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Recommendations of RILEM TC 177-MDT: 'Masonry durability and on-site testing'

MD.E.1: Determination of moisture distribution and level using radar in masonry built with regular units

The text presented hereafter is a draft for general consideration. Comments should be sent to the TC Chairperson: Prof. Luigia Binda, Politecnico di Milano, Department of Structural Engineering, Pza. Leonardo da Vinci 32, I-20133, MILANO, Italy; Tel.: +39 02 2399 4318; Fax: +39 02 2399 4220; Email: luigia.binda@polimi.it, by 30 September 2005.

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SUMMARY

There is an enduring interest in the durability of masonry acting as a composite material especially because a very large proportion of the world's heritage buildings and civil engineering structures are predominantly constructed from this material. There is a continuing need for information on the best way to maintain a state of good preservation of masonry and on sympathetic techniques for repair and reinstatement of deteriorated masonry.

A major factor in cause of damage to masonry is an elevated moisture content. Before conducting any repairs, it is important to assess the moisture situation of a structure to be able to identify the causes of moisture as well as to determine the moisture content and its distribution rapidly and, whenever possible, non-destructively. This Pulsed RADAR based technique is non-destructive, can be performed from one accessible side of a wall and facilitates determination over wide areas of a structure to give a more comprehensive picture of the state of a building than single – position tests such as drilling / coring.

1. SCOPE

This recommendation describes the use of impulse radar as a method to determine the variation in moisture distribution and mean moisture content in solid masonry walls made with prismatic, solid masonry units. The method is based on the influence of moisture content on the dielectric properties of the masonry material which in turn influence the travel time and the attenuation of electromagnetic impulses through the masonry. To determine mean water content, calibration tests are necessary. . These parameters are interrelated by calibration curves. As measurement values, the travel time and the attenuation of the electromagnetic impulses are determined.

Guidance is given to the selection of useful test positions, the principle of the method, the optimum conditions of testing, the apparatus, the procedure of data recording and analysis, the assessment of the moisture situation and the test report. It is recommended that this method is only be used by experienced practitioners.

2. BACKGROUND

A major factor in cause of damage to masonry is an elevated moisture content [1]. Before conducting any repairs, it is important to assess the moisture situation of a structure to be able to identify the causes of moisture as well as to determine the moisture content and its distribution rapidly and, whenever possible, non-destructively.

In the past it was highlighted that current methods for quantitative determination of moisture were often not adequate [2, 3], *i.e.* the measurement results are not accurate enough, they are frequently not repeatable as they are not always completely non-destructive and they can often only be carried out to examine small areas whereas large-scale scanning investigations are to be preferred.

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For some decades now different microwave methods have been employed to determine the moisture content of solid materials [4, 5]. They are based on experimental determination of the dielectric properties of materials, as the real and the imaginary parts of the complex dielectric constant are directly influenced by moisture. In general, such moisture measurements are based on transmission of continuous microwaves through the target material.

In the pulsed impulse radar method, the moisture determination is based on reflection or transmission measurements but generally from one side of structures such as walls. The advantage of this technique over other methods (*e.g.* bore-hole based) using continuous microwaves is that the measurements are completely non-destructive and that large surfaces may be scanned rapidly [6-13].

3. TEST SITE

Typical test sites are usually masonry walls with thickness up to 36 cm for new building constructions and up to 1.5 m of historical brickwork for traditional constructions. The thickness of the wall has to be known or has to be determined using methods other than radar. The area to be investigated has to be accessible, because the measuring antenna has to be in direct contact with the surface of the wall. A smooth surface is not required since the coupling of the antenna to the surface has only a negligible influence on the measurement results.

The number of scans over the wall is governed by the desired resolution. A suitable grid should be marked onto the surface of the wall under investigation.

When access on both sides of the masonry wall is possible, transmission measurements can be performed. Here, two antennas operating as transmitter and receiver are positioned face to face at opposite sites of the wall.

In most cases, the wall under investigation is only accessible from one side and measurements have to be done in reflection mode. Thus, for the calculation of moisture content, a reflection from the back face is required. Since the penetration depth of the electromagnetic impulses depends on the frequency and moisture content, the appropriate antenna has to be selected. For very thick and moist walls the attenuation may be too great, and the wall will completely absorb the reflection from the back face. Moisture measurements with radar will then not be possible.

4. PRINCIPLE OF THE METHOD

The use of microwaves for moisture measurements is based on the experimental determination of the dielectric properties of dry and moist building materials. The complex dielectric constant of a heterogeneous system, such as a moist building material, is determined by the geometry of its components. There are quite a few mixing theories which may be used for the theoretical characterisation of such a heterogeneous system using different methods of approximation [14, 15]. However, the calculated values often deviate from the experimentally determined values. For this reason experimentally determined calibration curves are still indispensable [6].

The experimental determination of the dielectric properties takes into account that the propagation velocity of electromagnetic impulses is influenced by the real part ε' of the dielectric constant of the respective building material which in turn is greatly effected by the moisture content, the temperature, the frequency range and the salt concentration. When the thickness z of a building material is known, the real part may be calculated by determining the travel time t, neglecting the effects of dispersion, using the following equation for reflection measurements:

$$\varepsilon' = \left(\frac{c_0 * t}{2 * z} \right)^2 \tag{1}$$

ε': real part of dielectric constant [1]
t: travel time [s]
z: thickness of the wall [m]
c_0: speed of light in vacuum [m/s]

In the frequency range between 1 and 10 GHz there is no measurable attenuation of radar pulses in dry building materials, while losses are quite high in water. This existing frequency range is therefore suitable to determine the moisture content of building materials by means of the imaginary part ε'' of the complex dielectric constant which characterises the absorption of a transmitted electromagnetic wave:

$$\varepsilon'' = -\frac{c_0}{\omega * z} \sqrt{\varepsilon'} \ln \frac{E_z}{E_0} \tag{2}$$

c_0: light velocity in vacuum [m/s]
ω: angular frequency [rad]
z: thickness of the building material [m]
ε': real part of the complex dielectric constant [1]
ε'': imaginary part of the complex dielectric function [1]
E_0: emitted amplitude of the electromagnetic wave [1]
E_z: received amplitude of the electromagnetic wave [1]

As all the parameters are either known or may be determined by means of the measurements, Equation (2) may be used to calculate the imaginary part of the complex dielectric constant.

The principle of the determination of moisture content with impulse radar is based on the measurement of travel time and amplitude of short electromagnetic impulses which travel through the material under investigation as shown in Fig. 1.

As mentioned before, the dielectric properties of brick masonry materials are primarily influenced by the moisture content but the temperature, salt content, and frequency also have an influence. Since the dielectric properties of dry brick masonry materials are nearly independent of these parameters, only the dielectric properties of water [and its salt content] contribute to these variations. These dielectric properties of free water can be calculated using the equations of Debye [16]. Between 500 MHz and 10 GHz, the real and imaginary part changes drastically with frequency. The content of dissociated salt ions has a great influence on the electric conductivity and

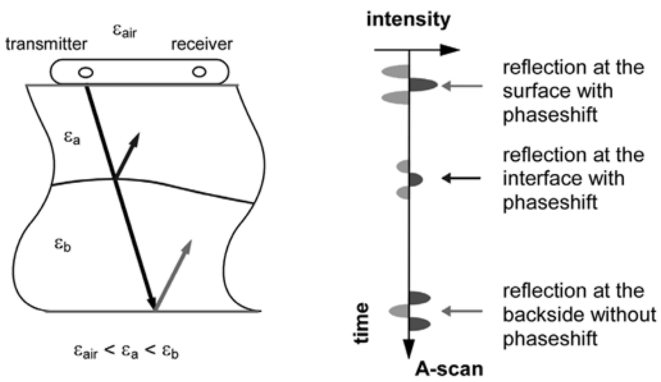

Fig. 1 - Principle of radar measurements in reflection configuration.

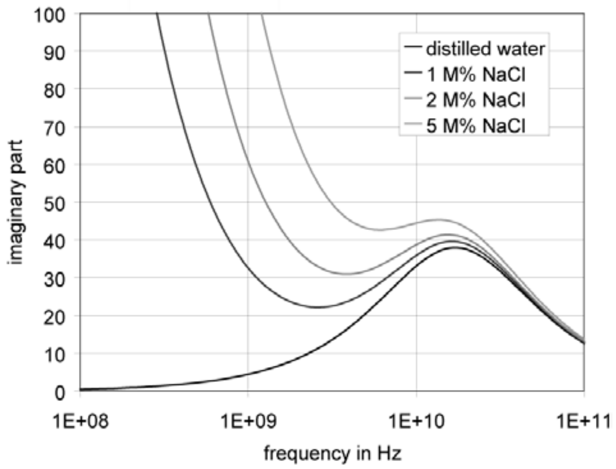

Fig. 2 - Imaginary part of the dielectric constant of water as a function of frequency for different salt concentrations.

thus on the imaginary part, as shown in Fig. 2. The real part as well the imaginary part are influenced by the temperature as described in [16].

Since the dielectric properties of moist building materials depend on the frequency, the travel time and absorption of the different frequencies forming the signal vary with the frequency. This effect is called dispersion and leads to a modification of the pulse shape in the time domain, *i.e.* the pulse becomes broader.

5. CONDITIONS OF TESTING

Tests can be performed under every condition except during heavy rain and when the temperature falls below 0°C and converts water to ice. The higher limit of the temperature is set by the available calibration curves. If there is a large temperature gradient across the cross-section of the wall, the surface temperatures on each side should be measured and taken into account for the calculation of the dielectric properties.

The masonry material should not be too inhomogeneous. Suitable materials are brickwork, blockwork or ashlar stonework. Masonry built with hollow or perforated units or stones with cavities is not suitable for the method. Render thickness has to be lower than 10% of the total wall thickness.

6. APPARATUS

Typical commercial impulse radar systems work in the frequency ranges from 200 MHz to 2.5 GHz depending on the antennas which are connected to the system. The main unit of a radar system consists of a Personal Computer containing a large hard disk or other large data storage media (tape) for digital data recording. For some radar systems, up to four antennas with different frequencies can be connected to the main unit. Depending on the application, different types of antennas like horn antennas or dipole antennas with the shape of triangles can be used [17]. The generators for the short electric impulses are located directly in the housing of the antennas or are connected to the antenna via a short high frequency cable. A survey wheel can be attached to these antennas for external triggering of the impulse generator in relation to the position of the antenna. A scheme of a typical radar system is shown in Fig. 3.

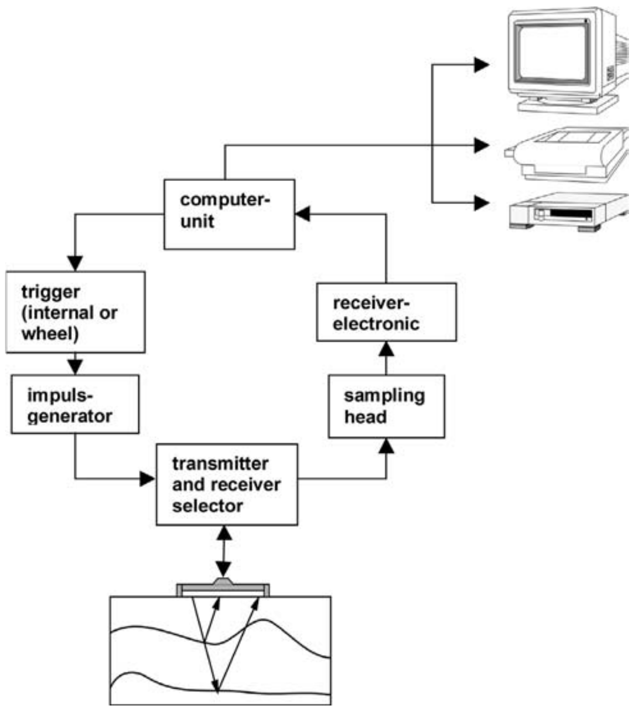

Fig. 3 - Principle of radar measurements in reflection configuration.

Commercial software programs are available for data analysis and presentation of 2D and 3D radar images of the tested structure. For fast data processing, a set of small individual programs written in C or selected macro languages might be very helpful.

The following equipment is required, to perform moisture measurements with radar:

- Radar system for measurement control and data storage
- Antenna system
- Survey wheel for triggering related to the recorded traces as well as measuring tape, folding ruler, plumb-line and water level for the preparation of a measurement grid on the surface of the building structure

- In some cases, the geometry of the measurement area is more complicated and requires the recording of positioning with an optical theodolite
- Camera, digital camera or video camera for the documentation of the building site as well as of the performance of radar measurements
- Software for signal processing

7. TEST PROCEDURE

Preparation work before testing includes the following:

- Layout of a grid of scan paths (traces) on the surface of the wall under investigation. The edges of this grid will be measured and have to be included in a plan to be related to the moisture values determined by radar. Typical grid line lengths are between 2 and 8 m, typical distances between grid lines can be varied between 20 and 100 cm.
- From the geometry of the investigated wall as well as from the expected moisture and salt contents the appropriate measurement frequency and thus the antenna system has to be selected. In some cases, it is useful to combine different antennas. For thin structures (up to 50 cm) a 900 MHz antenna should be used and for thicker structures a 500 MHz antenna may be needed. For moist material, the maximum wall thickness should not exceed 100 cm.
- Determination of the thickness and, if possible, the internal structure of the wall under investigation. This is required for the determination of the propagation velocity and thus the calibration of the depth scale.
- Determination of the surface temperature on both sides. The temperature has an influence on the propagation velocity.
- Determination of the salt content at reference positions using chemical or physical methods. Dissociated salt ions enhance the conductivity of the material and thus the absorption of the electromagnetic waves.

The detailed testing procedure depends on the goal and the structure to be investigated. Presently, there are no standards for the performance of moisture measurements with radar.

Usually, for the measurements with one selected antenna in the reflection configuration mode the following steps will be performed:

- Selection of the measurement set-up while the antenna has direct contact with the surface of the wall. The following parameters have to be optimised: length of the time scale, gain function depending on time and thus on depth (compensation of absorption), number of impulses and radar scans per recorded metre, horizontal and vertical electronic filters, external or internal triggering (survey wheel or marker).
- Performance of measurements by moving the antenna along the selected grid lines.
- Visualisation of the measurement data and repetition of measurements with different parameters if required

- Data storage on hard disc and a second storage medium for data backup

8. TEST RESULTS

8.1 Data analysis

In the reflection mode, the **real part of the dielectric constant** of the brick masonry material is calculated from the difference in travel time of the reflection from the surface and the back of the wall side reflection using Equation (1). For the calculation of the relative position of each signal on the time scale, any of the following methods can be used:

- Determination of the time where the signal starts to raise over a predefined threshold
- Determination of the time of the first extreme value
- Determination of the first zero crossing after the first extreme value

Several simulations and calculations have been performed to get the best method for data processing. It has been shown that simulations and calculations have the best conformity if the difference in travel time has been determined from the difference of the positions of the **first extreme values** as it is demonstrated in Fig. 4.

For the determination of the **imaginary part** as described in Equation (2), it has to be considered that the intensity of the signal which propagates through the material is not only attenuated due to absorption but also due to reflection at the front and backside, respectively. The opening angle of the antenna as well as scattering effects at other reflection positions also contribute to the reduction of signal intensity. Therefore, in most cases the determination of the imaginary part from reflection measurements is very inaccurate and is only relevant for relative investigations (no absolute values being determined).

From the real and/or imaginary part, the moisture content can be calculated by using calibration curves [6]. An example of these calibration curves is shown in Fig. 5. If no

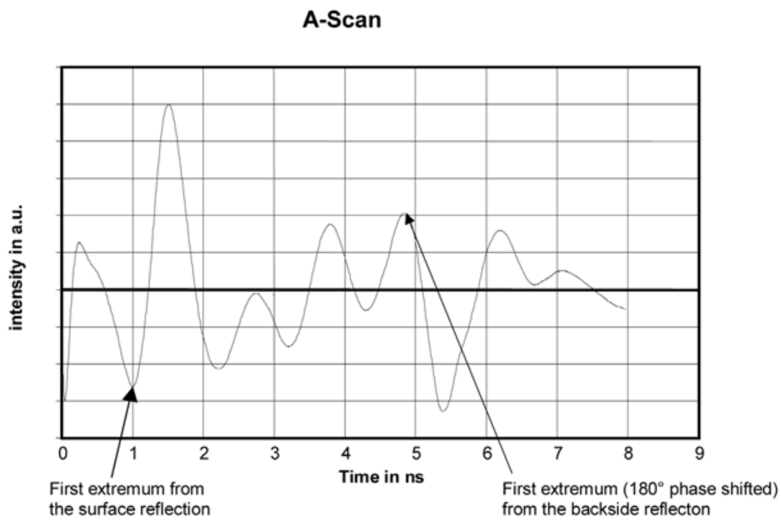

Fig. 4 - A typical radarscan recorded in reflection configuration with the extrema of the surface and back face (backside) reflection.

calibration curves are available, theoretical models can be applied but larger errors have to be considered. Very often, only information about the relative moisture distribution is required. In these cases, calibration is not necessary.

Measurement test results can be presented in tables and/or in 2- and 3-dimensional images. As an example, Fig. 6 shows the real part of the complex dielectric constant of a test specimen made of sand-lime brick which was stored for several weeks in distilled water. After removing the specimen and during the drying process, the radar measurements were performed. The diagram shows the real part as a function of the height of the specimen and as a function of the total moisture content as determined from weighing of the whole sample.

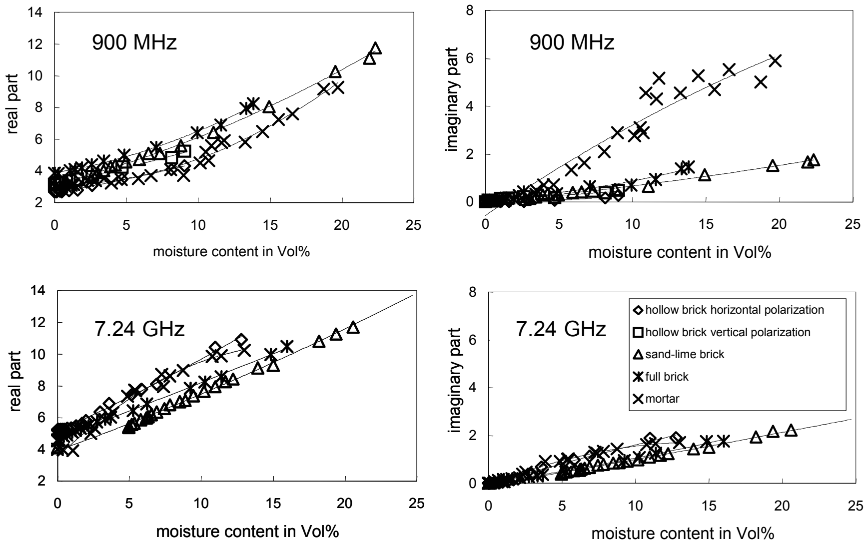

Fig. 5 - Real (left) and imaginary part (right) of the complex dielectric function of different building materials as a function of moisture content measured at 900 MHz (top) and 7.24 GHz (bottom).

8.2 Verification of the results

For verifying the results of moisture distribution and content obtained from the radar measurements, in most cases the extraction of small cores is required at selected areas. The number of cores depends on the size and homogeneity of the investigated structure, but usually three cores (diameter: > 1 cm) are sufficient (diameter: > 1 cm). It is very helpful if these cores are extracted with a core bit. These cores give information on the absolute moisture content (Darr drying), the salt content, the maximum water absorption and also about the composition and layout (position of bricks masonry units and mortar) of the investigated wall. If core extraction is not possible, also endoscopic investigations can be useful or the RILEM drilling method (See 'other recommendations') might be acceptable.

If information on the moisture distribution along the cross section of the investigated structure is required, radar can be combined with microwave borehole absorption measurements [18, 19].

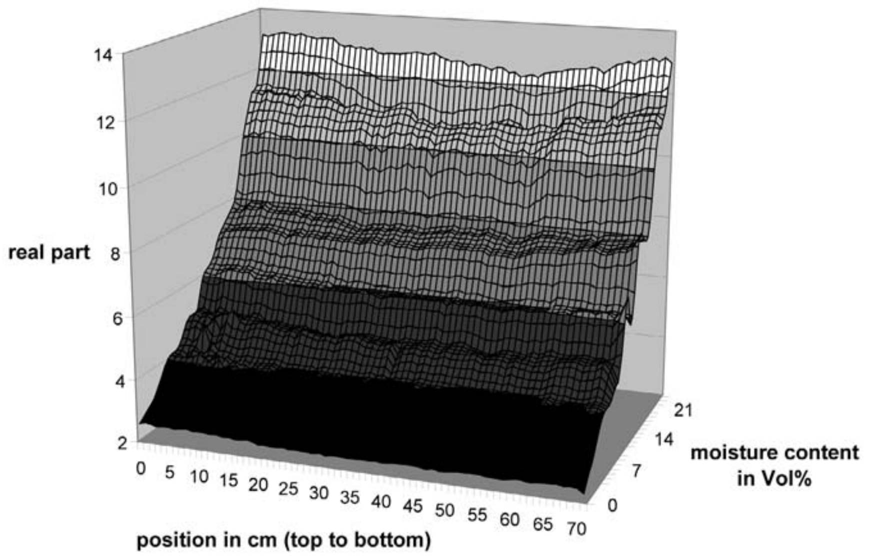

Fig. 6 - 3-dimensional presentation of the real part of permittivity (900 MHz) as a function of position along a vertical line and of the mean moisture content of a physical model made of sand-lime brick during the drying process after storing in distilled water.

9. TEST REPORT

The test report should include the following standard items in addition to any interpretation:

- Reference to this RILEM standard recommendation and a description of any deviations from these recommendations.
- Date, time, location and weather (climate) conditions during the measurements
- Temperature of the object under investigation
- Accurate description of the object under investigation including geometrical data and the main aim of this test, photos
- Information about the building material (*i.e.* porosity, salt content, maximum possible water absorption etc)
- Visual Condition of the object under test (*i.e.* cracks, efflorescence etc)
- Plan containing the position of the measurement traces recorded with radar
- Information about the equipment used (type of system, type and frequency of the antenna etc)
- Data acquisition and signal processing parameters.
- Graphical radar images. Presentation of measured result (radargram)
- Presentation of interpreted results (moisture distribution)
- Results from any additional companion tests (destructive and/or non-destructive)

- Summary of the results, possible performance and recommendations for further investigations, if applicable.

10. RELATIONS TO OTHER RECOMMENDATIONS

- TC127MS D.3 [20]
- Guideline of the impulse radar method for non-destructive testing in civil engineering, German Society of Non-Destructive Testing, 2001, 28 p. [in German].
- RILEM recommendations of tests for masonry materials; Measurement of moisture content by drilling, *Mater. Struct.* **30** (1997) 327-328.

11. GUIDELINES FOR THE USERS

Typical moisture problems where moisture measurements are required for analysing the basic cause are related to the following situations and damages:

- Rising moisture due to capillary action caused by a defect or absent horizontal moisture barriers
- Enhanced moisture content due to a defect or missing vertical moisture barrier
- Hygroscopic moisture related to presence of salt in the wall
- Condensation at the inner surface of the walls
- Unsealed service openings (pipes or cables) through the wall in the basement for entries
- Broken water pipe
- Defective sealing and construction of the roof
- Monitoring the repair work

For each case, radar enables the mapping of moisture distribution over the area of wall and the mean moisture content along the cross section.

The limits for the determination of moisture using radar are:

- Maximum wall thickness: 50cm using a 900MHz antenna; 100cm using a 500MHz
- Maximum antenna frequency : 1GHz
- Wall thickness measurement: Thickness accuracy has to be in the same range as the needed accuracy of moisture determination

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