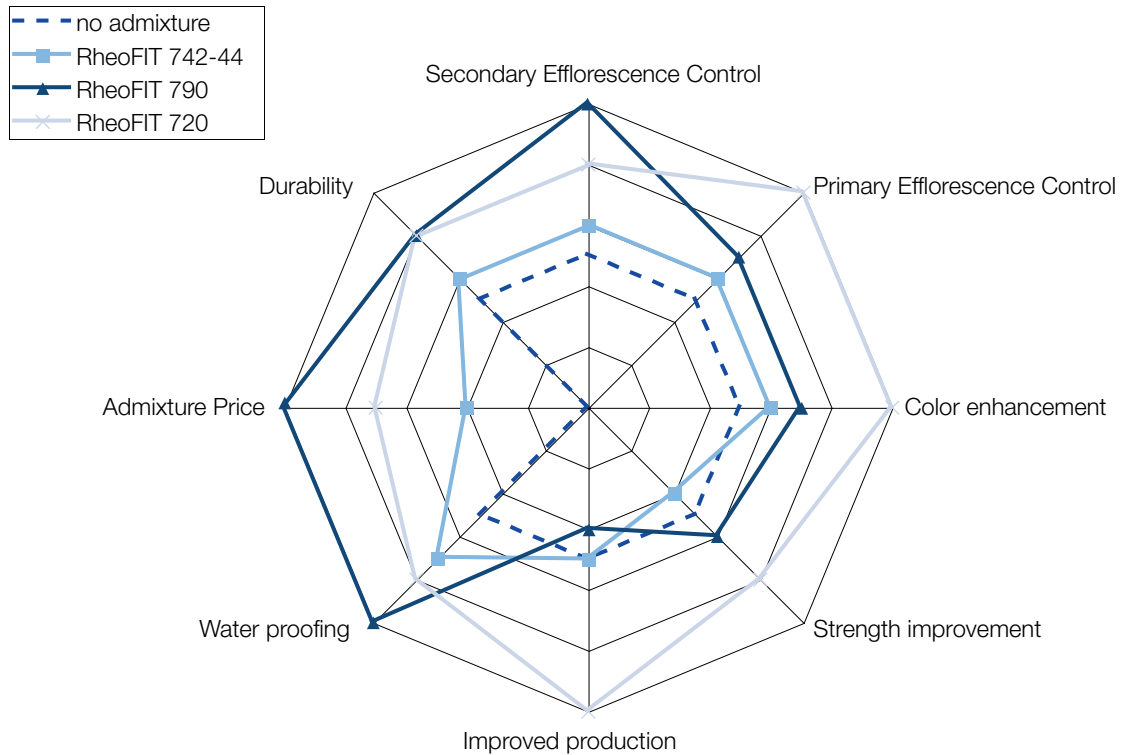


Figure 15

Added value by BASF Efflorescence Control products compared to concrete without admixture use

BASF Construction Chemicals is a leading provider of innovative chemical admixtures for concrete. Manufacturers of concrete products such as pavers, architectural blocks and landscaping stones are particularly affected by efflorescence problems. The answer to the industry's need is known as the FIT 4 VALUE concept (Figure 16), where all process steps leading to high-quality products are addressed by considering the four elements essential for manufacturers of concrete products:

- FIT for economics
- FIT for performance
- FIT for aesthetics
- FIT for durability

Here, FIT means meeting every requirement for economics, performance, aesthetics and durability. RheoFIT products are specifically engineered to optimise mix design, to enhance tolerance to mixing water, to boost the production process, to extend durability of concrete products and especially to maximise their aesthetic appeal, in particular in terms of efflorescence control.

A unique advantage for industrial partners is given by the clear customer-based approach of the FIT 4 VALUE concept. In a systematic project realisation the exclusively developed BASF Production Efficiency Method plays a central role, as the reliable simulation of the production process of the manufactured concrete products industry is achieved. The combination of this evaluation method with extensive admixture expertise enables BASF experts to offer the most advantageous admixture product for concrete mix optimisation and

ultimate efflorescence control. This innovation corresponds with BASF's typical drive for technological development and the desire to work in partnership with manufactured concrete products manufacturers.

For further information or assistance, please do not hesitate to get in contact with BASF experts;
www.basf.com, info-ase@basf.com.



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