A NON-DESTRUCTIVE METHOD FOR MEASUREMENT OF MOISTURE IN BUILDING MATERIALS

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Abstract: *The measurement of moisture in porous building materials is an important issue in many situations. Especially in the case of the restoration of historical monuments, it is desirable to use non-destructive methods that can be easily adapted to field conditions (e.g., for assessment of moisture in building walls). Such a method is proposed in this work. It is based on the measurement of the incoherent (Compton) scattering at backward angles, of gamma-rays emitted by a source. This approach is rather flexible because both the source and the detector can be placed on the same side of the measured object (e.g., a wall). A simple experimental setup is presented, and used to demonstrate the possibility to measure the water contents in a common building material, red fired-clay bricks. The method gives, in general, at least an indication concerning the moisture content, a condition to get a quantitative estimation being the homogeneity of the investigated material(s).*

Keywords: *non-destructive measurement; moisture content; building materials; gamma-ray Compton scattering.*

1. INTRODUCTION

The interplay between water and different materials is an important theme in many fields. In particular, the water mediates most of the processes that cause the degradation and decay of the buildings. This is because many of the inorganic building materials, such as brick, stone, plaster, mortar, and concrete, are porous and absorb and transmit water through capillarity. Especially in the case of degraded historical monument buildings considered for restoration, it is important to detect the water infiltrations which lead to humidity of the walls above the normal limit, and contribute to processes of physical, chemical, and biological degradation [1, 2].

There are direct and indirect methods to measure the moisture in building materials, or in building walls. The direct methods (gravimetric, that is, weighting the water contained in a sample, or chemical, which measures the product of a chemical reaction with the water from a sample) are destructive, because samples from the measured object are needed. In many situations and especially in the case of the restoration of historical monuments, this procedure in not desirable or not acceptable. There are many indirect methods for moisture measurement, which rely on measuring a physical property which is known to change with water addition, and many of them are non-destructive. For example, a rapid method of inspection is that of measuring the electric resistance, or another electric property, between two points (electrodes) on the surface of the material – but this is not a quantitative method, as it only gives an indication about the moisture on the surface, which also depends on the quantity of salts present in the solution. A large category of indirect methods is based on probing the desired material by electromagnetic or nuclear radiations [3]. For example, the nuclear magnetic resonance is a very precise method but it can be applied only on samples and requires costly equipment [4, 5]. Neutron transmission or backscattering is also a

sensitive method, but it requires relatively bulky and costly devices [6, 7]. In this work we focus on the use of the attenuation and scattering of nuclear electromagnetic radiations (X-rays or gamma rays).

The interaction of gamma rays with materials is a well understood process, and can be used to probe inside of bulky objects, because they penetrate at appreciable depths (depending on the incident energy and on the type of material, depths of the order of several centimeters are usual). For photons (radiations) with energies between tens of kiloelectronvolts (keV) and 1-2 MeV, there are two interaction processes of interest. The first is the photoelectric effect, which means a complete absorption of the energy of the photon by a bound atomic electron [3]. The second is the incoherent (or Compton) scattering, by which a photon interacts with an electron of the medium, and is scattered at a certain angle with respect to its initial direction, after giving part of its energy to the electron. Multiple scatterings of this kind make take place before a final photoelectric absorption act. Of interest to us is that these interactions take place on the electrons of the examined material, therefore they will depend on the electron density – which in many cases has a simple relationship with the mass density of the material. Therefore, their measurement can be used to determine density or changes of density (which may be caused by voids, insertions of other materials with a different density, or water addition).

There are two categories of measurements that can be performed with gamma rays. First, one can measure the *attenuation* of a gamma-ray beam at the passage through a certain thickness of material. This attenuation is sensitive to both the density and the chemical composition. The method was used, e.g., to determine the moisture in soil, by measuring the variation in density due to water addition [8]. By using two gamma-ray sources with different energies, one can employ this method to simultaneously determine the dry density and the moisture content [9]. However, this is a *transmission* experiment, that is, the radiation source and the detector must be on opposite sides of the measured object. In most of the cases, and notably in the case of building walls, such measurements cannot be done. The measurement of the *Compton scattering* by an object also provide information on its density, but, unlike the attenuation method, the source and the detector can be placed on the same side of the measured object, a fact that gives an increased flexibility to the method [3]. For this reason, the Compton backscattering of gamma rays found numerous applications, some examples being: in medicine, for variations in the density of bones, soft tissues, superficial organs; inspection of concrete structures or underwater pipelines; inspection of corrosion in aircrafts, or on surfaces; water content of soils (see [3] for these and other applications).

In this work is presented a method based on the Compton backscattering of gamma rays to determine variations in density due to moisture. Under certain conditions, its immediate application concerns the examination of porous building materials. The experiments that we performed concentrated on a simple device that can be easily used in field measurements, and on a reliable method of data processing that provides a reasonable response in terms of the measured effect for small moisture contents.

2. EXPERIMENTAL SETUP

Fig. 1 shows an ideal setup for the measurement of a single Compton scattering process. A source **S** is strongly collimated such that it irradiates the material to be examined (which has an electron density $\mathbf{D_e}$) with a narrow beam of intensity $\mathbf{I_0}$. One Compton scattering takes place inside the material, and the resulting photon deviated by the angle $\boldsymbol{\theta}$ is recorded in the detector **D** which is also strongly collimated and does not see the source directly. The intersection of the two fields of view (of the source and of the detector) defines a small volume **V** that is actually investigated.

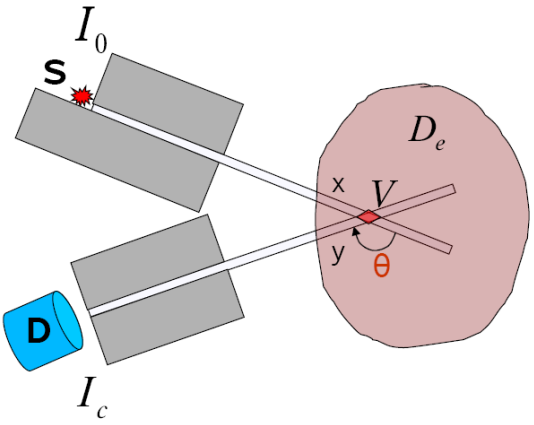

Fig. 1. Sketch of an ideal setup for measurement of single Compton scattering events.

With this setup we can therefore control the depth within the material where we measure. The intensity I_c of the radiation detected by the detector is given by the expression:

$$I_c = I_0 C_i V D_e e^{-\mu_i x} e^{-\mu_f y} + m.s. \qquad (1)$$

Here C_i is a constant that accounts for geometry, detection efficiency, and probability of the Compton event, V is the investigated volume, D_e is the electron density of the material, and the two exponentials give the attenuation of the incident (i) and final (f) photons (according to the well-known exponential law [3]) on the distances x and y traveled into the material, respectively, μ_i and μ_f being the corresponding attenuation coefficients. "m.s." denotes a possible multiple scattering events contribution, which is very small if the collimation is strong. If eq. (1) corresponds to dry material, a similar equation can be written for the wet material, in which the electron density and the attenuation coefficients are increased due to the addition of water. .

We performed experiments on a common building material, red fired-clay bricks. A ^{241}Am source was used, with an activity of 0.385 GBq (385 million decays per second). This source emits practically only one gamma ray, with energy of 59.5 keV (comparable with the energies emitted by radiographic X-ray devices). The attenuation coefficient of this radiation in our bricks was measured as μ=0.40 cm^{-1}, which means that the 59.5 keV beams, reduces its intensity to one half after passing through 1.73 cm. With the available gamma-ray source intensity, measurements with both the source and the detector strongly collimated, as in Fig. 1, led to long times of measurement (of the order of tens of minutes, too long for practical in field measurements). Therefore we performed measurements with the detector completely uncollimated, as shown in Fig. 2. As a detector, we used a 2"x2" plastic scintillator crystal made of lanthanum bromide doped with cerium ($LaBr_3$:Ce) [8].

Fig. 2. The experimental arrangement of the present experiments.

The source is placed inside a lead brick, in a 6 cm deep hole of 5 mm diameter (visible in the photo). The detector, completely uncollimated, is placed along the lead protection. The measured brick (seen from above, left side of the photo) is placed at 8 cm distance from the face of the detector. This type of geometry is not so usual in Compton backscattering measurements [3] because it allows the detection of multiple scatterings too.

On the other hand, the good energy resolution of our detector allowed a good enough estimation of the single scattering events, as will be discussed later.

3. MEASUREMENTS AND RESULTS

The procedure of our measurements was as follows. A number of bricks were selected from the same batch. Their density, deduced by measuring their geometric sizes and the weights, was found constant with a good accuracy, 1.58 g/cm^3 with an error of 3%, that indicated a good homogeneity of the material used for the batch. One brick was kept "dry", as a reference, while the others were loaded with different water quantities, determined by weighting the wet brick, after letting it a long enough time such that the water distributed itself uniformly within the whole brick, by capillarity. We defined the moisture content as

$$U = \frac{M_{wet} - M_{dry}}{M_{wet}} \qquad (2)$$

where M is the mass of the brick measured in the specified state.

Then, spectra of the backscattered radiations from both the dry brick and the wet bricks were measured in the geometry shown in Fig. 2. For this, the signals from the detector, amplified with a linear amplifier, were analyzed with a multichannel analyzer which provides the energy spectrum as the number of events registered by the detector as a function of a channel number. The channel number is proportional to the energy of the radiations, and a calibration of this (usually linear) relation is obtained by detecting known sources. An example of measured spectra is shown in Fig. 3. The upper panel shows a spectrum measured with a weak ^{241}Am source placed directly in front of the detector. Besides the expected 59.5 keV peak, another peak with energy of 32.0 keV is visible. This is due to the weak intrinsic radioactivity of the detector itself, a characteristic of this type of detectors [10], which in the present case constitutes a nice calibration point.

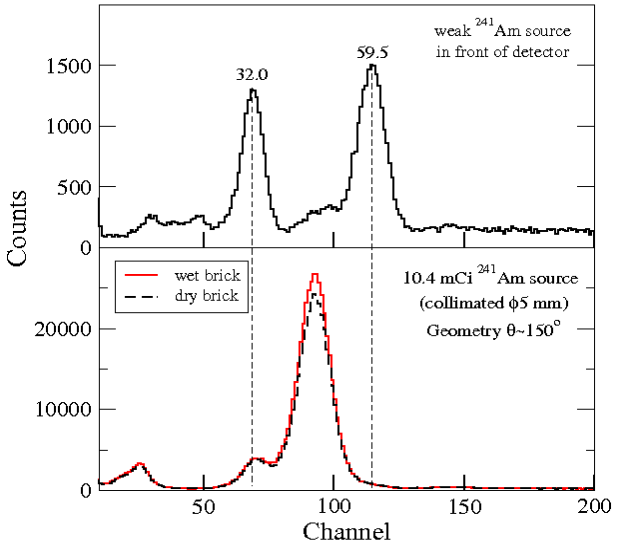

Fig. 3. Spectra measured in the geometry of Fig. 2.

Upper spectrum: measured with a weak ^{241}Am source in front of the detector. The peaks are labeled with theis energy in keV. Lower spectrum: Compton scattering on two bricks. Dashed line histogram: measured for the reference (dry) brick. Solid line histogram: measured for a wet brick (saturated with water). In the lower spectrum of Fig. 3 one can see the large peak representing the radiation Compton scattered by the bricks, having a lower energy, of 48.9 keV, which corresponds to the expected energy of a 59.5 keV photon [3] scattered at the average angle of about 150^0 in the geometry in Fig. 2.

One notes that this peak contains more counts in the case of the wet brick (relative to the dry brick).

This fact reflects an increased density, which we interpret as due to the water addition. By comparing the measurements of wet bricks with the dry reference, we define the measured effect:

$$E = \frac{I_{c(wet)} - I_{c(dry)}}{I_{c(dry)}} \qquad (3)$$

where I_c is the measured intensity of the scattered radiation (as shown in Fig. 1) in the specified situation. This I_c is, actually, the area of the Compton scattered peak from Fig. 3. By measuring the effect E as a function of different (controlled) moisture contents U, one obtains a calibration curve which can be used when bricks with unknown U are measured. The intensity I_c is obtained either simply by adding up the contents of the channels of the large peak in Fig. 3, or, more exactly, by using a computer program which fits the spectrum with standard peak shapes (as observed in the upper spectrum of Fig. 3). This last procedure is preferred because in this way one can remove some of the multiple scattering events which are visible in the lower spectra of Fig. 3 as a slight asymmetry on the low-energy side of the Compton scattering peak (this procedure will be detailed in [11]).

Before presenting results, let us make an estimate of how large we expect the measured effect E to be. For this we use eq. (1) but, for simplicity, we assume the extreme situation that we measure only at the surface of the material (x and y equal to zero in Fig. 1). This means that we have no attenuation of the radiations (the exponential functions in eq. (1) are equal to 1). Under this simplifying assumption, only the electron densities of the dry, and wet brick, respectively, will determine the value of eq. (3). These two densities can be written as:

$$D_e = \frac{\rho}{u}\Sigma w_i \frac{Z_i}{A_i} = 0.5\frac{\rho}{u}; \qquad D_{e(wet)} = (0.5 + \frac{10}{18}\frac{U}{1-U})\frac{\rho}{u} \qquad (4)$$

The first expression in (4) is the usual one for a material composed of several elements with atomic number Z_i, mass number A_i, and mass weights w_i; ρ is the mass density and u is the atomic mass unit [3]. Because in the composition of a usual clay brick we have light elements (like O, Na, Al, Mg, Ca, Fe) with Z/A values of 0.5, one sees that in this case the electron density is proportional to the mass density ρ. In the case of the wet brick (the second expression) water was added in the proportion U defined by eq. (3), and the expression was derived taking into account that the volume of the brick remained the same after absorbing the water. From equations (1), (3), and (4) one gets (for x≈0):

$$E \approx \frac{I_{c(wet)}}{I_c} - 1 = \frac{D_{e(wet)}}{D_e} - 1 = 1.111\frac{U}{1-U} \qquad (5)$$

which, for small values of U, becomes:

$$E \approx 1.111U \qquad (6)$$

We note that this is the maximum effect that we can expect. In our measurements we actually perform a bulk measurement, and the effect will be smaller than that of eq. (5) because of the attenuations of the incident and scattered radiations (Fig. 1 and eq. (1)).

Fig. 4 shows results of our measurements. Two sets of measurements were performed, one in which the measuring time was of 10 minutes per point (spectrum), and a second, on a different set of bricks, in which the measuring time was of 2 minutes per point. Each point in this graph, calculated with eq. (3), represents an average of at least two independent measurements; for each brick, we measured the scattering on at least two regions, chosen at random on different faces of the brick. The good concordance obtained between such measurements ensured that the material was homogeneous and that the water was uniformly distributed inside.

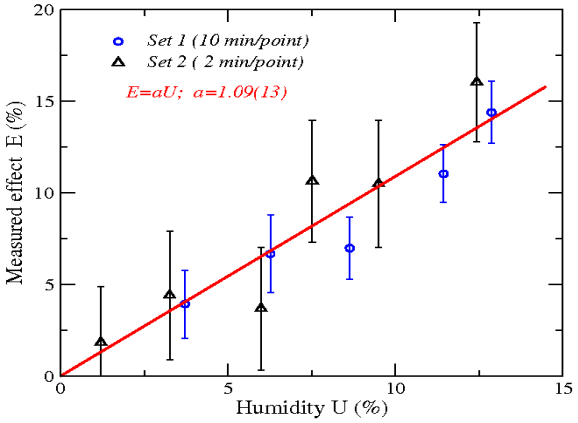

Fig. 4. Results of two sets of measurements (see text for details). The line is a straight line fit to the data points, with the indicated slope of 1.09.

Although the second set of measurements has larger (statistical) errors, it agrees well with the first one. The line in the plot is a straight line fit (passing through the origin) to all these experimental points. The slope of this line is 1.09 (with an error of 0.13) which is close to what we expected [equation (6)].

4. CONCLUSIONS

We have shown that measuring the Compton backscattering of the 59.5 keV gamma ray of a ^{241}Am source can be used as a non-destructive method for the determination of the moisture contents within massive objects. This was demonstrated on a porous building material, fired-clay brick. With the geometry used in our measurements, with an uncollimated detector, this is a bulk measurement. It is difficult to estimate the investigated volume in our geometry, but, based on the measured attenuation coefficient one can state, qualitatively, that we measure an effect averaged on depth of up to 1-2 cm. This measurement is an indirect, relative one, it needs a reference material (in our case, the "dry" brick), and a calibration curve (like that in Fig. 4). It is very important to emphasize what is measured. What we actually measure is a variation in the density of the material. If the material we study is highly homogenous, then we can relate the observed variation to the moisture content, as it was done, in a controlled way, in the present study. Our bricks behaved like a rather homogenous material, but in practice this may be a rare case – insertions of other materials, of a different density, or voids, could also lead to a variation of the apparent density. One should also conduct studies for more materials (cement, mortar, stone, layered structures). The setup used in these experiments (Fig. 2) is rather compact and light; therefore it lends itself to field applications. In principle, it would be desirable to collimate also the detector and thus be able to measure at given depths within objects (or materials). To do this in reasonably short measuring times, one should use stronger gamma-ray sources. This, however, requires more massive protection, thus increasing the size and weight of the apparatus.

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Manuscript received: 28.04.2010
Accepted paper: 18.05.2010
Published online: 22.06.2010