Available online at **www.hormigonyacero.com**
0439-5689 / Hormigón y Acero 2020; 71(292):, e1-e12
https://doi.org/10.33586/hya.2020.3020

Computed tomography beyond medicine: Applications to the microstructural study of concrete and other engineering materials

La tomografía computerizada más allá de la medicina: Aplicaciones al estudio microestructural del hormigón y otros materiales de la ingeniería

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Received 7 May 2020; accepted 10 September 2020

ABSTRACT

Computed tomography (CT) scanning is a very powerful technology for microstructural study of materials, as can be checked in the huge amount of papers published in recent years. Beyond its well-known use in medicine, CT scanning has spread to many other scientific fields. Some of them are revised in this work, with particular interest in concrete technology. Among its most relevant applications its use in paleontology and heritage to analyze the internal structure of fossils and relics without any damage can be highlighted. On the other side, it is also very used in the study of engineering materials, such as metals, composites, asphalt mixtures in pavements, rocks and concrete. In all cases, the data obtained by means of CT-scans is applied to improve the knowledge about the macroscopic response of those materials under any kind of loads, both mechanical and environmental ones. In the specific case of concrete, among its principal applications the analysis of internal matrix can be noticed, as well as the study of crack patterns and finally the study of fiber-reinforced concrete.

KEYWORDS: Computed tomography, metals, composites, asphalt mixtures, rocks, concrete.

RESUMEN

La tomografía computerizada (TC) es una tecnología muy potente para el estudio de la microestructura de los materiales, lo que se refleja en la gran cantidad de trabajos publicados durante los últimos años. Más allá de su conocido uso en medicina, la TC se ha extendido a otros muchos campos científicos. En este trabajo se recogen algunos de ellos, con especial interés en el estudio del hormigón. Entre sus aplicaciones más relevantes destaca su uso en paleontología y patrimonio para analizar el interior de fósiles y restos arqueológicos sin dañarlos. Por otro lado, también se emplea con frecuencia en el estudio de materiales de la ingeniería, como los metales, los materiales compuestos, las mezclas bituminosas de los firmes, las rocas y el hormigón. En todos los casos, los datos obtenidos por los escáneres de TC se usan para mejorar el conocimiento de la respuesta macroscópica de dichos materiales frente a todo tipo de acciones, mecánicas o ambientales. En el caso particular del hormigón, entre sus aplicaciones principales se encuentran la del análisis de la matriz interna, el estudio de los patrones de fisuración y finalmente el estudio del hormigón reforzado con fibras.

PALABRAS CLAVE: Tomografía computerizada, metales, materiales compuestos, mezclas bituminosas, rocas, hormigón.

1.
INTRODUCTION TO COMPUTED TOMOGRAPHY

Computed tomography (CT) scanning is a non-destructive technology used to characterize the internal structure of matter at the microscopic scale. This technique is based on the attenuation or energy loss suffered by X-rays when passing through matter, which is governed by the Beer-Lambert law (Ec. (1)).

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How to quote this article: Mena, A., González, D.C., Mínguez, J., Vicente, M.A. (2020). La tomografía computerizada mas allá de la medicina: Aplicaciones al estudio microestructural del hormigón y otros materiales de la ingeniería. Hormigón y Acero, 71(292), e1-e12. https://doi.org/10.33586/hya.2020.3020

$$I = I_0 \exp\left[-\int \mu(s)\, ds\right] \tag{1}$$

Where I is the final intensity of the X-ray, I_0 is the initial intensity and μ(s) is the linear attenuation coefficient along its path. The last parameter basically depends on the density ρ of the matter crossed by the X-ray. It is verified that the ratio μ/ρ is approximately proportional to Z^3, where Z is the atomic number of the element.

Therefore, the basic operating principle of CT is the direct relationship between the energy attenuation of X-rays and the density of the matter through which they pass. A CT scan is composed of two main elements: an intensity-controlled X-ray source and an intensity detector. The specimen is placed between them and during the scanning process it is crossed by X-ray beams from several directions at several heights. The CT scan records the initial and final intensity of every X-ray, hence the density of all points of the specimen is finally determined.

If the CT scan emits only a single X-ray at each instant, the scanning process will be undeniably too long. Consequently, several technical solutions for multi-beam X-ray emission have been developed. The conventional one consists on a source that emits a linear X-ray beam which is received by a linear detector. During the scanning process both elements remain fixed in place while the specimen is rotated, elevated and lowered until all regions are scanned. However, the scanning process continues to be slow and its accuracy is poor because of the limitations of the mechanical components used to move the specimen. A more efficient solution is the use of CT scans equipped with sources that emit X-ray cone beams that are received by an array of detectors. This way the scanning area at each moment increases and thus the total duration of the process is greatly reduced. In addition, a suitable resolution along the three spatial directions is obtained since the relative movements between the emitter-detector device and the specimen are small. This technology was first developed in the 1980s [1], although its application was not widespread until the early 2000s.

The practical result of a CT scanning is a set of images or stack in which every image represents a cross section of the specimen at a given height. Digital image processing (DIP) software is used to merge all the images of the stack, creating a spatial image. The resolution of a tridimensional image is determined by the voxel size. A voxel is simply a 3D-pixel whose resolution on X and Y axes is given by the images of the stack and its resolution on Z axis is given by the separation between consecutive images. Moreover, each voxel has a grey value (ranging from 0 to 65535 in the case of 16-bit images) which is related to the average density of the voxel. Clear grey tones correspond to high densities while dark grey tones correspond to low densities.

Additionally, CT has several limitations that are worth noting. In the first place, the specimen size is limited since X-ray beams need to keep a minimum energy after attenuating during their way through the sample. If the specimen is too thick, it will absorb a lot of energy, resulting in a soft X-ray flow and hence a poor image quality. Maximum specimen size generally varies from around 15-20 cm with high-resolution micro-CT scans to 30-40 cm in the case of high-energy scans with 300-400 kV X-ray tubes. Therefore, core drilling and then extrapolations always have to be performed when analyzing rock walls and large concrete elements. Secondly, maximum resolution is also limited and depends on the specimen size and the type of scan. In general, high-resolution micro-CT scans can reach resolutions of about 1 µm in small specimens, while conventional devices only have 30-40 µm. Thus, the maximum defect size (pores, cracks, etc.) that is detectable by the CT scan must be taken into account when studying the microstructure of concrete, metals or composites. Finally, as previously mentioned, the operating principle of CT is based on density variations of the materials crossed by X-ray beams. As a result, the closer the densities of the materials of a specimen are, the more difficult it will be for the CT scan to divide them. This last fact is rarely worrying in the study of concrete because its components have very different densities (concrete matrix, air voids and cracks, steel fibers or rebar, etc.). However, the analysis of composites made of plastics with similar density, for example, can actually be an issue. Some alternatives in such cases consist on trying to improve the resolution (either with a smaller specimen or with a more powerful scan) or adding an additive that only reacts with one of the components by changing its density (this is more common in the field of biology).

As is well known, CT is closely related to medicine. In fact, this technology was first applied in this field in the 1970s [2] as a non-invasive technique to display internal body parts (organs, tissues, bones, etc.) and detect certain pathologies. Since then and particularly from the 1980s, its use has been spreading across other science and engineering fields. It is appropriate to mention at this point that there are significant differences between a CT scan for medical treatment and a CT scan for scientific research and industry. The most relevant one is the fact that low-intensity sources are used in medicine in order to avoid damaging human tissue, while high-intensity X-rays can be used with inert objects, which provides high-resolution images.

Over recent decades, CT techniques have been applied in many scientific fields, especially in those that analyze the microstructure of materials or elements, their mechanical properties and/or their macroscopic response. Figure 1 shows the number of journal papers published between 1990 and 2019 in the most relevant scientific fields that use CT. Data have been obtained from WoS (Web of Science) [3], a widely used bibliographic database that groups the most influential international journals of all scientific and technologic fields.

A marked increase in the number of publications over time in all fields is observed in Figure 1. Furthermore, there is an exponential growth in the majority of them with a clear increase since the 2000s, just when X-ray cone beam scans began to be implemented. According to the data collected, the scientific fields whose use of CT techniques is greater are those which study metals, composites, rocks and concrete. On the contrary, their use is less relevant in the rest of the fields reviewed.

This paper intends to review and summarize the current state-of-art of CT applied to science beyond its well-known use in medicine. Therefore, the most relevant research works of several fields that use this technology to study the microstructure of materials are highlighted, with a particular focus on the case of concrete.

The rest of the document is structured as follows: the applications of CT to paleontology and heritage studies are examined in sections 2 and 3, respectively. Then, the most rele-

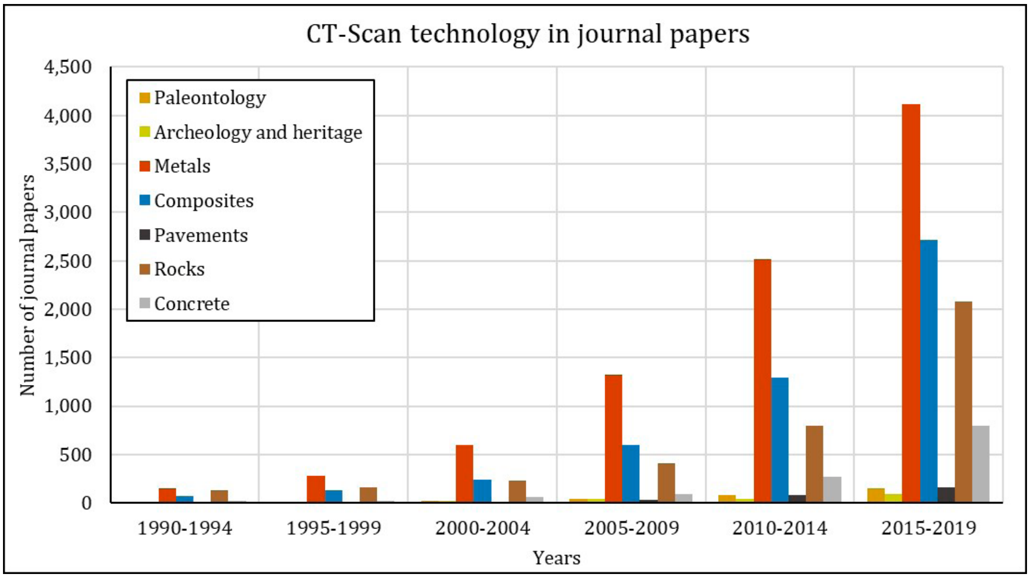

Figure 1. Increase in the number of scientific publications related to CT-Scan technology (1990-2019).

vant aspects of its use in metals and composites are underlined in sections 4 and 5, respectively. Subsequently, the use of CT in some fields of civil engineering such as pavements, rocks and concrete is described in sections 6, 7 and 8, respectively. Finally, the main conclusions are collected in section 9.

2.

COMPUTED TOMOGRAPHY IN PALEONTOLOGY

The use of CT-Scan technology in this field started early. One of the first works dates from 1979 and was developed by Jungers [4]. This researcher applied the technology to compare fossil bones of different primate species. Some of the advantages of CT are already highlighted in his publication, such as the identification of tissues with similar density or the analysis of fossils with excessive mineralization.

However, CT scans coming from medicine were used in this early stage, which were not powerful enough to identify the internal structure of fossils with appropriate sharpness. This is due to their greater density compared to that of human tissue. Thus, novel analysis techniques were rapidly applied and new CT scans generations able to solve this problem were developed.

Although CT is not as popular today as it used to be in its origins, it continues to be the core technology in much research [5–8]. Most of these works are framed within paleobiology, and particularly in the study of fossils. The fossilization process of an organism takes place over thousands of years during which the mineralization of organic matter occurs. Soft tissues commonly decompose, while skeletons remain almost unchanged due to their higher mineral content. The result is unique and extremely fragile samples whose scientific value in some cases is enormous.

In this context, CT is a very useful tool as it produces very clear sectional images, and by using digital image processing software it generates virtual reconstructions of the specimens (Figure 2). In this way, the manipulation of the fossils is reduced and hence the risks of deterioration and breakage associated with it. In fact, it is even possible to manufacture replicas using modern 3D printers [5].

In addition, the study of the samples with CT is sometimes better than what can be achieved with the naked eye. On the one hand, when it is physically impossible to remove the sediments adhered to a fossil without breaking it, a virtual "cleaning" of the sample can be performed [6]. On the other hand, when having skeleton fragments belonging to the same organism, complete 3D reconstructions can be realized, connecting bones and even simulating their movements [7].

Other applications of CT to paleontology are the detection of skeletal and spinal malformations, and the identification of dental history.

3.

COMPUTED TOMOGRAPHY IN ARCHEOLOGY AND HERITAGE

Archeological findings and other objects belonging to the cultural heritage share certain similarities with fossils. In both cases, the samples are unique and of singular value, so they must be handled with great care. In addition, the conditions under which they are extracted from the deposits are usually inadequate and they are often covered by hard layers of sediment very difficult to remove without damaging them.

The implementation of CT techniques in this field began in the mid-1980s. One of the first works was developed in 1986 by Notman [9]. In this article, the advantages of CT over magnetic resonance imaging (MRI) in the analysis of Egyptian mummies are mentioned, and it is proposed as the preferred non-destructive method. The use of these techniques for the study of mummies and other ancient human remains has con-

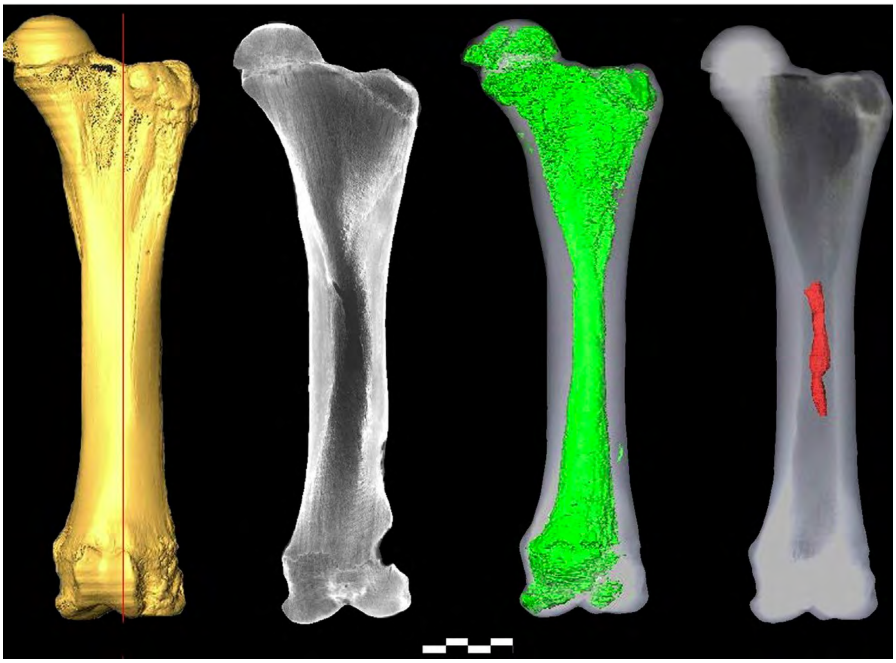

Figure 2. Left femur of an adult *Palaeoloxodon antiquus*, an extinct species of elephant that inhabited the Pleistocene. From left to right, three-dimensional model generated from CT scanning, cross section, segmentation of the different tissues (green) and segmentation of the medullary cavity (red) [8].

tinued to the present day. In this line, works on the detection of pathologies in Egyptian mummies or the analysis of relics of religious martyrs stand out.

Another application of CT in this field is the study of archeological objects. Sometimes, the main purpose is the virtual reconstruction of the finding, particularly when it is broken into different parts or it is desired to know the internal structure of the materials. In other cases, when dealing with artifacts, CT is used to understand the manufacturing process or the working mechanism (Figure 3). In recent years, quite interesting research has been carried out on these issues [10–12]. Furthermore, although this technology is currently not very popular in this field, there are some works that have had a great impact on the media, such as the Antikythera Mechanism [12].

In all cases, the procedure followed is very similar. First, the complete pieces, or all the fragments if the piece is fractured or incomplete, are scanned. Then, by means of digital image processing software, a virtual reconstruction is performed and the non-desired elements are removed (rock sediments, etc.). In addition, one or more replicas can be reproduced with 3D printing, while the original is preserved from deterioration. Likewise, museums can store the originals for security, exhibiting only the replicas.

4.
COMPUTED TOMOGRAPHY IN METALS

Metals are materials widely used in all fields of civil and industrial engineering. In the current market there is a wide range of metals and alloys, each one designed with specific properties depending on its use: weight, strength, ductility, toughness, energy absorption, electrical conductivity, thermal transmissivity, abrasion resistance, hardness, corrosion resistance and porosity, among others. Moreover, the manufacturing processes are also very diverse, from the most conventional casting and molding to the most modern procedures, such as stamping, injection and additive manufacturing. Therefore, this heterogeneity implicit in metals, both in products and processes, is a perfect environment for the application of CT.

The first studies using CT for the analysis of metals and alloys are very premature, emerging from the advances in medical applications. In particular, it is worth mentioning the work of Hildebrand and Harrington in 1981 [13], which highlights the potential of CT for the location and mapping of residual stresses in metals. Over time, the use of this technology in metallurgy has become consolidated and is now very common.

One of the applications of CT is the study of defects during the manufacturing process of a product. This is a typical application in sectors that produce high value-added components (aeronautics, aerospace, automotive and bioengineering, among others) in which an innovative improvement in quality control or in the assembly line can lead to savings of millions of dollars. In this regard, some projects have been carried out to study the most common defects, such as pores, residual stresses or cracks [14–17].

In addition, additive manufacturing techniques that are currently revolutionizing the manufacturing processes of metal elements deserve a special mention. In concrete terms, one of the most common technologies is selective laser melting (SLM). This technique allows the creation of objects from thin layers of pulverized material that are selectively fused with a high power laser. The design possibilities are practically unlimited, which explains its great popularity. In recent years,

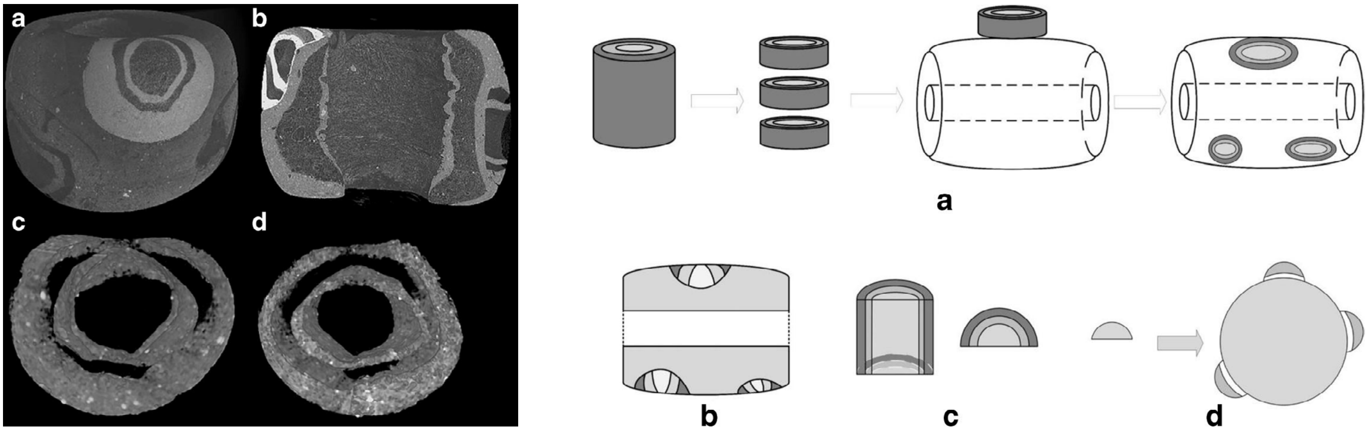

Figure 3. Cross-section images of glass beads found along the ancient Silk Road in the Xinjiang Uygur Autonomous Region of China (left) and analysis of the handicraft manufacturing process (right) [10].

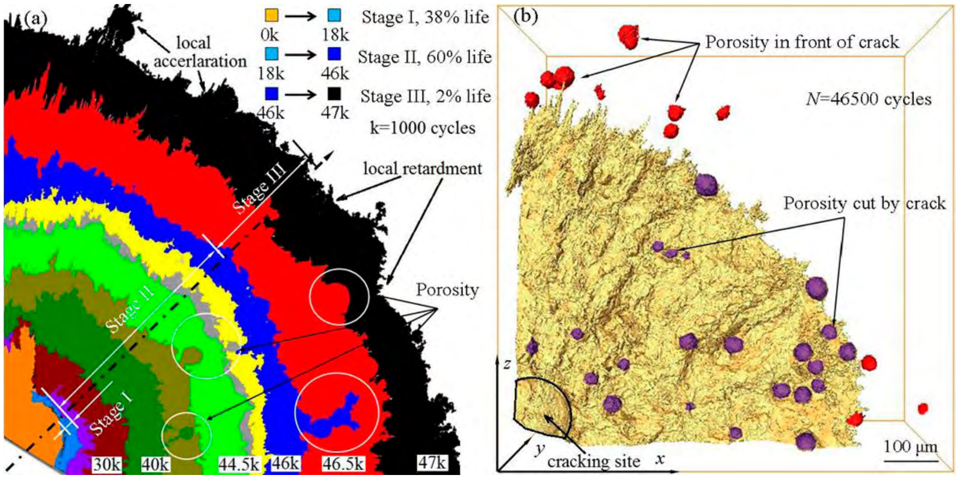

Figure 4. Analysis of fatigue crack propagation in a AA7020-T651 aluminum alloy specimen welded with hybrid laser: (a) advancement of the indicated crack front in different colors, (b) 3D rendering of the fatigue crack using CT scan images [29].

many scientific papers have been developed using CT to detect porosity, analyze residual stresses, study the mechanical properties of a part produced under different orientations, etc. [18–23].

Another frequent research line is the combination of CT techniques and mechanical tests to set correlations between the internal microstructure of a material and its macroscopic response [16,22,24]. The ultimate goal is to optimize quality control by replacing mechanical tests with CT scanning, which is cheaper and easier to implement in the production process. Furthermore, the information provided by the CT scan can serve as a basis for the development of predictive finite element models, which can be calibrated with the results of the mechanical tests [17,25]. The advantage of CT is that it enables the creation of accurate numerical models, providing the exact location of all phases and defects (pores, cracks, etc.) that constitute the specimen. Other applications of CT in this research line is the analysis of the influence of the internal microstructure of metals in fracture mechanics and in their behavior under fatigue loads [18,24–27] (Figure 4).

Finally, it is also worth noting the possibilities provided by CT for the study of welding joints [14,28]. Welding is the most widely used procedure for connecting two metal parts. Therefore, it is necessary to have an adequate control of its quality. In this sense, CT techniques allow the study of its microstructure and the evaluation of its defects, contributing to an improvement of the process.

5.

COMPUTED TOMOGRAPHY IN COMPOSITES

Composites are now used in many fields of engineering. They generally consist of a polymeric or metallic matrix and a reinforcement of fibers or other similar elements. Fibers (glass, carbon or steel, among others) provide strength and stiffness, while the matrix protects them and transfers the applied loads. In this way, the matrix and the reinforcement create a new material with mechanical properties that are impossible to achieve separately. In addition, due to the wide range of polymers, metals and fibers on the market, it is common for composites to be designed for a particular use, such as adding strength, efficiency or durability.

As in the case of metals, the application of CT-Scan technology to the study of composites began in early stages. One of the first works to be developed specifically for industry was the one by Moore in 1983 [30], which used a CT scan to analyze

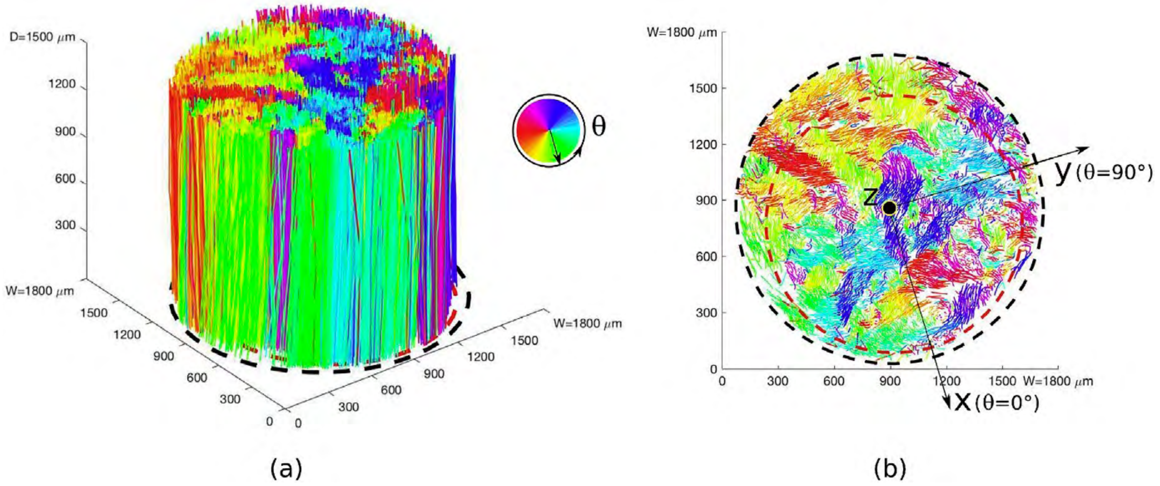

Figure 5. Study of fiber orientation of a glass fiber reinforced polymer: (a) three-dimensional lateral view obtained from CT, where the color of each fiber is associated to the azimuth θ of its direction, (b) view of a cross section [38].

specimens of carbon fiber reinforced carbon (CRFC). Since then, its use has increased and nowadays it is a proven technology for the analysis of any type of composite material.

The manufacturing process of composites is quite complex, due among other factors to the great heterogeneity of their composition and the need to achieve a correct arrangement of the reinforcement. In this context, CT is a tool that helps to optimize quality controls. In recent years, research works have been published that analyze the pores and cracks produced during fabrication [31–35], as well as the efficiency achieved in the orientation of the fibers [36,37] (Figure 5). Besides, in some cases CT scanning is combined with mechanical and thermal characterization tests, so that empirical correlations are established between the microstructure of the composite material and its macroscopic response [31,33,34].

Additionally, over the last few years there is certain scientific interest in the analysis of the variations suffered by the microstructure (fiber reorientation, etc.) and the damage mechanisms (fracture mechanics, fatigue crack propagation, etc.) of composites subjected to all kinds of mechanical and/or environmental actions [38–41].

Lastly, just as with metals, the possibility of generating finite element models from the data provided by CT scans should be noted. Thus, numerical simulations of any element can be made for its later comparison and adjustment with experimental data [42,43].

6.

COMPUTED TOMOGRAPHY IN PAVEMENTS

Road pavements are typically classified as rigid, consisting of concrete pavement, and flexible, consisting of bituminous pavement. In Spain the latter are used preferably, although both solutions may be correct depending on the design criteria. Among the advantages of flexible pavements are the greater comfort in driving, the greater ease in achieving the right properties of friction, less noise pollution and, finally, the lower cost of construction.

Flexible pavements are composed of asphalt mixtures, which are the result of the combination of aggregates, filler and a hydrocarbon binder (usually bitumen). It is a sort of "composite material", since the coarse aggregate forms the resistant skeleton while the filler-bitumen system provides the necessary cohesion to the whole. However, given its heterogeneity, small variations in the shape and distribution of aggregates, bitumen content and/or porosity, cause significant changes in the mechanical properties of these materials. Therefore, the application of CT for the study of the microstructure of asphalt mixtures is very interesting.

The application of CT for the study of asphalt mixtures is relatively recent. Nevertheless, the use of this technology is now quite widespread and arouses significant interest, which is reflected in a rising scientific output in recent years. The first relevant results were published about 20 years ago by Masad [44], focusing on the study of porosity.

The analysis of microstructure is obviously one of the main research lines. In this case, CT has its application when seeking to know the permeability of asphalt mixtures, or determine the influence of materials or mixing conditions on the final microstructure [45–47] (Figure 6). Moreover, as seen in metals and composites, it is also possible to generate finite element models with the data provided by the CT scan. In this regard, there are some works that develop models based on experimental results, so that they are able to simulate the behavior of asphalt mixtures against fatigue loads produced by traffic [48–50].

In addition, during the last years there is an important scientific interest in the self-repair capacity of asphalt mixtures, as well as the techniques to produce it (induction, microwave or microcapsules radiation, among others). In this environment, the CT is an essential tool since it helps to evaluate the evolution in the closing of cracks, the influence of the type of aggregate on the self-repair capacity, etc. [51–53].

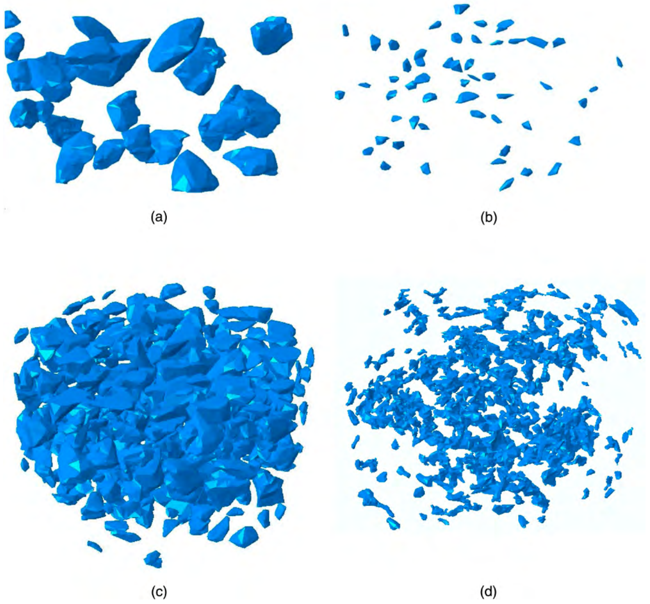

Figure 6. Segmentation of all phases that compose an asphalt mixture by means of CT: (a) selection of coarse aggregate, (b) selection of fine aggregate, (c) total aggregate, (d) pores [50].

Finally, although to a lesser extent, the CT is also applied for the analysis of rigid concrete pavements, focusing on permeability or cracking studies [54,55].

7.
COMPUTED TOMOGRAPHY IN ROCKS

Similar to composites and asphalt mixtures for pavements, rocks are materials with a high degree of heterogeneity. In general, any rock mass is made up of a rock matrix and a series of defects that can be microscopic (pores, cracks, etc.) or macroscopic (areas of weakness, faults, joints, etc.). These internal defects are precisely the ones that characterize the quality of the rock mass and hence its mechanical properties and real structural behavior.

Regarding its relationship with civil engineering, rocks are the most important material in a wide range of works, particularly in the case of tunnels and dams. In relation to tunnels, the strength of the rock matrix, the permeability and the presence of discontinuities in the rock mass strongly determine the stability and the level of convergence of tunnels and consequently their construction process. The same occurs with dams, especially with arch and dome dams. The structural elements of this type of dams are embedded in the rocks, so the mechanical behavior of the rock mass greatly affects the structural safety of the dam. If differential settlement occurs in the dam's support area, the arch may move from its natural state of total compression to experience local bending. This can lead to the formation of cracks, filtrations and, eventually, the ruin of the dam. This is the reason why this type of dam is usually located in narrow valleys in mountain areas, where the quality of the rock masses is very high.

The influence of defects on the macroscopic behavior of rocks makes CT a useful tool in this field. In fact, CT techniques began to be employed in rock and mineralogical research in the early 1980s, being one of the first fields of civil engineering to use this technology. Among the first works published is that of Petrovic in 1982 [56], which used a CT scan to measure the apparent density of rocks. The use of this technology is currently very intense and a considerable amount of papers on rock research supported by CT have been published.

CT-Scan technology leads to a better understanding of their mechanical behavior. In this sense, it is interesting to compare the data provided by CT scans with the results of usual tests to determine the quality of rock masses, in which parameters such as density, porosity, sonic speed, strength or durability are measured. In addition, one of the most relevant research lines is the one that studies permeability and its influence on rock degradation. Defects in rock masses, and in particular cracks, are one of the preferred ways for the appearance of water filtrations and permanent flows, which over time can further damage the mass. This aspect is of interest in coal mining, as demonstrated in the numerous works published in recent years [57,58] (Figure 7).

Another application is the analysis and characterization of the damages produced by environmental actions. In particular, there are several publications that evaluate the variations in the microstructure of rocks as a result of freeze-thaw cycles [59] and thermal effects [60]. Besides, some projects have been recently developed to analyze the interaction of rocks used in construction with the polluting gases of the atmosphere [61]. This topic is particularly interesting for the design of the maintenance in historic buildings, such as cathedrals.

The study of rock fracture mechanics is another research line in which CT has potential applications. On the one hand, this is a field related to mining, with the aim of having a better control of induced cracking [62]. In these cases, CT scanning can help to generate predictive models of crack propagation, so that the exploitations are able to produce blocks of optimal size,

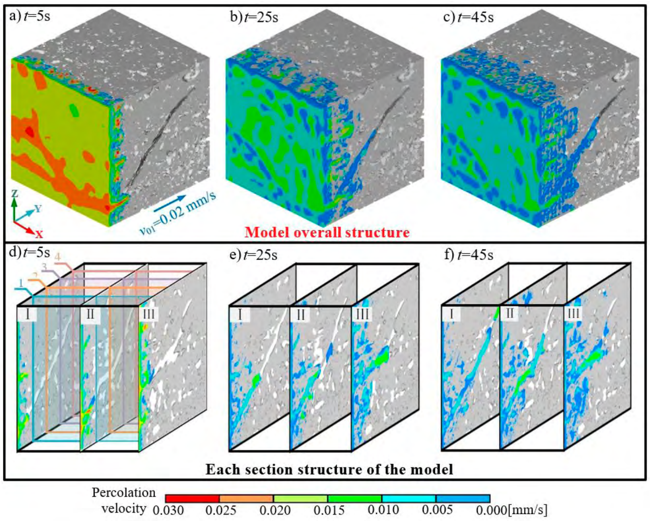

Figure 7. Analysis of water filtration in a model of a carbon specimen generated from CT images: (a-c) general distribution of filtration at different times, (d-f) distribution of filtration in a series of monitored planes [57].

with the consequent savings in costs. On the other hand, this issue is also linked to hydraulic fracturing (or fracking). In recent years, several studies have been published using CT to explore the internal microstructure of all phases of the rock mass (solid, liquid and gaseous), as well as its evolution over time [63].

At present, there are some novel research lines that apply the CT to the study of rocks. One of them is the generation of models to simulate the behavior of masses under different actions or to analyze the water flows inside them [57]. There are also some recent works that combine CT scanning and 3D printing to evaluate the microstructure of rocks [62].

8.

COMPUTED TOMOGRAPHY IN CONCRETE

Concrete is the most commonly used building material worldwide. Among its most important advantages are its low cost, a globally accessible production technology, the ease of adaptation to any geometry and its durability. However, it also has well-known disadvantages, such as its low tensile strength (in the case of plain concrete), the reduced dimensional accuracy of the elements and the high dispersion of its mechanical properties. This last issue is the most important in terms of the application of CT-Scan technology.

The macroscopic behavior of concrete depends largely on its microstructure. However, the control of the internal matrix of concrete is quite complicated, since it is a heterogeneous material by nature. The CT fits perfectly in this environment, allowing the analysis of all the phases found in its internal microstructure: aggregates, cement, water, pores, cracks and in some cases, fibers.

The first investigations that applied CT techniques to study concrete are quite early. One of these works is the one carried out by Morgan in 1980 [64], in which pores and cracks in concrete were analyzed with a precision of about one millimeter. Nowadays, this technology is more and more widespread, and a remarkable number of articles have been published using data provided by CT scans.

Three fields of application of CT to concrete are worth considering separately: the analysis of the internal matrix (with special emphasis on porosity), the study of crack patterns and the study of the microstructure of fiber-reinforced concrete.

8.1. Applications to the study of the internal matrix

As previously mentioned, the microstructure of concrete has a determining influence on its mechanical properties, which partly explains the dispersion it shows. For this reason, the study of the internal porosity of concrete arouses great scientific interest. In this sense, CT in combination with digital image processing software, enables to obtain the geometrical parameters of the pores (position, length, surface, volume, etc.). Furthermore, these data can be used for the generation of finite element models that simulate the mechanical behavior of concrete. There is a large number of articles published recently on this subject [65–69].

Another point is the study of the influence of the different types of additives on the final microstructure of concrete. In particular, in the last few years several investigations have been conducted on the effects caused by super absorbent polymers (SAP) [70,71]. This is a novel additive whose function is to mitigate the autogenous shrinkage of concrete.

Moreover, the data obtained from CT scans are used as a basis to develop statistical studies that eventually allow establishing correlations between the microstructure of concrete and its macroscopic behavior. Many research projects have studied the influence of porosity on the durability of concrete, its response to cyclical fatigue loads and its behavior under freeze-thaw cycles [70,72].

In addition, the analysis of the internal matrix is related to the study of special concretes; in particular, pervious concrete [73] and recycled aggregate concrete [74]. Finally, it should be noted that microstructural studies not only help to understand the behavior of hardened concrete, but also of fresh concrete. In this case, there are several works that use CT to study the evolution of porosity with the curing time of concrete [71,75] (Figure 8).

8.2. Applications to the study of crack patterns

Another very interesting application of CT-Scan technology is the analysis of the distribution of crack patterns, given their close relationship to the durability of concrete. In this respect, a post-processing with digital image processing software allows to filter out the defects present in concrete, discarding pores and isolating cracks. In recent years, several articles have been published using CT to study fracture mechanics in concrete and other quasi-brittle materials [76,77]. Moreover, scan data are sometimes used to generate predictive models that simulate the fracture behavior of concrete.

The non-destructive nature of CT allows scanning to be performed at different stages throughout the life of concrete. This is highly relevant for phenomena such as fatigue and freeze-thaw action, which cause accumulated damage to concrete in the shape of micro-cracks that progress to the failure of the structural element. There are a great number of published articles that evaluate the damage produced by cyclic fatigue loads [78–80] and freeze-thaw cycles [81–83], as well as their evolution in time. It is also interesting the comparison made in some of these works between the crack patterns in cyclic tests and the results of equivalent static tests [84] (Figure 9).

8.3. Applications to the study of fiber reinforced concrete

At present, one of the most active research lines is examining fiber-reinforced concrete. CT is of great help in this field, allowing to isolate each fiber and obtain its location, distribution, orientation, etc. Several works have been published studying the distribution of different types of fibers in concrete [78,85]. Besides, a particular case of the analysis of fibers is the study of its orientation, since this parameter is determining in the macroscopic response of the concrete. For this reason, various projects have also been carried out in this respect, even evaluating techniques to induce the alignment of the fibers [86,87].

As with conventional concrete, the use of CT in fiber reinforced concrete is the basis for establishing correlations

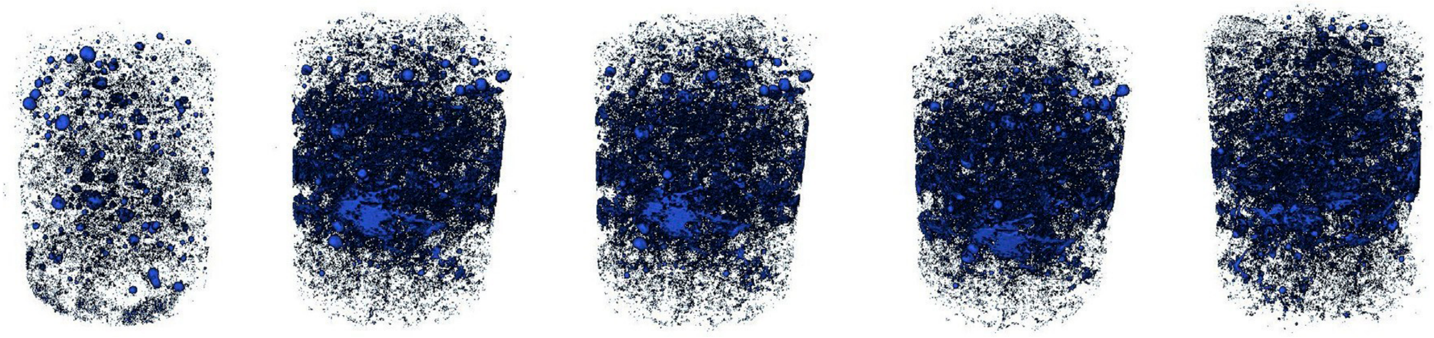

Figure 8. Porosity development in a steel fiber reinforced mortar specimen over curing time. From left to right: days 1, 2, 3, 4 and 7 after casting [75].

between the microstructure (in particular, pores and fibers) and the macroscopic response. In the last few years, numerous works have been published studying the influence of porosity and fibers (distribution, orientation, etc.) on fracture behavior [88], fatigue strength [78] or ductility [87] (Figure 10).

Finally, a research line also existing lately, although less explored, is the application of CT to study the effects of fibers during concrete curing [75].

9.
CONCLUSIONS

Computed tomography is a technology with great application potential in many fields of science and technology, as evidenced by a significant number of scientific articles published in the last two decades. In particular, in the case of engineering one of its most relevant utilities is the microstructural analysis of materials, which serves as a basis for researchers to a better understanding of their macroscopic response.

In this paper, some of the fields in which the use of CT has a greater interest are collected: paleontology, archeology, metals, composites, pavements, rocks and concrete. However, there are other disciplines in which this technology is used, as well as many other applications that have not yet been explored in detail.

Data supplied by CT scans can be used at various levels. The most basic use consists of the interpretation of the images with the naked eye without any kind of post-processing. Obviously, this is a very poor use of this technology, missing its full potential. The next step is to use digital image processing software to extract the most relevant data from CT images. In this way, it is possible to have a quantitative knowledge of the microstructure of materials. Furthermore, by performing statistical studies that combine CT data with mechanical test data, correlations can be established between the microstructure of a material and its macroscopic response. Finally, it is possible to take the information provided by CT and export it to a finite element software. In this way, exact models of the specimens can be created, including all the defects with their real position and size. Therefore, the numerical simulations carried out are much more precise than those made with ideal theoretical models, allowing a better adjustment of the latter.

It is expected that over the next few decades technological advances will bring about more efficient CT scans, with

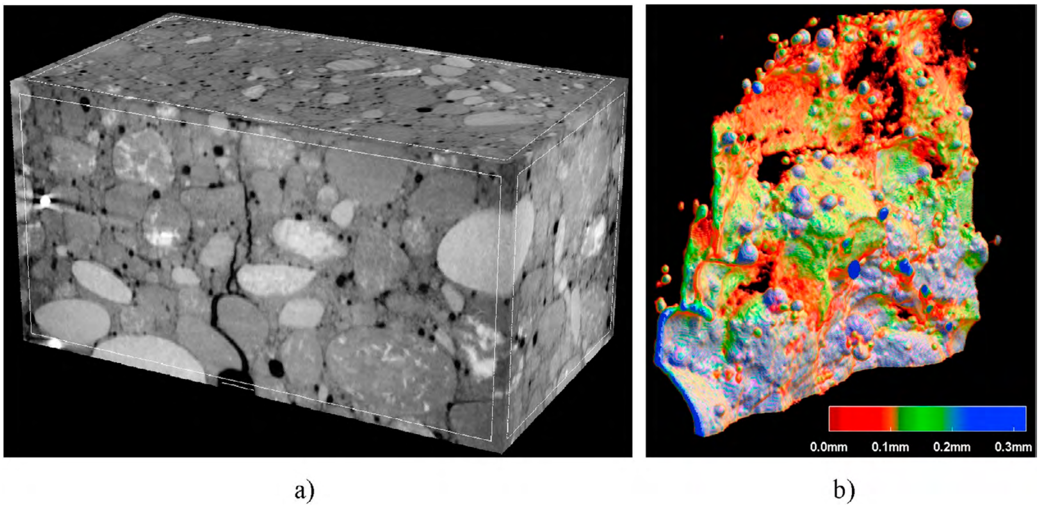

Figure 9. (a) CT image of a concrete specimen subjected to three-point bending, (b) segmentation to obtain the resulting macro-crack and study the size of its opening [84].

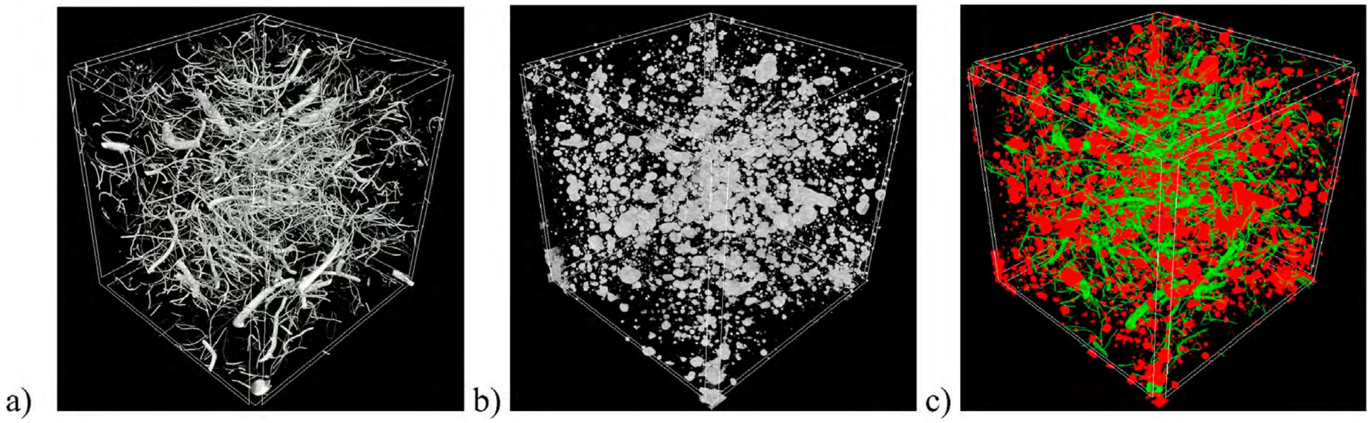

Figure 10. Segmentation of a recycled steel fiber reinforced concrete specimen: (a) distribution of steel fibers, (b) distribution of pores, (c) combination of fibers (green) and pores (red) [88].

lower processing times and higher resolutions. In this context, researchers will be able to use them to get a better understanding of the microstructure of materials and hence a better understanding of their behavior.

Acknowledgements: The authors are grateful for the financial support from the *Ministerio de Economía y Competitividad*, BIA2015-68678-C2-R, Spain.

Conflicts of interest: The authors declare that there are no conflicts of interest.

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