# STUDY OF CAPILLARY ABSORPTION KINETICS BY X-RAY CT IMAGING TECHNIQUES: A SURVEY ON SEDIMENTARY ROCKS OF SICILY·

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## 1. Introduction

The knowledge of capillary absorption kinetics in porous materials represents a fundamental aspect in recovery and conservation of Cultural Heritage. Capillary absorption in sedimentary rocks is the consequence of different attraction forces between pore wall and fluid, with a resultant upwards tracking force. Rates of the advance front inside the pores can be described by both diffusive and frontal advance equations, depending on validity of the reliable assumptions. In the first case, the diffusion coefficient is proportional to the partial derivative of capillary pressure as regards water saturation; furthermore, calculated displacements are essentially of diffusive kind (*percolative behavior*).

The second case considers the wetting front rate to be proportional to capillary pressure gradients as the distance, taking into account flat advance fronts (*piston like displacement*). This phenomenon mainly depends on rock permeability, porosity, wetting tendency and interface tension between intrinsic phase (air/water steam biphasic blend) inside the pores and imbibition phase (advancing water).

Basic assumptions are that the capillary forces overcome the floating and viscous ones and that the movements take vertically place upwards. Water volume variations in sedimentary rock pores, due to different temperature conditions (daily as well as seasonal), in addition to chemical reactions with pollutants transported by fluids (air and water) inside the porous space of sedimentary rocks, lead with the time to the deteriora-

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*Figure 1. Geographic location of the most known Greek temples in the Western sector of Sicily. Baroc Val di Noto area is placed in the South-Eastern corner of the Island.*

tions of materials. Studies exposed in the present paper deal with sedimentary rocks used for building the Greek temples in the archaeological sites of *Agrigento*, *Segesta*, *Selinunte* as well as for the Baroc buildings in the Sicilian *Val di Noto* area [1].

Fig. 1 shows the geographic location of the considered archaeological areas.

CT (*Computerized Tomography*) scanning results [2], referred to samples relevant to the above situated archaeological quarries, allow us to state the rule of average height variations of wetting front in *Val di Noto* porous rocks. This behavior can be illustrated by a flat pattern based on the Handy model [3]. The same assumptions are valid for the samples coming from the archaeological areas of *Selinunte* and *Segesta*. In fact, these specimens are homogeneous enough, at least at the resolution scale of CT scanning (a tenth of millimeter). On the contrary, sedimentary rock, pertaining to the quarries of the archaeological area of Agrigento, presents a relatively great heterogeneity as regards the other samples. This is the reason for which the wetting front variation can be schematized by a stochastic law as the *Langevin* one [4]. In this model a stochastic term, denominated "quenched disorder", describes the heterogeneity of the material [5].

In order to protect cultural heritage against the adsorbed capillary water into the lapideous materials, hydrorepellent and consolidating materials are used to permit a possible restoration of the damaged structures. Imaging techniques, by CT scanning, permit to evaluate the performances of protecting test products.

## 2. Principles of capillary absorption

The capillary absorption is a typical phenomenon of porous media, strongly connected with the interfacial wettability regarding two surfaces and governed by the Washburn law. The capillary absorption in a porous material occurs only in case of wettability and, of course, when the structure is not entirely immersed in the water (porous could be full). Capillary absorption can be minimized or reduced by means of a hydrophobic substance. In the next paragraphs, the most important parameters linked to capillary absorption phenomenon as well as related noticeable models and approaches will summarily be described.

### *2.1. Imbibition*

The imbibition is expressed as the movement of a fluid from a porous medium for the action of another fluid, as a consequence of the sole capillary forces.

In the past, various differential equations have been proposed for describing the air displacement due to the water imbibition process, but these equations are not analytically resolvable [6]. Nevertheless, approximate solutions for water-air imbibition have been found, leading towards the derivate of an equation describing the piston advance of the wetting front, based on the assumptions of the Handy model.

### *2.2. Handy model*

The Darcy law states the efflux velocity of a fluid with μ viscosity through a porous media $v(z)$ (or the discharge $Q(Z) = v(z) \cdot A$). In detail, the Darcy law is defined by this well-known relation:

$$v(z) = K \cdot \frac{\partial \phi}{\partial z}$$

where

$\frac{\partial \phi}{\partial z}$ = hydraulic gradient

$\phi = z + \psi$ = total piezometric head

z = gravitational head

$\psi$ = suction head.

The proportionality constant $K$ is called hydraulic conductivity: it can be considered as a measure of movement capability of water into a porous space. This coefficient depends on the fluid parameters (that is viscosity, density) as well as on the pore parameters of the medium (that is dimension, shape, tortuosity, specific surface, porosity, saturation grade). In particular, if the saturation $S$ increases, also $K$ augments; if $S \to 1 \Rightarrow K \to Ks$, where $Ks$ expresses the hydraulic conductivity in saturation state.

In a number of cases, the imbibition rate is analogous to the capillary rise in a porous medium. From this analogy, fundamental assumptions are:

- water penetrates by a piston advance;
- pressure gradient of the gaseous phase, above the wetting front, can be neglected.

In the vertically upwards imbibition, the efflux velocity depends on water permeability and viscosity, gravity acceleration, water/air density difference and wetting front position, the capillary pressure being considered constant.

In the kinetics of a capillary tube, sorptivity acquires a notable importance. It is defined as the tendency of a porous medium to absorb or desorb a liquid by capillarity, and it is mathematically illustrated as the cumulative infiltration at time $t$. In general, this parameter roughly expresses the described phenomena when saturation gradients occur. Nevertheless, the here considered data, pertinent to the rock samples of *Val di Noto* area, satisfy the assumption to retain the gravitational forces lower than the capillarity ones. On the other hand, data relevant to Agrigento area exhibit a different behavior, due to the greater heterogeneity of the material (assigned as “quenched noise”), as it will be highlighted in the successive paragraphs.

### *2.3. Percolation*

The capillary water adsorption in a porous medium can be described by the percolation theory, for which the dynamic process of imbibition simulates the movement of a fluid caused by another one. When the water comes in contact with a porous medium, the capillary forces overcome the viscous forces: so, the process dynamics are determined by the local radium $r$ of the pore. The capillary forces are greater in narrowest porous necks. This fact is consistent with experimental observations in order to depict displacements as a series of discreet time jumps, where water expels the air from the smallest available porous.

### 2.4. Stochastic approach to the efflux in a porous medium

The fluid efflux in porous medium is a classic experimental result of the non-equilibrium motion of an interface in a disordered environment. In a typical case, a *d*-dimensional self-affine interface characterized by *h(x, t)* height, moves in a disordered ($d+1$) dimensional medium. In literature, two main classes of disorder have been discussed. The former, called thermal or "annealed", depends only on time. The latter, assigned as "quenched", is connected with the medium. The presence of the "quenched" disorder permits an analogy with the critical phenomena, describing two classes of universality [7].

The continuous interface motion needs the application of a push force *F*. A critical value $F_c$ takes place so that – for $F < F_c$ – the interface will be blocked by the disorder after a certain time *t*. For $F > F_c$ , interface moves indefinitely with a constant *v* velocity. This means that the push motion of a corrugated interface in a disordered medium can be considered as a transition phase, called "*depinning transiton*" [8, 9, 10].

A universality class is described by a Langevin type non linear equation, given by Kardar-Parisi-Zhang equation [11], in which various characterizing parameters are involved. In particular, a "*quenched noise*" term depicts the corrugation effect of the surface.

A second universality class is described by a more simple *Langevin*-type equation, given by the *Edward-Wilkinson* equation [12], For a number of different models [8, 9] belonging to the second universality class – referred as isotropic growth – the "depinning transition" coefficient of the Kardar-Parisi-Zhang equation can be $\lambda = 0$ or $\lambda \to 0$.

For a better understanding of the above illustrated phenomenon, a square network is considered with *L* side and periodical contour conditions along the *L* direction, as shown at the left in fig. 2, instead the right part of the same figure reports the corrugation of the wetting front as a consequence of the "quenched noise", in the *Agrigento"* sample.

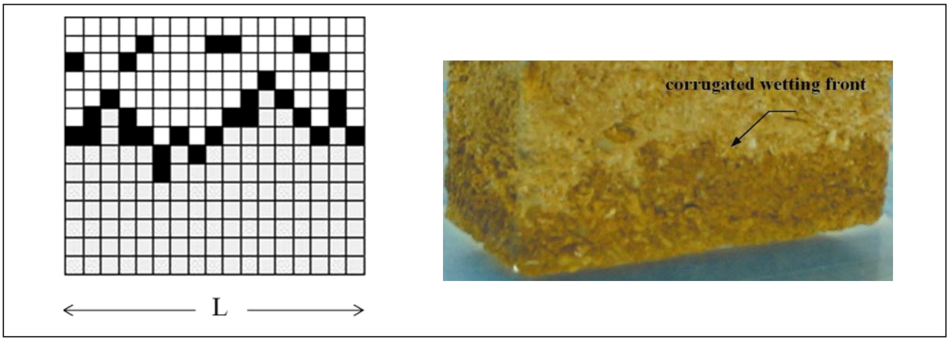


*Figure 2. Left image shows the formation of the corrugated wetting interface. White, dark and gray squares refer respectively to non-blocked dry cells, to blocked dry cells and to wet cells. Right image exhibits the corrugated wetting profile as a consequence of the "quenched noise" in the Agrigento sample.*

To every $I$ cell of the side, a uncorrelated random number is assigned, that is the $\eta_i$ disorder, with uniformly distributed amplitude in the [0,1] range. The role of $\eta_i$ is to model the "random pinning" forces generated by the disorder. Now, the "pinning" forces are compared with the $F$ push force, where $0 \leq F \leq 1$. If the "pinning" forces in a definite cell is greater than the push force, then the cell is well recognized as "blocked", otherwise it is identified as "non-blocked".

Considering that this model has been developed for imbibition studies, the "invading" region is considered as "wet", instead the "invaded" region as "dry".

At $t = 0$ time, all the cells of the first row below in the network are wetted. Then, a column was randomly selected and all the "unblocked" cells, pertaining to the column nearest to the wet cell, are wetted. Besides, a rule is imposed that all the dry "blocked" cells under a wet cell become wetted, calling it "rule of overlying erosion".

A "pinning cluster" is defined as any group of blocked cells connected with the near or quite near groups delimiting blocked cells. Any "pinning cluster", the linear dimension of which is lower than the system size, can not prevent from the interface advance.

Indeed, every "pinning cluster" – that does not expand the system – will eventually be circumscribed by the invading fluid, because the invading front can move only around finite "obstacles" and the overlying erosion rule states that – after encircled – the "pinning clusters" become wet. Lastly, when the "pinning" forces overcome the push forces – or when the "pinning clusters" have expanded the whole sample length – the wetting front is stopped with the front corrugation effect.

## 3. Experimental section

### *3.1. Materials and methods*

Surveys have been carried out on samples coming from quarries of the archaeological areas of *Agrigento, Segesta, Selinunte* and *Val di Noto* area, in Sicily. Samples were cut in cubic shape, with 50 mm side. After a warming at 65 °C for a week in a "muffle" oven, samples were subjected to a successive cooling, up to environmental temperature, for three hours in a drier, with the aim to remove any humidity trace.

An appropriate plexiglas container was designed to hold in continuous contact the sample bottom with water. This container is illustrated in fig. 3. Continuous supply of water, with the aim to maintain fixed its level, is guaranteed by a small pump and a tube system for the exceeding inlet-outlet water. Various samples have been arranged for every origin site. CT images, constituted by 60 different slices 0.625 thick, have been performed over every sample.

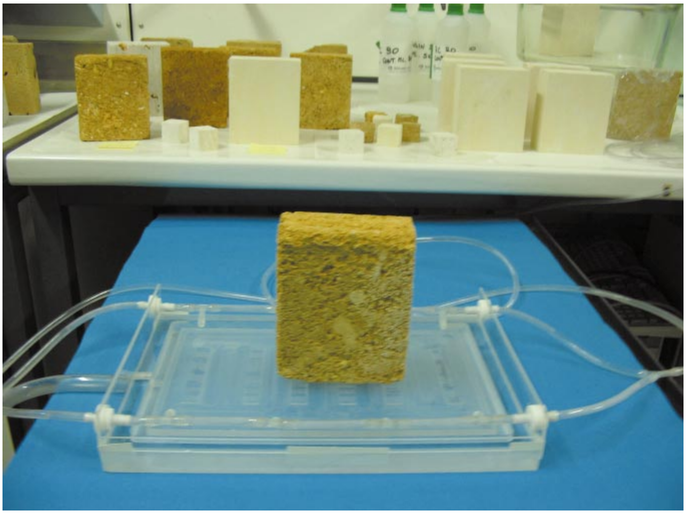

*Figure 3. Picture of the plexiglas container with the positioned sample. In this case, prospected rock comes from Agrigento area. Inlet and outlet tubes of water are also shown. A small thickness, carved by the cutter in the sample, guarantees the contact between a constant water level and the bottom of the sample.*

CT images have been acquired by means a computerized tomography instrument *multislice* Philips Brilliance 40 (Philips Medical Systems, Eindhoven, The Netherlands). In fig. 4, the CT tomography is shown together with the experimental apparatus used for the imaging acquisition.

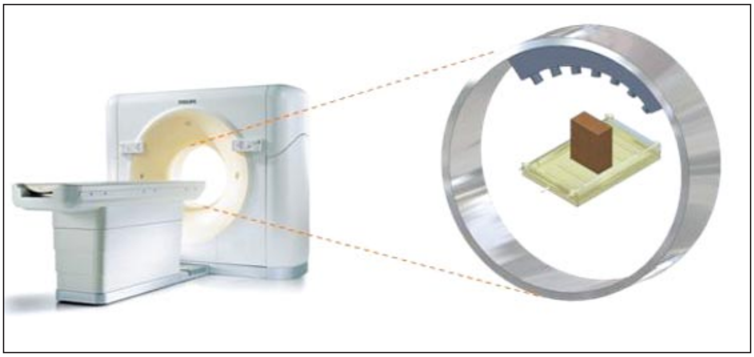

*Figure 4. A schematic picture of the CT computerized multislice tomography with the experimental apparatus used for the sample imbibition.*

The voltage of the electronic tube was fixed to 120 kV value and the current to 600 mA, with the aim to guarantee the maximum penetration of X-rays and a good imaging quality. During imaging acquisition and post-processing, a *bone* filter was used. Besides the contact with water, the time-recorded images, before and after the treatment with protective materials, have been utilized for the evaluation of water distribution within the porous spaces.

Hounsfield unit is used in CT radiology applications [13]; this is defined by the following equation:

$$H_{Hounsfiled} = \frac{\mu_{voxel} - \mu_{air}}{\mu_{water} - \mu_{air}} \cdot 1000$$

where $\mu_{\text{voxel}}$, $\mu_{\text{air}}$ e $\mu_{\text{water}}$ are the absorption linear coefficients of X-rays for – respectively – the generic considered voxel, the air and the water. In this way, it is possible to settle the scale of Hounsfield values. According to this representation, if the voxel is filled of water, the Hounsfield value is –1000 and assumes zero for water. In this scale, the cortical bone, for example, assumes the value of about +1000.

A schematic illustration of the Hounsfield scale is showed in fig. 5.

Due to the essentially carbonate origin of the sampled rocks, the average value of the Hounsfield number results occurs – in the considered *region of interest* (ROI) – in the 900 ÷ 1400 range, depending on density and heterogeneity presented by samples. The aim is to calculate the different values of the Hounsfield number for every voxel relevant to all the slices, in both dry and wet conditions and at different contact times with water.

In the imbibition process, water expels the air from the porous spaces, with a consequent increase of X-rays absorption as well as of the Hounsfield number. Being the dimension of any image of 512 × 512 pixels, size of any voxel results 0.35 mm × 0.35 mm, with a 0.625 mm thickness.

By recording the Hounsfield values for every voxel, a matrix of scalar values $A(H_{i,j}\ t_k)$ is obtained for every slice, in such a way permitting a 3-D representation of the dynamic evolution of the wetting front within the porous spaces of the sedimentary rock. Measures have been repeated, in the same conditions, after a treatment with hydrophobic products.

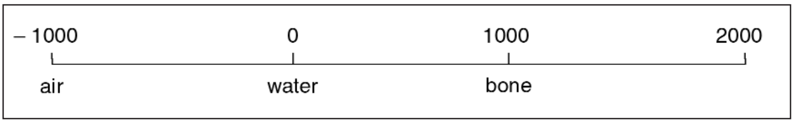


*Figure 5. Scale of Hounsfield values.*

An estimation of the time acquisition for CT imaging has been executed by means of the gravimetric method, carried out according to UNI 10859 standard (determination of water absorption by capillarity). As a result of the carried out measurements, the sample coming from the archaeological area of *Selinunte* showed very speed kinetics of capillary absorption. An opposite behavior was exhibited by the sample relevant to the *Alcamo* site. Samples of Agrigento and Val di Noto showed intermediate temporal kinetics: in detail, the *Agrigento* sample displayed a greater velocity of absorption. In order to optimize the CT acquisition measurements, because the used apparatus were located in a hospital unit, measures were executed only on the *Agrigento* and *Val di Noto* samples. A further study on morphology of pores has been carried out by a stereomicroscope and by a scanning electronic microscope (SEM).

### *3.2. Results*

The petrography features of sedimentary rock samples, considered in this paper, are reported in tab. 1.

Fig. 6 illustrates pictures of sample fragments and images given by SEM microscope, executed at two different observation scales.

The SEM images of *Agrigento* and *Selinunte* are shown, respectively at center and at right – at 100 μm and 30 μm observation scales. Instead, SEM images of *Val di Noto* and *Segesta* are related to 30 μm e 3 μm respectively. In particular, the SEM image of the *Agrigento* sample exhibits a small shell with 2 μm size. These images confirm the notable heterogeneity of the *Agrigento* rock as regards the other more homogeneous samples, when observed at the observation scale of the CT resolution (a tenth of millimeters). Furthermore, the same *Agrigento* sample offers also the presence of shells of considerable size as well as of pebbles of the same magnitude order. These examinations will reveal, as it will be detailed below, a different behavior of the wetting front motion in the

*Table 1. Petrography features of rock samples.*

| | AGRIGENTO | SELINUNTE | SEGESTA | VAL DI NOTO |
|---|---|---|---|---|
| *Classification* | calcarenite | calcarenite | siltite | siltite |
| *Size of rock grains* | 0.2 ÷ 8 mm | 0.2 ÷ 0.5 mm | ~ 0.060 mm | ~ 0.060 mm |
| *Porosity type* | intergranular | intergranular | secondary for dissolution | intergranular |
| *Porosity* | medium-high | high | scarce | absent or scarce |

*Figure 6. The left column shows – up to down – images of sedimentary rock samples coming from the archaeological areas of Agrigento, Selinunte, Val di Noto and Segesta. The successive right columns represent images obtained by the SEM microscope at two different observation scales.*

various samples, being possible to propose the piston motion, based on the Handy hypotheses, for the *Selinunte*, *Segesta* and *Val di Noto* samples. The *Agrigento* sample, in consideration of its considerable heterogeneity, does not present a piston motion behavior, but it suggests a stochastic approach based upon the percolation theory.

A first evaluation of the capillary absorption kinetics for any kind of sedimentary rock has been proposed by means of the gravimetric method executed according to the UNI 10859 normative. Fig. 7 shows the water quantity $Q_i$ adsorbed, for surface unit (expressed in milligrams to square centimeters), by the test specimen at $t_i$ time and in function of the square root of time.

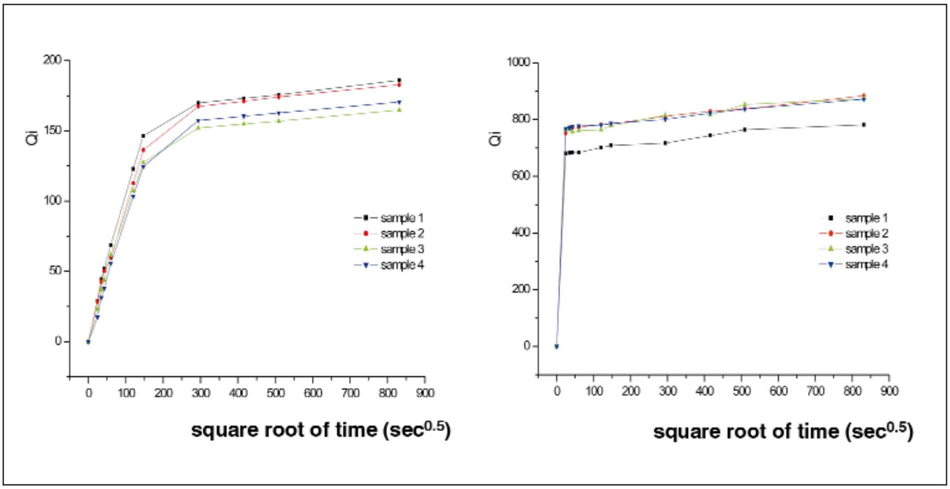


*Figure 7. Capillarity index $Q_i$ for samples coming from Val di Noto (at left) and Agrigento (at right).*

Four samples have been prepared for every kind of rock; they have been weighed in dry as well as in wetting conditions at different contact times with water, up to saturation.

The time sequence of the X-Ray CT image acquisitions is reported in tab. 2.

After the CT image acquisition, matrices of scalar values $A(H_{i,j}\, t_k)$, obtained for every slice, have been elaborated by MATLAB software. Fig. 8 shows the false color images in Hounsfield units: they exhibit the variations of Hounsfield number with the capillary water invasion into porous spaces. In particular, images shown in the same figure are related to the middle slice of the *Val di Noto* sample.

Fig. 9 shows a comparison among the images of the last column of fig. 8 and the relevant CT images at 256 grey-scale.

*Table 2. Time sequence of the X-Ray CT image acqusitions (seconds) relevant to the Agrigento and Val di Noto samples.*

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Agrigento | $t_o$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_6$ | $t_7$ | $t_8$ |
| | 0 | 30 | 90 | 180 | 300 | 600 | 780 | 1200 | 1470 |
| Val di Noto | $t_o$ | $t_1$ | $t_2$ | $t_3$ | $t_4$ | $t_5$ | $t_6$ | $t_7$ | $t_8$ |
| | 0 | 120 | 240 | 360 | 900 | 1320 | 2100 | 3300 | 5100 |

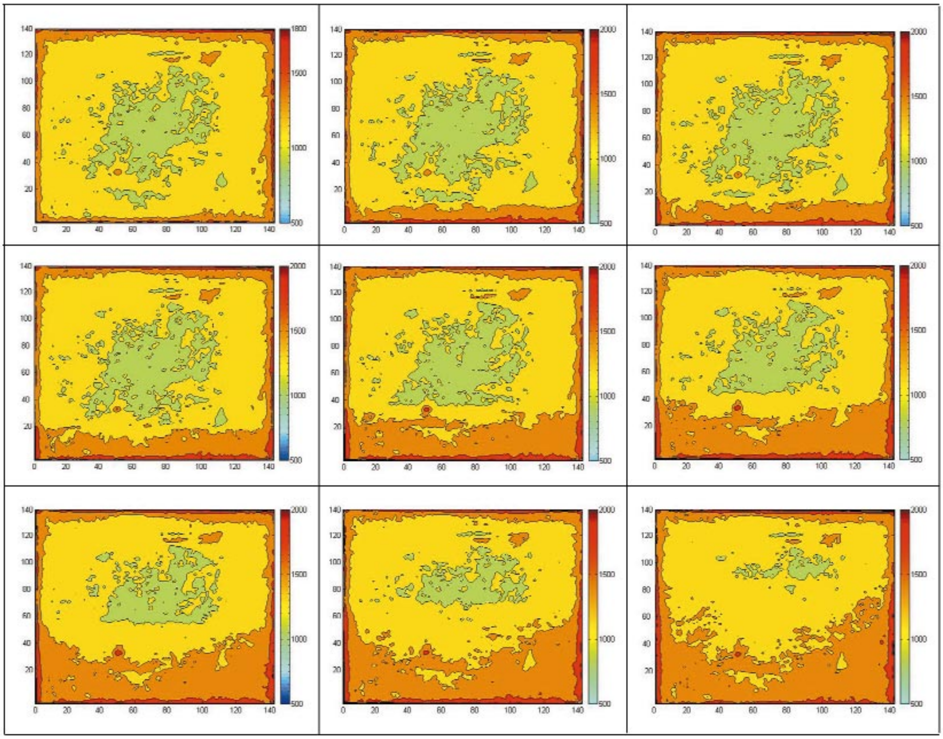

*Figure 8. The water imbibition in the sedimentary rock (Noto sample) is shown through the variations of the Hounsfield number in the CT images. The first upper image (at left) is related to dry conditions, the other ones are related to images acquired at different contact times with water and with a temporal sequence equal to 120, 240, 360, 900, 1320, 2100, 3300 and 5100 seconds.*

The lower part of samples reveals a greater absorption of X-rays as regards the medium part, due to the greater upwards absorption of capillarity water. The *best fitting* of the obtained data confirms the good agreement with the Handy model (see above equation), as reported in fig. 10.

Fig. 11 presents the false color images in Hounsfield units for the central slide of the *Agrigento* sample.

In fig. 12, the comparison among the images of the last column of fig. 11 relevant to the time sequences 90, 600, 1470 seconds and the corresponding CT images at 256 grey-scale shows that – in this case – it is not possible to correlate the wetting front advance with a law describing a piston type displacement. Indeed, the hetero-

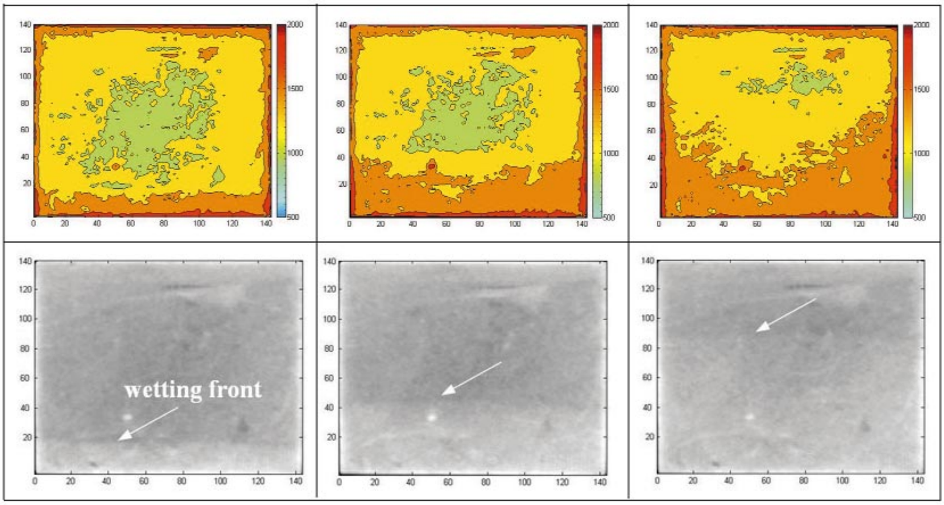


*Figure 9. A comparison is illustrated among the false color images obtained by MATLAB procedure and the corresponding CT images at 256 grey-scale.*

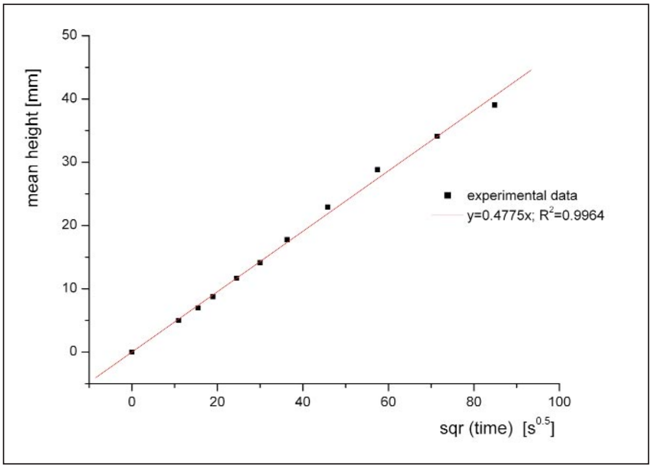


*Figure 10. Best fitting of data with the Handy model.*

geneity of the material causes an excessive corrugation of the wetting front. This permits to conclude that, for this typology of materials, the imbibition process can be described by the percolation theory. The Kardar-Parisi-Zhang equation well agrees with the description of dynamic evolution of the wetting front for this typology of material.

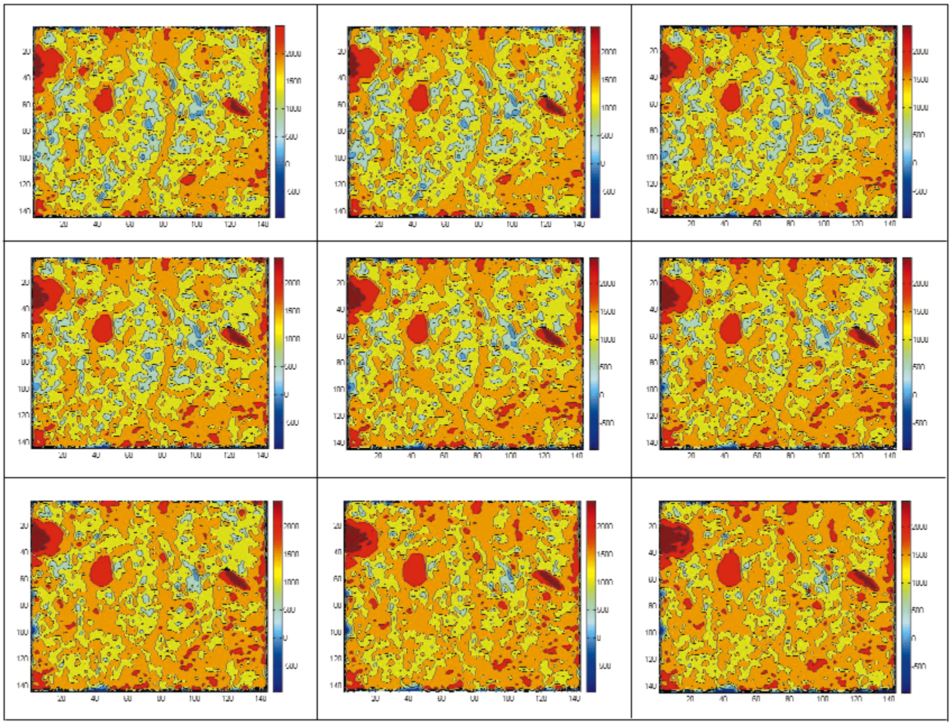

*Figure 11. The water imbibition in the sedimentary Agrigento rock sample is shown through the Hounsfield number variations in CT images. The first upper image (at left) is referred to dry condition, the other ones are related to the images acquired at different contact times with water, and with a temporal sequence equal to 30, 90, 180, 300, 600, 780, 1200 and 1470 seconds.*

3-D representation methods, as surface contour lines, allow us to evaluate penetration and distribution uniformity of hydrophobic products used like hydrorepellent, consolidant materials in the restoration and conservation of historical lapideous monuments. In particular, fig. 13 exhibits a couple of 3-D surface contour lines related to the *Agrigento* sample.

The left part of this figure shows the 3-D surface contour line relevant to the Agrigento non treated sample. The right part is referred to the same sample treated with an ethyl silicate (Rodhorsil RC 90). Images have been elaborated by MIRA$^{TM}$ software, using a threshold Hounsfield value of +900.

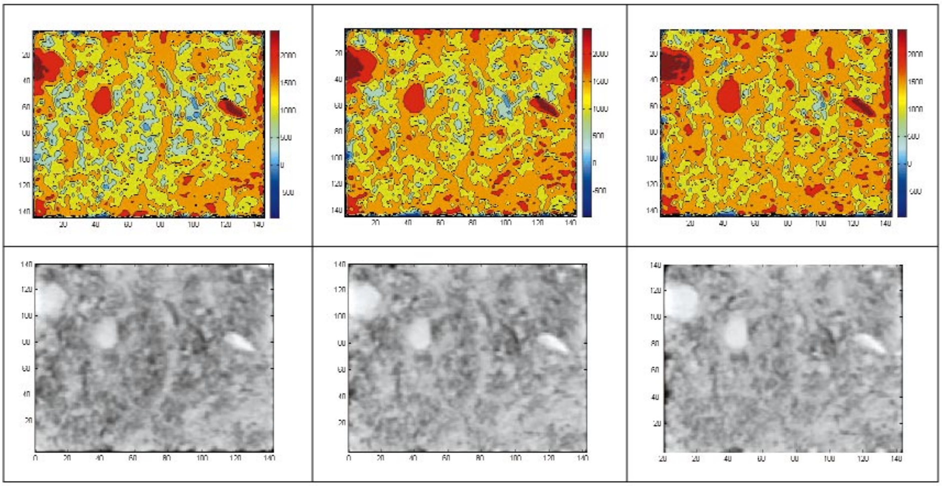

*Figure 12. A comparison is shown among the false color images obtained by MATLAB elaboration and the corresponding ones at 256 grey-scale.*

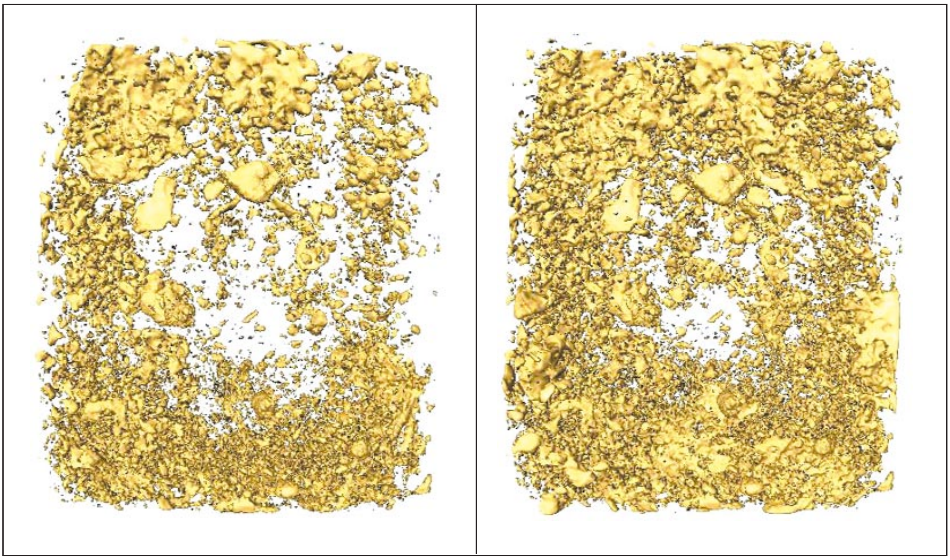

*Figure 13. The left part of this figure shows the 3-D surface contour line relevant to the Agrigento non treated sample. The righ part is referred to the same sample treated with an ethyl silicate (Rodhorsil RC 90).*

## 4. Conclusions

The outcomes of this paper confirm the validity of CT imaging techniques for detailed studies of capillary kinetics of water absorption in sedimentary rocks. The motion of the wetting front in a porous medium is described by stochastic equations of Langevin-type. Furthermore, under certain assumptions (Handy model), it is possible to correlate the average height of the wetting front by a relatively simple law exhibiting a dependence by the square root of time. Evaluations of the Hounsfield number in a voxel matrix and MATLAB processing permit to define the kinetic evolution of the wetting front into the porous medium.

3-D images show the dynamic evolution of the wetting front as well as the distribution into porous spaces of hydrophobic, consolidant products used for the protection and conservation of lapideous historical works. The use of diagnostic medical techniques in cultural heritage studies, supported by specific data processing, appears to be promising for characterizing and analyzing the protective effects on the involved materials. Furthermore, the obtained experimental results permit to validate the solving of complex differential equations as the Kardar-Parisi-Zhang stochastic equation: this describes the percolative behavior of water in heterogeneous media as the sample coming from the archaeological area of *Agrigento.*

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**Summary**

Sedimentary rocks are natural porous materials with a great percent of microscopic interconnected pores: they contain fluids, permitting their movement on macroscopic scale. Generally, these rocks present porosity higher then metamorphic rocks. Under certain points of view, this feature represents an advantage; on the other hand, this can constitute an obstacle for cultural heritage applications, because the porosity grade can lead to a deterioration of the lapideous monument for water capillary absorption.

In this paper, CT (Computerized Tomography) image techniques are applied to capillary absorption kinetics in sedimentary rocks utilized for the Greek temples as well as baroc monuments, respectively located in western and southeastern Sicily. Rocks were sampled near the archaeological areas of *Agrigento*, *Segesta*, *Selinunte* and *Val di Noto*. CT images were acquired at different times, before and after the water contact, using image elaboration techniques during the acquisition as well as the post-processing phases. Water distribution into porous spaces has been evaluated on the basis of the Hounsfield number, estimated for the 3-D voxel structure of samples. For most of the considered samples, assumptions based on Handy model permit to correlate the average height of the wetting front to the square root of time. Stochastic equations were introduced in order to describe the percolative water behavior in heterogeneous samples, as the *Agrigento* one.

Before the CT acquisition, an estimate of the capillary absorption kinetics has been carried out by the gravimetric method. A petrographical characterization of samples has been performed by stereomicroscope observations, while porosity and morphology of porous have been surveyed by SEM (Scanning Electron Microscope) images. Furthermore, the proposed methods have also permitted to define penetration depth as well as distribution uniformity of materials used for restoration and conservation of historical monuments.

**Riassunto**

Le rocce sedimentarie naturali sono materiali porosi con una grande frazione di pori microscopici e

fra loro interconessi, che contengono fluidi e permettono il loro trasporto su dimensioni macroscopiche. In generale esse si presentano maggiormente tenere rispetto alle rocce metamorfiche. Sotto certi punti di vista questa caratteristica costituisce un vantaggio; d'altra parte, questo può essere un inconveniente per applicazioni nei beni culturali, poiché il grado di porosità può condurre al deterioramento del monumento lapideo per assorbimento capillare di acqua.
In questo lavoro, sono presentate tecniche di immagine TC applicate allo studio delle cinetiche di assorbimento capillare in rocce sedimentarie siciliane utilizzate nella costruzione dei templi Greci della Sicilia occidentale e dei monumenti storici del periodo barocco della Sicilia sud-orientale. Le rocce sono state campionate in cave nelle prossimità delle aree archeologiche di *Agrigento*, *Segesta*, *Selinunte* e della *Val di Noto*. Sono state acquisite immagini TC a tempi differenti, prima e dopo il contatto con acqua, usando tecniche di elaborazione delle immagini, sia in fase di acquisizione che di post-processing. La distribuzione dell'acqua all'interno degli spazi porosi è stata valutata sulla base del numero di Hounsfield stimato sulla struttura 3-D a voxel dei campioni. Per la maggior parte dei campioni considerati, assunzioni basate sul modello di Handy permettono di correlare l'altezza media del fronte di bagnamento alla radice quadrata del tempo. Equazioni di tipo stocastico sono state introdotte per descrivere il comportamento percolativo dell'acqua in campioni eterogenei, quale è quello di *Agrigento*. Prima delle acquisizioni TC, una valutazione delle cinetiche di assorbimento capillare è stata eseguita mediante il metodo gravimetrico. Una caratterizzazione petrografia dei campioni è stata effettuata mediante osservazioni allo stereomicroscopio e considerazioni sulla porosità e morfologia dei pori sono state eseguite mediante l'esecuzione di immagini al microscopio SEM. Il metodo proposto permette inoltre la determinazione della profondità di penetrazione e della uniformità di distribuzione dei materiali usati per il restauro e la conservazione di monumenti storici.

## Résumé

Les roches sédimentaires naturelles sont des matériaux poreux avec une grande fraction de pores microscopiques et interconnectés entre elles, qui contiennent des fluides et permettent leur transport sur des dimensions macroscopiques. En général, elles se présentent plus tendres par rapport aux roches métamorphiques. Sous certains points de vue, cette caractéristique constitue un avantage; d'autre part, ceci peut être un inconvénient pour des applications dans les biens culturels, puisque le grade de porosité peut conduire à la détérioration du monument pierreux par absorption capillaire d'eau.
Dans cet ouvrage, sont présentées des techniques d'image TC appliquées à l'étude des cinétiques d'absorption capillaire en roches sédimentaires siciliennes utilisées dans la construction des temples Grecs de la Sicile occidentale et des monuments historiques de la période baroque de la Sicile sud-orientale. Les roches ont été échantillonnées dans des gorges dans les environs des zones archéologiques d'*Agrigente, Ségeste, Sélinonte* et de *Val di Noto*. Des images TC à temps différents, avant et après le contact avec l'eau, ont été acquises, en utilisant des techniques d'élaboration des images, tant en phase d'acquisition que de post-processing. La distribution de l'eau à l'intérieur des espaces poreux a été évaluée sur la base du nombre de Hounsfield estimé sur la structure 3-D à voxel des échantillons. Pour la majeure partie des échantillons considérés, des suppositions basées sur le modèle de Handy permettent de corréler la hauteur moyenne du front de mouillement à la racine carrée du temps. Des équations de type stochastique ont été introduites pour décrire le comportement percolatif de l'eau dans des échantillons hétérogènes, tel celui d'*Agrigente*. Avant les acquisitions TC, une évaluation des cinétiques d'absorption capillaire a été effectuée moyennant la méthode gravimétrique. Une caractérisation pétrographique des échantillons a été effectuée moyennant des observations au stéréomicroscope et des considérations sur la porosité et la morphologie des pores ont été effectuées moyennant la réalisation d'images au microscope SEM. La méthode proposée permet, en outre, la détermination de la profondeur de pénétration et de l'uniformité de distribution des matériaux employés pour la restauration et la conservation de monuments historiques.

## Zusammenfassung

Die natürlichen Sedimentgesteine sind poröse Materialien mit einem großen Teil von mikroskopischen und mit einander verbundenen Poren, die Flüssigkeiten enthalten und die solche Flüssigkeiten auf makroskopischer Ebene transportieren. Normalerweise sind sie weicher als metamorphe Gesteine. Dieses Merkmal kann in gewisser Hinsicht Vorteile mit sich bringen aber kann auch einen Nachteil für die Anwendungen in Kulturgütern darstellen, weil der Grad der Porosität das Verderben des Monuments aus Stein wegen der kapillaren Wasserabsorption verursachen kann.

In dieser Schrift werden TC Bilder- Techniken für die Studie zu den Kinetiken der kapillaren Absorption in sizilianischen Sedimentgesteinen vorgestellt, die für den Bau von griechischen Tempeln im westlichen Teil von Sizilien und für den Bau von historischen Monumenten der Barockzeit im südöstlichen Teil von Sizilien verwendet wurden. Die Proben aus den Steinen wurden in den Steinbrüchen in der Nähe der Ausgrabungsstätten von *Agrigento, Segesta, Selinunte* und des *Val di Noto* genommen. Es wurden TC- Bilder zu verschiedenen Zeitpunkten aufgenommen, bevor und nachdem die Steine mit Wasser in Kontakt gekommen waren, dabei wurden Techniken für die Verarbeitung von Bildern angewendet, sowohl während der Aufnahme als auch in der Post-Processing-Phase. Die Wasserverteilung in den porösen Räumen wurde durch die Hounsfieldzahl bewertet, auf der Basis der 3-D Voxel-Struktur der Muster. Für die meisten bewerteten Muster ermöglichen Aufnahmen auf der Basis des Modells "Handy", die Mittelhöhe der Durchfeuchtungsgrenze mit der Quadratwurzel der Zeit in Korrelation zu bringen.

Es wurden stochastische Gleichungen verwendet, um die Perkolation des Wassers in heterogenen Mustern zu beschreiben, wie zum Beispiel im Muster von *Agrigento*. Vor den TC-Aufnahmen wurden die Kinetiken der kapillaren Absorption durch die gravimetrische Methode bewertet. Die petrographische Charakterisierung der Muster erfolgte durch Beobachtungen durch ein Stereomikroskop und die Porosität und die Morphologie der Poren wurden mithilfe von Bildern durch das SEM-Mikroskop bewertet. Außerdem ermöglicht es die vorgeschlagene Methode, die Tiefe des Eindringens und die Gleichmäßigkeit der Verteilung der Materialien festzustellen, die für die Restaurierung und die Erhaltung von historischen Monumenten angewendet werden.

## Resumen

Las rocas sedimentarias naturales son materiales porosos con una gran fracción de poros microscópicos interconectados entre sí, que contienen fluidos y permiten su transporte en dimensiones macroscópicas. En general se presentan más blandas que las rocas metamórficas. Bajo ciertos puntos de vista, esta característica constituye una ventaja; por otra parte, eso puede ser un inconveniente para aplicaciones en los bienes culturales, ya que el grado de porosidad puede conducir al deterioro del monumento lapídeo por absorción capilar de agua.

En este trabajo se presentan técnicas de imagen TC aplicadas al estudio de las cinéticas de absorción capilar en rocas sedimentarias sicilianas utilizadas en la construcción de los templos Griegos de Sicilia occidental y de los monumentos históricos del período barroco de la Sicilia sudoriental. Las muestras de las rocas se han recogido en canteras en las inmediaciones de las áreas arqueológicas de *Agrigento, Segesta, Selinunte* y el *Val di Noto.* Se han tomado imágenes TC en momentos distintos, antes y después del contacto con el agua, usando técnicas de elaboración de las imágenes, tanto durante la fase de adquisición como durante el post-procesado. La distribución del agua dentro de los espacios porosos se ha evaluado a partir del número de Hounsfield estimado en la estructura 3-D en voxel de las muestras. En la mayor parte de las muestras consideradas, las estimaciones basadas en el modelo de Handy permiten correlacionar la altura media del frente de humectación con la raíz cuadrada del tiempo. Se han introducido ecuaciones de tipo estocástico para describir el comportamiento percolativo del agua en muestras heterogéneas, como en las de *Agrigento*. Antes de las tomas TC, se ha efectuado una evaluación de las cinéticas de absorción capilar mediante el método gravimétrico. Se ha efectuado una caracterización petrográfica de las

muestras mediante una observación con estereomicroscopio; también se han tomado imágenes con microscopio SEM para efectuar consideraciones sobre la porosidad y morfología de los poros. El método propuesto permite además determinar la profundidad de penetración y la uniformidad de distribución de los materiales usados para la restauración y conservación de monumentos históricos.


## Резюме

Натуральные осадочные горные породы представляют собой пористый материал с большим количеством микроскопических пор, связанных между собой и и содержащих жидкость, что позволяет им пермещаться в макроскопическом пространстве. Обычно эти породы более мягкие, чем метаморфические породы. С некоторой точки зрения эта особенность является преимуществом, с другой стороны, может представлять собой недостаток при создании памятников культуры, так как степень пористости может привести к разрушению каменных изделий из-за капиллярного впитывания воды. В этой работе представлены методы изображения ТЧ (TC), примененные в изучении кинетики капиллярного впитывания в сицилийских осадочных породах, использованных при постройке греческих храмов в западной Сицилии и исторических памятников периода барокко в юго-восточной Сицилии. Осадочные породы были отобраны в карьерах недалеко от местопроведения археологических раскопок в Агридженто, Сегесте, Селинунте и Валь ди Ното. Были сделаны снимки ТЧ (TC) в разное время, до и после контакта с водой, используя технику обработки изображений, как во время проведения съемки, так и post-processing. Распределение воды на пористых поверхностях было оценено с ссылкой на число Хунсфильда (Hounsfield), полученного при помощи трехпространственного измерения исследуемых материалов. Для большинства изучаемых образцов замеры, проведенные по модели Ганди (Handy), позволяют сопоставить среднюю высоту омываемой поверхности с квадратным корнем времени. Уравнения стохастического типа были введены для описания перколяционного поведения воды в различных образцах породы, находящихся в Агридженто. До применения ТЧ оценка кинетики капиллярного впитывания проводилась с помощью гравиметрического метода. Петрографический анализ материалов был проведен при использовании стереомикроскопа, а исследование пористости и морфологии пор было проведено при помощи изображений, полученных под микроскопом SEM. Представленный метод позволяет к тому же определить глубину проникновения воды и равномерность распределения материалов, используемых в реставрации и сохранении исторических памятников.