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Phenomenological Simulation of Efflorescence in Brick Constructions

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Abstract
In human constructions, repetitive patterns can be handled by different texturing methods. However, almost all techniques do not consider weathering phenomena, missing a very important visual effect for realistic rendering. Among a great number of weathering effects occurring on constructions - in particular on fired-clay brick walls - efflorescence implies important visual changes and their removal (surface cleaning) is an economic problem in numerous countries. Due to the complexity of the physics involved, we propose in this paper an original phenomenological simulation of this weathering process on fired-clay bricks. In this case, efflorescence is materialized by a thin white powdery deposit of water-soluble salts on the surface or in the pores of masonry. We propose a method to generate the texture of efflorescence-affected fired-clay brick. First, we synthesize a brick solid texture from digital photographs using a classical solid texturing technique. Then, we add efflorescence by a phenomenological algorithm representing salt transport and crystallization in porous building materials for each brick separately. We can build aged walls by changing the parameters of efflorescence for each brick.
Key words : natural phenomena, weathering phenomena, efflorescence, 3D texture synthesis

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1. Introduction

In human constructions, repetitive patterns can be handled by procedural textures or by specific image-based techniques [LP00]. Computer synthesized images often look too smooth, too perfect, and too clean to be considered realistic. To solve this problem, a great number of phenomena such as dirt and dust accumulations, cracks, scratches must be taken into account. These phenomena can appear with different shapes, affecting geometry and/or light reflection properties and/or textures. This issue is actually more and more investigated in computer graphics by using new techniques in both modeling and rendering fields. One can group these techniques into two main categories:

- Global techniques: try to provide generic methods to take into account different weathering phenomena. With these methods, the control parameters do not depend on the physical characteristics of the modeled phenomena (like in [CDM*02] for example)
- Specialized techniques: focus on specific weathering processes. They can be empiric as well as physically valid, providing more precise control parameters, but restricted to one class of defects (like in [BMPG04] for example).

Figure 1: *Walls affected by efflorescence*

This paper belongs to the second group, focusing on an important but specific defect: physically plausible efflorescence. This phenomenon is composed of different physical and cheminal steps: wetting and drying processes through porosity, crystallization, chemical compounds and their dissolution among others [BN04]. In order to propose a model accounting for this weathering process without using too many and difficult-to-handle parameters, we propose to build a phenomenological model. It permits to obtain physically plausible results with only a few intuitive parameters.
Fired-clay bricks and masonry exposed to the environment are attacked by atmospheric contaminants such as carbon oxides, sulfur and nitrogen existing in rain (acid rain for

example). These liquids are not confined to the surfaces of objects but penetrate inside them at some distance, because construction materials such as fired-clay bricks are porous ([PKBL95]). The full effects of fired-clay bricks weathering include color changes, formation of dirty crusts, formation of efflorescence, erosion of surfaces and structural damages such as cracking. This paper specifically focuses on formation of efflorescence, due to their great visual importance (see figure 1).

A solid texture is a function that returns a color value at any given point in 3D space [DG01]. Solid textures are ideal for simulating materials such as wood or marble but can also be very efficient to deal with surface and volume modifications of objects colors. The nature of efflorescence is volumic: water infiltration propagates this effect even deeply inside the brick [Ahl03]. Moreover, a 3D knowledge of efflorescenced parts will be useful to account for other weathering processes, in particular induced by this specific defect (please see future work in section 6). As a first approximation, a classical texture mapping technique could lead to good results. However, it would not permit to account for efflorescenced geometrically-damaged bricks for example. Moreover, this technique would require to compute several maps for each brick, depending on its environement, as bricks can be seen alone, extracted from aged walls. Thus our method provides a solid texture synthesis technique appropriate for the efflorescence weathering phenomenon. Note that some other visually important defects have already been studied (see section 2).

Next section deals with previous work. Section 3 presents an overview of the basic physical principles leading to efflorescence in fired-clay bricks. In section 4 we explain the synthesis technique. Then section 5 shows comparisons between our obtained results and real efflorescence. Finally we conclude and propose future work.

2. Previous work

In this paper, we use only basic texture synthesis techniques, using a 3D block of colors. Numerous techniques for solid texturing can be divided into two categories (a complete survey on this topic can be found in [DG01]).

- empirical solid texturing: the texture is entirely defined by a certain program code as opposed to be defined by an explicit data structure. For example, empirical procedural texture synthesis can lead to visually convincing results [Per85], often at reasonable computation cost.
- analytical approaches: solid texture are synthesized automatically [GD95], [HB95]. With these approaches, the user supplies at least one model of the texture (digitized image of a natural texture for example), and the system performs a 3D synthesis automatically, for example by spectral/stochastic analysis.

As stated in the introduction, weathering phenomena in computer graphics are of growing interest. Surfaces imperfections have been first handled by using a fractal based texture synthesis technique in [BB90]. Dusty surfaces were investigated by Blinn [Bli82] and Hsu and Wong [HW95], tarnished surfaces by Miller [Mil94] with accessibility shading algorithms. In [WNH97], Wong et al. provided a geometry dependent method to represent dust accumulation, patinas and peeling. Impacts onto surfaces have been studied in [PPD01]. Paint peeling and crackling was presented in [PPD02]. A global technique to authoring solid models has been proposed in [CDM*02] and permits to apply weathering to some objects with specific operators. More recently, the growth of lichens has been studied in [DGA04].

In order to obtain, when needed, more plausible results, some physically-based techniques have also been developed. Dorsey [DPH96] proposed a model to take into account dirtiness brought onto surfaces by flow processes. Weathering of non-porous stones has been studied in [DEJ*99]. Corrosion (both patinas and destructive corrosion) has been investigated in [DH96] and in [MDG01]. Scratched surfaces have been studied in [BMPG04].

3. Efflorescence: basic principles

3.1. Creation

One of the major cause of deterioration of porous building materials is salt weathering. Efflorescence is a salt deposition/penetration phenomenon occurring on a great variety of materials. In particular, this defect is of great importance in the case of building materials, specifically fired-clay bricks [HACF01]. Efflorescence occurs during wetting/drying cycles due to the affected material environment and is often seen as a thin surface deposition of salts: water charged with salts (taken from polluted environment, from mortar or dissolved clay bricks chemical constituent themselves) penetrates inside the porous material. During the drying process, water evaporates and deposits these salts while reaching the surface. Thus, efflorescence can be seen as a 3D process, depending on connections among pores inside affected materials. Figure 2 summarizes basic phenomena occurring during the cycles of wetting and evaporation:

- (a) and (b) represent the wetting process: water penetrates inside the brick through pores, bringing salts from air and/or mortar as well as dissolving brick components [BN04]. This phenomenon is more important at the mortar/brick interface due to the high porosity of mortar as well as its high concentrations in salts;
- (a') and (b') represent the evaporation process: salts are deposited progressively inside the pores. This deposition increases with evaporation rate, thus with proximity to the interfaces (brick/air and brick/mortar).

Numerous papers in material science concerning efflorescence deal with surface interaction only, because of the important aesthetic problem it causes [BN04]. It has also been shown that the 3D nature of efflorescence can have a great

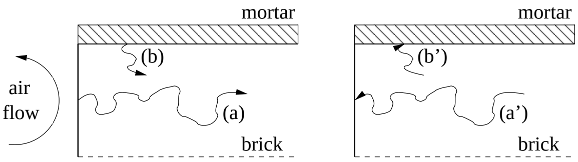

Figure 2: *Basic principle of salt migration. During wetting (left) water penetrates through porous paths inside the material. During the drying step, salts are deposited along the porous paths.*

influence on building weathering: salts deposited underneath the surface can crystallize and grow. The implied pressure can generate permanent damages [ZA89] such as cracks for example.

3.2. Color and shapes

Efflorescence is usually white in color (see figure 1). However, some chemical compounds may produce green or brown deposits. During the synthesis process, colors are directly taken from real photos permitting to take real color into account without introducing any chemical counpound parameter.

Efflorescence can take numerous aspects, depending on a lot of parameters. In particular, crystallization can occur onto the brick surface, exhibiting random "crust" shapes. In this paper, we do not take into account the specific cases where crystallization is strong enough to modify the external visible geometry of the bricks (called crypto-efflorescence). Thin efflorescence are very common [BN04] and we propose to handle their "thickness variations" by simply using bump mapping when needed. Figure 3 illustrates this purpose by showing a zoom on a real brick attacked by efflorescence. It can be easily observed that the efflorescence-covered parts do not present a larger geometric scale than the clean brick part bumps.

Figure 3: *Zoom on a real fired-clay brick attacked by efflorescence: bump mapping is sufficient to handle these specific efflorescence geometric variations.*

4. Efflorescence texture synthesis on fired-clay bricks

Figure 5 shows a real wall composed of numerous bricks (left: a clean wall, middle: efflorescence-affected wall). Each brick behaves in a specific way, depending on numerous parameters (see introduction and section 3). However, data driving the salt transfer phenomenon taking place in porous matrix are still lacking in material science, as stated recently by Ahl [Ahl03]. Thus we have to introduce different empiric perturbations for each brick individually.

To generate virtual walls accounting for weathering processes such as efflorescence, we have to:

- individually instantiate each brick. For each brick we store specific informations such as faces adjacent to mortar or air-visible faces.
- generate a solid texture accounting for weathering process according to each brick environment.

In order to obtain realistic clean bricks (without efflorescence), we propose to use a classical solid texturing technique: extrusion of a real 2D digital photo, perturbed on each step (see figure 4). Then we manipulate this solid texture to introduce efflorescence.

4.1. Obtaining a clean brick

We generate a discrete 3D block (solid texture) B of size N^3, by using an input 2D model (digitized image), called M, representing a view of the desired 3D texture. The discrete 3D block is defined as a set of N^3 voxels. Using only one 2D view implies that the inside of the 3D block B has to be approximated. As bricks do not present any specific order in the repartition of their constituents, we can suppose that the 2D view is enough representative of each layer of voxels in the direction of the future 3D texture (there are N layers for each 3D block B).

We want to obtain a discrete 3D block B of size N^3 that approximately resembles to the original 2D model. We propose to extrude the first layer along its perpendicular direction to synthesize the solid texture. Since real brick appearance is not uniform and in order to give a natural aspect to the texture, we empirically perturbate the extrusion process. For simplicity we use Perlin-noise [Per85], applied to each layer of block B. Figure 4 summarizes this classical process. As the texture is unique for each brick, we propose to use $N = 128^3$ to create walls. Using $N = 256^3$ do not show noticeably different rendering results.

4.1.1. Summary of the model parameters

As our goal is to obtain a phenomenological simulation of efflorescence in fired-clay bricks, we propose to summarize the parameters of our model, providing links between these parameters and their phenomenological meaning (see table 1).

Figure 5: *A real brick wall. On the left a clean version and on the middle, the same wall attacked by efflorescence. On the right: a wall synthesized by our method.*

Parameter	description	value	phenomenological meaning
p	porosity of the fired-clay brick	usually between 0.2 and 0.4	material science porosity definition
N_p	number of starting points	texture size * p	penetrating water paths
P_p	primary propagations	results driven (between 100 and 1000)	time steps of the efflorescence propagation
N_s	secondary propagations points	26 * p	account for interconnections of pores
P_s	secondary propagations	$P_p/100$	account for interconnections of pores

Table 1: *Summary of parameters*

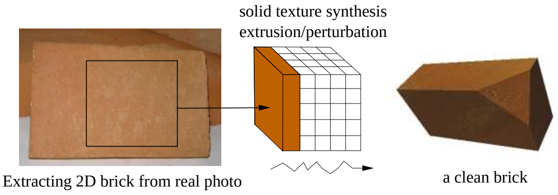

Figure 4: *Summary of the classical solid texture process. A digitized image is used as the first layer of the solid texture. It is then extruded and perturbed to fill the complete block of colors.*

4.2. Efflorescence: starting points

The main aspect of efflorescence process resides in the porosity of fired-clay bricks. Wetting and drying phenomena are directly linked with pore paths throughout the material. We use a number of points N_p of efflorescence departure. It is a control parameter of the texture synthesis (see table 1). Physically, N_p depends on the porosity p of the material, representing the proportion of pores at the surface, thus the potential number of porous paths. We simply use the product of fired-clay bricks porosity between 0.20 and 0.40 (given for example in [PKBL95]) by the number of voxels on a layer of the virtual brick as the number of starting points. This directly leads to use $texturesize * p$ as the number of starting points. Due to basic porosity definition, this number can be seen as the proportion of "porous voxels" onto the brick surface.

These points are chosen in preferential zones: the neighborhood of the mortar (figure 6). This is easily computed during instantiation of bricks. The starting points zone thickness is chosen as a proportion of the brick size. This can be linked to open porosity. Open porosity represents the amount of porosity directly linked to the surface, as opposed to closed porosity which is only present inside the material without any connection to the surface, see [MDG00]. Shape (mean diameter) and depth of open pores influence evaporation rate. To take into account this phenomenon, and driven by graphical results, we choose 5 % of the brick volume as the starting points zone parts, located close to mortar around the brick (see figure 6).

Moreover, depending on salts present in air (in polluted environment for example), some starting points may be chosen on visible parts of bricks. It is again trivial to find brick faces that are air-visible. However, a complete quantification of the phenomenon remains very difficult as we need to know the exact air composition. Thus we propose to empirically choose this starting point number. We use these points to develop efflorescence propagation. Depending on the de-

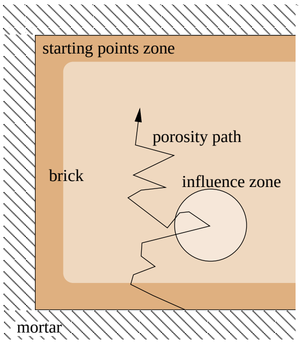

Figure 6: *Efflorescence texture synthesis principles. Starting from a specific zone (paragraph 4.2) a porous path is randomly chosen (paragraph 4.3.1). The influence zone takes into account interconnected porosity (paragraph 4.3.2)*

sired effect (figure 1 and figure 5 show different real behaviors), the amount of starting points chosen on air-visible faces is a parameter of the model. This empirical parameter choice is not a utilisability problem as the full efflorescence texture synthesis on a brick remains very fast. If needed, one can synthesize bricks with different values to choose the desired behavior (see sections 4.3.1 and 5).

4.3. "Inverse" growth process

Our efflorescence growing process is divided into two steps. The first one accounts for a global porosity path inside the material. However, in real materials, pores are interconnected making penetrating water following several paths at the same time: at each pore cross section, water continues its main path due to capillarity forces, but can also take new paths.

4.3.1. Porosity path

During the wetting step, water penetrates through pores, bringing salts. During the drying step, evaporation of water deposits salts on the path to the surface. We do not want to perform a full simulation of this process as the main goal of our technique is to obtain visually plausible images. Moreover, it is chemically too complicated/expensive to simulate the progressive obturation of pores due to crystallization. Thus we propose to consider the amount of salts deposited on each step (making efflorescence appearing) as a constant. This permits to avoid a quantification on the initial amount of salts in the penetrating water.
This assumption permits to simplify the process into one simple technique: finding porosity paths inside the brick (porosity paths can be randomly choosen [HE02]). Porosity paths are random walks inside the brick (see figure 6) composed by P_p steps. Each step of this random walk represents a time step in our inverse efflorescence propagation. Each random-walk step permit to mark a voxel as affected by efflorescence. We change the color of each of these porosity-path-voxel using a random color chosen in an efflorescence-covered zone on a real brick digital photo.
Time quantification is difficult to handle with respect to the complexity of efflorescence phenomenon: salt diffusion speed examples (for Finnish red bricks) can be found in [Ahl03]. However, the full kinetic of salt deposition/crystallization depends on a lot of other parameters such as the salt concentration or thermal conditions. On one hand, just after a construction, mortar is heavily charged in salts and efflorescence can occur in a few days only. Then the kinetic of this process reduces as mortar/brick salts dissolve. On the other hand, moisture continues to bring new salts directly or through mortar, increasing efflorescence kinetic to many years [BN04]. Taking into account these behaviors could lead to a very large amount of non trivial parameters. Thus we prefer to use an empirical quantification, driven by graphical results. Computing a 128^3efflorescence texture takes half a second on an Athlon 2800 for 400 random walk steps applied to 6000 starting points, leading to figure 7-right.

4.3.2. Pore interconnections: influence zone

Porosity is also tightly interconnected inside a material: many paths are present and crossing each other. Penetrating water does not follow only one path. To take into account this behavior, we add an influence zone at each propagation step (see figure 6). For each step, we start a new "small" propagation, choosing a number of random directions into the influence sphere and propagating efflorescence in those directions. To take into account the main capillarity forces driving water penetration on a preferential way: water penetrates deeper into lower diameters pores (due to Jurin rule). We choose the number N_s of new directions in relation with the material porosity. On each propagation step voxel, we have 26 neighbors. As porosity in fired-clay bricks is usually around 35 %, we propose to randomly choose 10 new propagation directions in the influence zone. However, interconnected pores do not have all the same mean diameters. Due to capillarity forces, another mechanism concerns air entrapment in dead-end pores, limiting water penetration. A physically-based diameter of our influence zone has to depend on these complex physical rules, coupling capillarity forces with pore size distribution. To keep our model as a phenomenological one, we propose to introduce a last parameter providing the influence zone number of ramdom walk steps S_p (equivalent to the influence zone diameter). With an usual porosity distribution varying with a factor 100, between 0.1 and 10 microns (see [CSE*04]), we propose to use $S_p = P_p/100$.

5. Results

Figure 5-right shows a weathered wall. Each efflorescenced brick has its own solid texture. Figure 7 shows on the right a

virtual brick affected by efflorescence: we choose $p = 0.36$, $N_p = (128 * 128) * p = 6000$ et $P_p = 400$. Mortar is present on both the upper and lower faces. The texture synthesis computation time is less than one second on an Athlon 2800. On the same figure, left part, we show a "reference" real brick, used to determine efflorescence colors.

Figure 8 shows the interior of two bricks at different evolution steps of efflorescence propagation. Figure 10 shows a scene with a wall composed of differently affected bricks. Instantiation of each brick gives information such as mortar presence. Then we use porosity variations among limits provided in table 1. Primary propagations also vary for each brick. Figure 9 shows the time evolution on a brick.

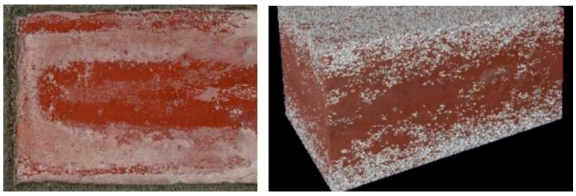

Figure 7: *Bricks affected by efflorescence. On the left a real brick and on the right a brick rendered with our efflorescence model*

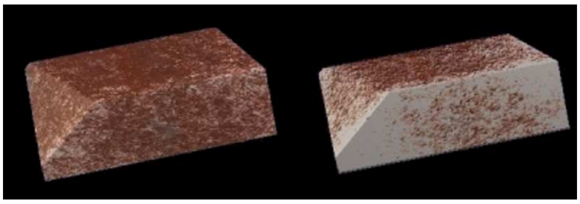

Figure 8: *Illustration of the solid texture of efflorescence*

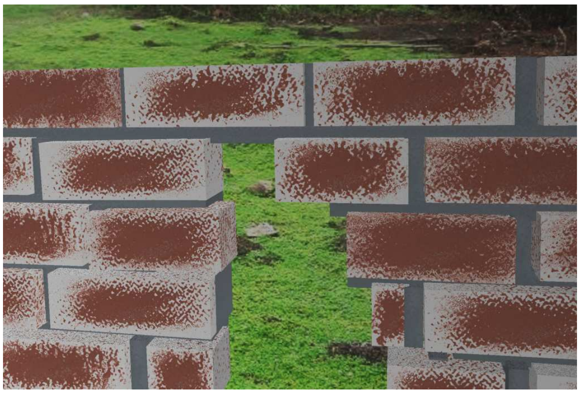

Figure 10: *An old wall, affected with efflorescence. We have also applied this weathering process to mortar.*

6. Conclusion and Future Work

We have presented a model to synthesize efflorescence on fired-clay bricks. This weathering process is very common as it affects a great number of human constructions. It has important visual effects. Our method is a phenomenological one as the efflorescence is a complex physical problem, depending on a lot of different parameters. These parameters are difficult to handle but are also difficult to find even in material science literature. Our method is simple to implement as it is based on well known solid texturing techniques. Moreover, we have only used a small number of intuitive parameters. Texture synthesis speed permits to control the final results easily.

This paper opens a large number of future work. Efflorescence can affect a lot of different construction materials (concrete for example). Moisture penetration in cracks or fissures leads to localized efflorescence. Moreover crystallization can occur with time on the surface of affected objects (leading to geometrical changes), as well as underneath the surface (leading to cracks and mechanical damages to constructions). Our 3D representation of efflorescences could permit to handle this weathering process. We will focus our future work in these directions.

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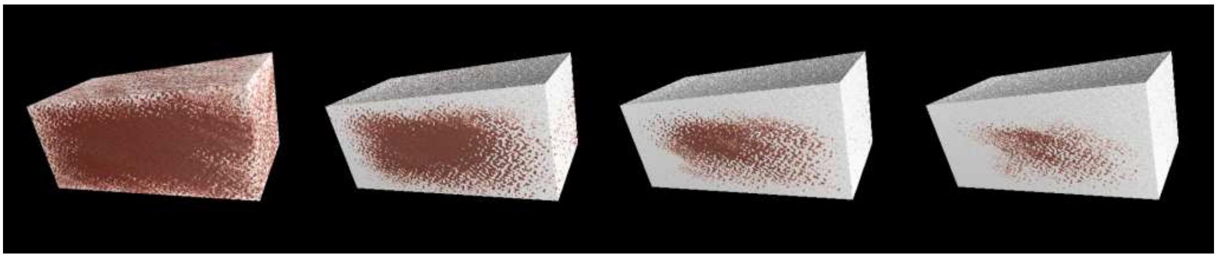

Figure 9: *Evolution of efflorescences with time using our time-related empiric parameter P_p, varying from 100 to 600, $N_p = 5000$.*

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