The feasibility of using electromagnetic waves in determining membrane failure through concrete

P. Kot[1], A. Shaw[1], M. Riley[1], A.S. Ali [2*] and A. Cotgrave[1]

[1]Built Environment and Sustainable Technologies (BEST) Research Institute
School of Built Environment
Liverpool John Moores University
Liverpool, UK
P.Kot@ljmu.ac.uk

[2] Center for Construction, Building and Urban Studies (CeBUS)
Faculty of Built Environment
University of Malaya, Kuala Lumpur, Malaysia
Tel: +603 7967 4494 Fax: +603 7967 5713
email: asafab@um.edu.my
*corresponding author

Abstract

Concrete flat roof defects such as water leakage present a significant and common problem in large buildings, particularly in tropical countries, where rainfall is high. To monitor this condition, effective non-destructive test methods are required to detect problems at an early stage, especially hidden defects within the concrete roof, which are critical. This paper presents the potential use of electromagnetic (EM) waves for determining possible leakage of the concrete flat roof as a result of failure of the waterproof membrane layer. This study was assessed, experimentally by investigation of the propagation of EM waves through the roof and their interaction with water. Novel Microwave sensors described in the paper operate in the 6 GHz to 12 GHz frequency range using a Marconi 6200A microwave test set. A range of existing methods was reviewed and analysed. Results of experimental tests confirmed that microwaves could be used as an alternative non-destructive method for identifying water ingress caused by membrane failure into the concrete roof surface.

Keywords: Horn Antenna; Electromagnetic waves; Microwaves; Sensor; Concrete Flat Roof; Membrane

1.0 INTRODUCTION

In recent years there has been an increase in the need for sustainability in building fabric and structure. To achieve the optimum life span of the fabric and structure it is important to monitor parameters such as the moisture content, temperature, influence of vibration and material fatigue. This is especially important for construction forms that are sensitive to environmental influences. Performance of building materials that is inconsistent or materials that cannot withstand the changing conditions and activities around them will result in the building not functioning as intended. In addition, it is recognized widely that the incorrect installation of materials and components during construction contributes to the occurrence of defects. For instance, membrane layers even when installed by an authorized manufacturer, continue to face durability problems and poor performance a few years later[1]. Building materials that require a special mixing ratio such as concrete, mortar and membrane layers will be subject to significant effects when exposed to unpredictable weather changes. David and Dane[2] through their study regarding defects in roofs highlighted especially that moisture and water penetration was due to factors associated with environmental problems.

Porous building materials such as concrete, bricks, wood, mortar and rock wool insulation are susceptible to moisture both from the air and other sources. Investigation of the moisture content of building materials is essential due to the ability of moisture to induce varying forms of physical, biological and chemical corrosion processes [3][4]. In some tropical countries such as Malaysia, the levels of temperature and rainfall throughout the year are severe when compared to European countries. Malaysia has an average rainfall of 3000mm to 3500mm per annum with the Sabah recorded the highest reading[5]. The humid conditions throughout the year as well as the quantity of rainfall are likely to affect the durability of materials used in buildings. Very high levels of rainfall cause significant issues in concrete flat roofs that have suffered failure of the membrane. This would potentially contribute to the occurrence of severe roof leaks, especially for buildings that use flat roof design solutions.

Many companies providing different types of membranes give warranties for 10 years or longer although it is not uncommon for failures to occur within a few years resulting in the requirement for expensive repairs. Membrane failure is very hard to identify due to the fact that leakage is visible internally in a different location from the original membrane defect. Currently there are a few methods available to determine the dampness of building fabrics these are discussed in detail in Section 2.2. Notably, much of the available equipment to measure moisture content is destructive to the building fabric, as they require additional drilling into the material to take a sample of the content. Moreover, these methods often provide inaccurate results. Better results are provided by the gamma ray method, however, use of this technique can lead to health problems. It is necessary to develop non-destructive equipment which will provide accurate readings for identifying potential damage by locating membrane failure. To address the aforementioned problem research was undertaken in developing a novel method using electromagnetic waves. During the research different ranges of EM waves were tested and also different types of antennae were used to identify the best parameters to provide accurate measurements.

2.0 RESEARCH BACKGROUND

2.1 Building Fabric

Common defects in concrete roof construction include roof parapet wall cracks and damage to the waterproof membrane [6]. Investigations by De Silva and Ranasinghe [7] on maintainability of concrete flat roofs found that the main causes of defects were design, construction, maintenance and environment. Through a condition survey, the study observed 50 multi-story buildings of between 5 and 25 years of age, comprising a proportion of residential (46%), commercial (30%), and office buildings (24%) [7].

Membrane layers that had been installed on a flat concrete roof revealed durability problems in the long term. Durability of the membrane layers will be affected by environmental conditions such as extreme heat, biological agents, UV radiation, chemical reactions and material compatibility to roof construction[8]. Thus, the appropriate choice of a suitable damp proof membrane and regular monitoring are required to mitigate problems of damage to the membrane.

Building defect investigations tend to commence when there are signs of damage that directly or indirectly interfere with the function of the building and the activities within it. For instance, buildings using composite materials exposed to sulfur and salt content will give a reaction when in the presence of tricalcium aluminate and high moisture content over time. Less flexible composite materials require platisizers to react with other substances. These platisizers may not be permanent and will disappear in the long term due to changes of temperature and surrounding weather[9]. The surrounding environment and weather characteristics such as acidic rain and extreme heat cause reaction to composite materials. This reaction will lead to increased expansion and shrinkage, which results in cracks on the surface of concrete structures.

The absence of as-built drawings also becomes an issue that contributes to the problem of accuracy when conducting investigations of building components. Most buildings have drawings for the purpose of construction; however, these do not necessarily give an accurate representation of the as-built form and do not record recent changes[10]. In concrete structures, information such as the position of reinforcement steel, as well as the properties of concrete used need to be reaffirmed before any decision on the structure can be made. This includes the application of destructive test methods for obtaining accurate information. It would be better if a more appropriate and effective non-destructive tests could be performed to address this issue.

2.2 Current Methods

2.2.1 Radiological Measurements

2.2.1.1 Neutron Method

Neutrons interact mainly with hydrogen nuclei and give a direct measurement of water content by volume. Higher energy neutrons emitted from a radioactive substances such as a radium beryllium source are slowed and changed in direction by elastic collisions with atomic nuclei. Thermalization refers to the process resulting in energy loss of high-energy neutrons through kinetic collisions with surrounding nuclei, the neutrons being reduced in energy to about the thermal energy of atoms in a substance at room temperature. Hydrogen has a nucleus of about the same size and mass; the neutron has a much greater thermalizing effect than any other element. A measurement of the thermal neutron density in the vanity of a neutron source will be a measure of the concentration of hydrogen nuclei on a volume basis, and thus a measure of the water concentration. The source and detector are placed in a probe, the neutron source mounted in a lead shield at the bottom of the gas filled detector tube. The unit is constructed to be set over an access hole in the porous material, and the probe lowered through the bottom of the shield into the hole. The resolution of probe is limited. It is impossible to measure accurately the water content within 150 mm of the surface [25].

2.2.1.2 Gamma Scattering Method

The interaction of gamma rays and orbital electrons occur in three ways. Firstly, the photoelectric effect in which the whole of the energy of gamma ray is absorbed occurs at low energies. The Compton Effect, which is the scattering of gamma rays by electrons at medium energies and finally the creation of positron- electron pairs, becomes important at high energies. Measuring the attenuation of gamma radiation enables the determination of material density. The essential components of that system are source of gamma rays, a detector, an amplifier, a discriminator and a device to record the pulses from the detector. At +/- 1.0 per cent, the gamma ray method is the most accurate method in measuring moisture content. Therefore there is no hysteresis and it has short measuring time. Also the effect of temperature change or of dissolved conducting materials is non-existent. Unfortunately, there are high capital costs and precautions are necessary with radioactive equipment. Gamma scattering method determines the moisture content of concrete by measuring the intensity of scattered radiation in limestone concrete using an indigenously built goniometer and an HPGe spectrometer[26].

2.2.2 Electrical Measurements

2.2.2.1 Electrical resistance measurement

Electrical resistance measurement is based on the fact that each material has electrical resistance capabilities and water content has a direct effect on the electrical resistance of material. More water means less resistance. Measurement of the electrical resistance is usually carried out using Needle-shaped electrodes are used for measuring electrical resistance. Two measuring detectors are placed by driving or drilling into a building element and electrical resistance as a function of the electrical conductivity is measured. There is higher conductivity and lower electrical resistance in wet materials. Results are indicated on the measuring device according to construction materials type, which can be converted into percentages of moisture. Determining moisture content of building elements using this method is simple and fast [3].

2.2.2.2 LTCC sensor

Low Temperature Co-Fired Ceramic (LTCC) sensors with design and fabrication of inductor-capacitor (IC) planar sensors have been applied to monitoring moisture content of the most often used buildings materials [3]. The sensor can be used in the following ways: it can be buried in the plaster during construction, and for already constructed walls, it can be imbedded through small cuts. Variation of the water content in the tested specimens is measured wirelessly, with an antenna coil that tracks changes in the sensor resonant frequency. This sensor consists of two dielectric layers. First layer has screen-printed LC structure and second layer has a window over capacitor’s electrodes. Through this window the sensor is exposed to moisture, which will then cause change of its dielectric constant and total capacitance and consequently the resonant frequency of the LC sensor. The sensor exhibits from 0% to 70% wide detection range of water absorption with high linearity and fast response [3].

2.2.2.3 Time Domain Reflectometry (TDR)

The Principle of TDR used for moisture measurement is to transmit an electromagnetic signal down parallel electrodes of a waveguide inserted into the dielectric material under investigation. The time taken for the signal to return after reflecting off the end of the waveguide is measured. This gives a direct measure of the permittivity of the surrounding material along the length of the waveguide [27].

2.2.3 Mechanical Property Measurements

2.2.3.1 Thermal method

As the moisture content of a material increases, thermal conductivity also increases. One of the methods used to determine the thermal conductivity is to supply a known heat input probe in the material, and to measure the rise in temperature at a fixed distance from the heat source using thermocouples or thermistors. Been independent of the salt content of the porous body is one advantage of thermal conductivity measurements. However, thermal conductivity does depend on environmental temperature, which can be compensated for, and also upon the density of the material requiring many calibration curves for different densities of the material measured.

One drawback of the thermal conductivity method is the difficulty in obtaining reproducible calibration curves, and each calibration curve is only valid for a specific density of the material. IR Thermography can be used to monitor moisture content of the buildings. This method requires scanning all the surface of building and comparing it to the image of the subject area. The identification of the damp areas is achieved by the comparison between the temperature of the dry and moist surfaces [28]. One of the thermal techniques is a ‘pad’ Sensor [29]. The inventors of this sensor demonstrated a non-destructive technique for the measurement of moisture content within a material using thermal diffusion wherein heat is delivered into a surface and the resulting temperature increase is detected at a distance from the injection point. In a ‘pad’ sensor method the heater and temperature sensor are fixed at the surface of a thermal insulation material block (the ‘pad’). The device offers the benefits of the traditional dual probe, but with the important advantage that no holes are required to be drilled in the material of interest [29].

2.2.3.2 Vapour pressure

Measurement of the equilibrium relative humidity of air in contact with a porous body enables determination of the water tension of the porous body, which can be correlated with the moisture content. Individual calibration is required for each type of porous material in converting water tensions to moisture content and this is an unreliable procedure. Vapour pressure method requires precise measurements of the equilibrium relative humidity between the porous body and the surrounding air [30].

3.0 MIRCOWAVES

The use of electromagnetic waves for the purpose of detecting anomalies for some objects is an approach that is being actively investigated [11]. This is because this approach has great potential to be commercialised and applied to several industrial sectors. Microwave is a technology that uses waves that are not harmful to the user and this technology has been successfully applied in several industries such as monitoring environmental pollution, wastewater quality , moisture content of materials and carbon emissions levels as well as for the purpose of monitoring human health and so forth [12]. The advantage of this method is it’s ability to effect real time monitoring using microwaves based on the interaction of electromagnetic waves with the object tested. Signal velocity changes indicated by the application of the microwave test illustrate the composition and texture of the object. Individual changes in the electromagnetic frequency, transmitted in real time, can be linked to changes in the composition and texture of the materials tested. Changes detected in the electromagnetic frequency sent discretely is important as it will give an indication of changes that can be linked with the composition of the texture of the materials tested.

Microwaves are radio waves with wavelengths ranging from one meter to one millimeter, or equivalently, with frequencies between 300 MHz (0.3 GHz) and 300 GHz [13]. Figure 1 depicts the full electromagnetic spectrum from long waves up to Gamma Rays [14].

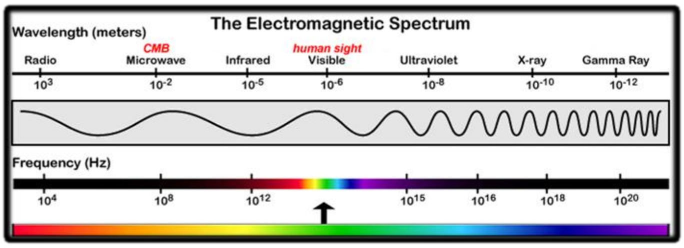

Figure 1: The electromagnetic spectrum

Source:[15].

There are different types of antenna that can be used to transmit and receive microwave signals. These are summarized as follows:

3.1.1 Wire Antennas

Wire Antennas have various shapes such as a straight wire (dipole), loop, or helix. This type of antenna is one of the most common and can be found in numerous applications such as cars, buildings and ships [16].

3.1.2 Aperture Antennas

There are different types of aperture antennas such as pyramidal horn, conical horn or rectangular waveguide. Microwave horn antennas produce a uniform phase front with a larger aperture than the waveguide and with greater directivity. A horn antenna consists of a rectangular metal tube closed at one end, flaring into an open-ended pyramidal shaped horn on the other side. The microwaves are introduced into the waveguide by a coaxial cable attached to horn antenna [17].

3.1.3 Microstrip Antennas

These antennae consist of a metallic patch on a grounded substrate. The metallic patch can take different configurations. The Microstrip antennae are low profile, comfortable to planar and non-planar surfaces, simple and inexpensive to fabricate using printed-circuit technology [16].

3.2 Dielectrics Properties of Building Fabric at Microwave Frequency

There has been growing interest regarding the utilization of electromagnetic waves and dielectric properties of materials in the investigation of materials and structural assessment. Together with other characteristics of materials, dielectric properties could be used to determine properties such as moisture content, bulk density, bio-content and chemical concentration [18]. Microwave imaging for building fabric detection is based on the contrast in dielectric properties of different types of materials and differing moisture contents. These properties allow detection of the source of leaks in roofs [19]. Dielectric properties of materials are associated with the relationship between the applied electric field strength E (V/m^2) and the electric displacement D (C/m^2) in the material. Categorization of dielectric properties of materials can by the use of a scalar effective complex permittivity denoted as ε_e^* to account for EM dielectric losses and conductivity of the material [18]

$$\varepsilon_e^* = \varepsilon_e' - j\varepsilon_e'' = \varepsilon^* + \frac{\sigma''}{j\omega} = \left(\varepsilon' + \frac{\sigma''}{\omega}\right) - j\left(\varepsilon'' + \frac{\sigma'}{\omega}\right)[18]$$

where ε_e' is the actual part of ε_e^* and is the capability of a material to retain the incident EM energy through wave propagation; ε_e'' is the imaginary part of ε_e^* and is the degree of EM energy losses in the material; j is the imaginary number. $\varepsilon^* = \varepsilon' - \varepsilon''$ is the complex permittivity (F/m); $\sigma^* = \sigma' - j\sigma''$ is the complex electric conductivity (Ω/m); and $\omega = 2\pi f$ is the angular frequency (rad/s) [18].

The materials used in this research have different dielectric properties at microwave frequency. This allows transmission of the microwave signal, which can then be analysed by collected reflection from the material as all materials will absorb signal at a different level [20]. In order to provide the most accurate results, it is essential to estimate the value of dielectric constant. It is important to use the Double Debye Relaxation equation to calculate the dielectric constant of water [21].

The dielectric loss of water increases with increase in the salinity in the water. Dielectric loss of pure water increases with increase in frequency, whereas in case of saline water it is found to decrease with increase in frequency [22]. At this stage of the research pure water will be used, where S=0 [23][21]. When considering building fabric, knowledge of the attenuation or losses of building materials is important for the study of microwave signal propagation in either indoor or outdoor environments [24]. It is essential to take into the account the permittivity of different materials such as gypsum, brick or concrete and objects which will be placed behind these materials such as timer, cables and pipes. Dielectric properties of the building materials will allow determination of the condition of the building structure or fabric by analysing changes, which occur in wave amplitude.

4.0 METHODOLOGY

There is increase in interest in novel methods for detecting waterproof membrane faults in flat concrete roofs because of the increasing amount of damage, cost of repairs and potential for consequential damage within buildings. The novel non-destructive EM wave sensor will be able to determine damage to concrete roof structures caused by membrane failure in real time measurement.

The sensor has been designed to be able to carry out numerous measurements without concern about displacement. Sensor parameters such as: Antenna angle, distance to object and temperature can be monitored in real time. The sensor frame has two calibrated displacement transducers attached, which enable clarification of the distance between the antennae and the roof. A third displacement transducer is located between the antennae to calculate their angle. A temperature sensor is also placed in front of the sensor frame. The sensor design as presented in Figure 2.

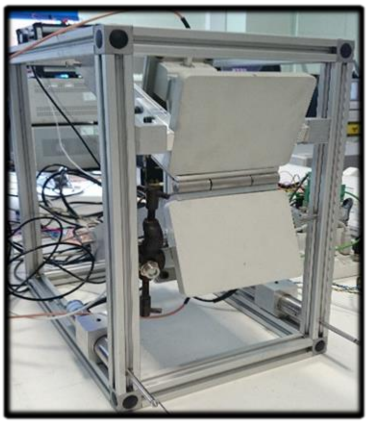

Figure 2: Sensor Design

A preliminary roof structure for testing is made from a pre-cast concrete paving slab (600x600x50mm), grade 20 without any reinforcement bar and with an applied rubber membrane. A paving slab has been placed on a metal frame 620mm high as indicated in Figure 3. This height is to ensure easy access for the sensor antenna during the experiment.

Figure 3: Concrete Paving Slab on Metal Structure

A typical waterproof rubber membrane is applied tight into a wooden frame above the slab to imitate the flat roof membrane. The membrane is placed on the top of the slab as shown in Figure 4.

Figure 4: Concrete Paving Slab with a Membrane Layer

One of the membrane samples was subjected to penetration damage with the creation of a 10 mm diameter hole. This is to allow water ingress mimicking membrane failure to the concrete roof as shown in Figure 5.

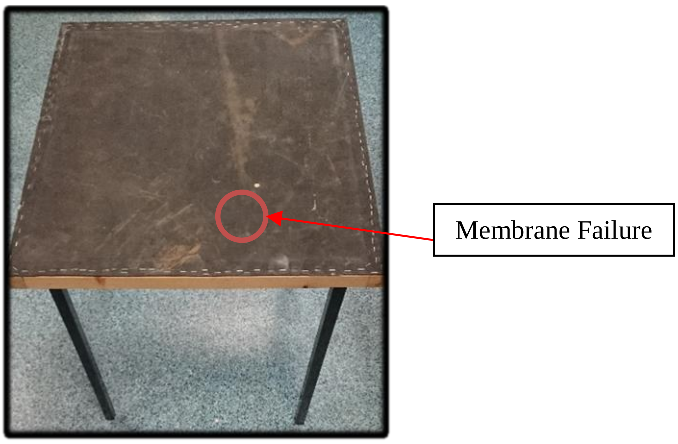

Figure 5: Membrane with a Fault

The microwave sensor was placed 20 mm beneath the concrete structure. A schematic diagram of the test setup is presented in Figure 6. The sensor was connected to a Marconi Microwave test set and laptop, which captured and stored data via software developed in LabVIEW as indicated in Figure 7.

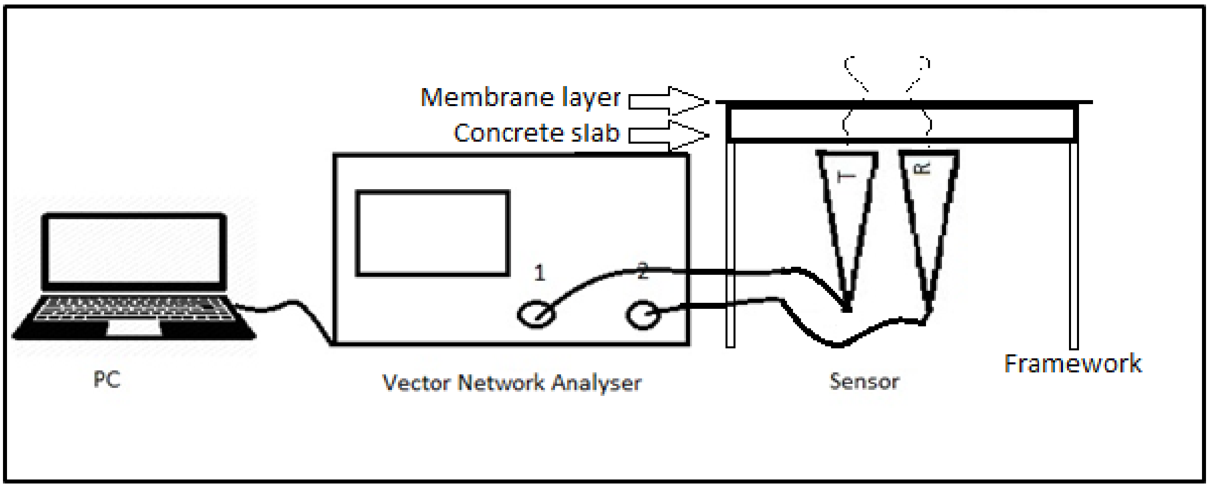

Figure 6. Schematic Diagram of the Test Setup

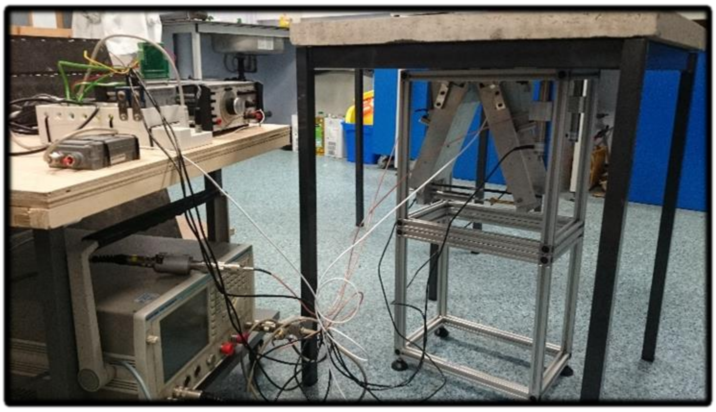

Figure 7: Preliminary Experiment Setup

An initial preliminary experiment was undertaken to identify differences between the membrane in different conditions and situated in different positions on the concrete (Figure 4). Results are presented in Figure 8.

5.0 RESULT

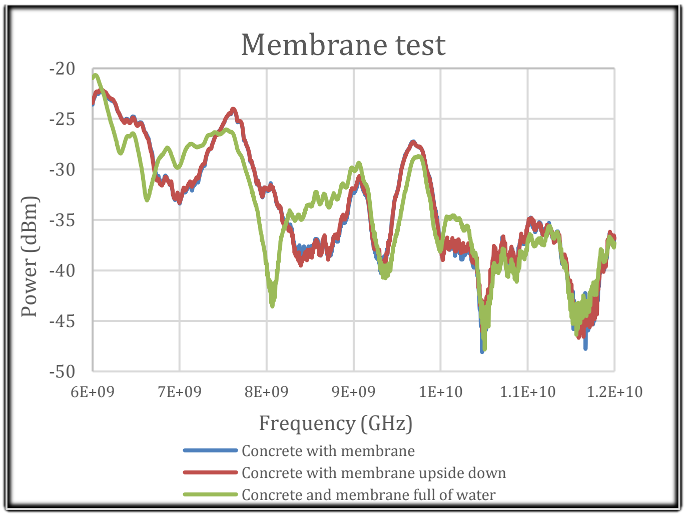

Figure 8: Membrane position experiment results

Figure 8 shows that the position of the membrane does not affect the results of experiment. Noticeable changes appeared after applying water on the top of the membrane, especially around 8GHz frequency range. Water absorbs electromagnetic waves very well because of its dielectric properties, which enabled observation of changes in microwave spectrum. Data analysis allows identification of the location of the water content.

A second experiment was then undertaken to monitor spectrum changes with water ingress thorough the damaged membrane.

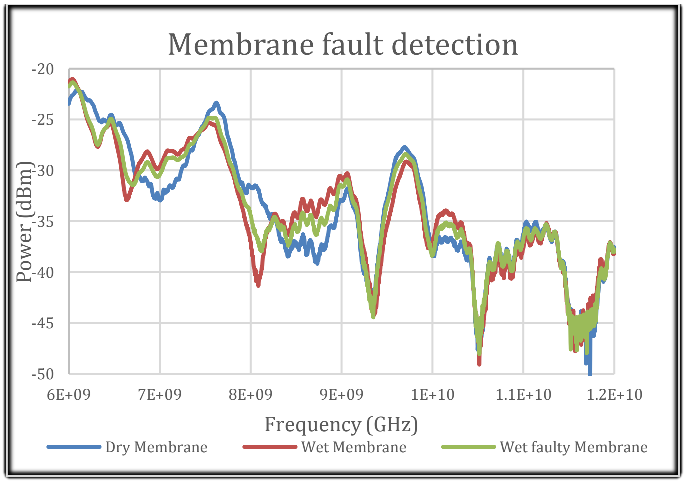

Figure 9: Membrane Fault Detection Experiment Results

Results from the second experiment proved the concept that it was possible to observe changes in the spectrum between 8GHz to 9 GHz frequency ranges, when water leaked through the damaged membrane and penetrated the paving slab as shown in Figure 9.

A third experiment has been undertaken to monitor the water drying off process in the paving slab. The sensor recorded data every 30 seconds and stored them in a defined database location.

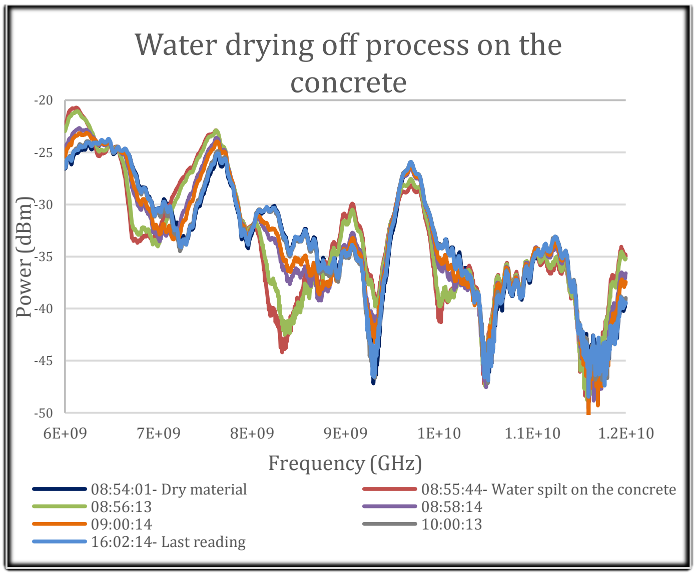

Figure 10: Water Drying Off Process on the Paving Slab Experiment Results

Results from the third experiment, as shown in Figure 10, enabled mapping of the drying off process at the range of frequency between 8 GHz to 9 GHz. Changes in the spectrum were caused by dielectric properties of the water, the reducing amount of water absorbs less EM energy, which enabled identifying the stage of the water drying process. Data analysis applied to the results can be used to identify the precise stage of the water drying process.

6.0 CONCLUSION

In conclusion, preliminary experiments prove that electromagnetic waves at the frequency ranges between 6GHz to 12GHz can be used to identify damage to concrete caused by water ingress arising from membrane failure in real time measurements and in a non-destructive manner. Further sensor development can be used for identifying damage in flat roof structures in differing environmental conditions.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support of the University of Malaya Research Grant (UMRG), grant no.RP007A/13SUS established at the University of Malaya, Sustainability Science Research Cluster

REFERENCES

[1] N. P. Mailvaganam and P. G. Collins, "Workmanship Factors Influencing Quality of Installed Parking Garage Waterproofing Membranes," *J. Perform. Constr. Facil.*, no. August, pp. 121–127, 2004.

[2] D. M. Bailey and D. Bradford, "Membrane and Flashing Defects in Low-Slope Roofing : Causes and Effects on Performance," *J. Perform. Constr. Facil.*, vol. 19, no. 3, pp. 234–244, 2005.

[3] M. Maksimović, G. M. Stojanović, M. Radovanović, M. Malešev, V. Radonjanin, G. Radosavljević, and W. Smetana, "Application of a LTCC sensor for measuring moisture content of building materials," *Constr. Build. Mater.*, vol. 26, no. 1, pp. 327–333, Jan. 2012.

[4] N. Gromicko and K. Shepard, "Moisture Meters for Inspectors," 2013. [Online]. Available: http://www.nachi.org/moisture-meters.htm. [Accessed: 05-Dec-2014].

[5] M. McGinley, "Climate of Malaysia," 2011. [Online]. Available: http://www.eoearth.org/view/article/151260/. [Accessed: 05-Dec-2014].

[6] Y. T. Lo, W. M. Leung, and H. Z. Cui, "Roof construction defects of medium-rise buildings in sub-tropical climates," *Struct. Surv.*, vol. 23, no. 3, pp. 203–209, Jul. 2005.

[7] N. D. S. . Ranasinghe, "Maintainability of reinforced concrete flat roofs in Sri Lanka," *Struct. Surv.*, vol. 28, no. 4, pp. 314–329, 2010.

[8] CIB and RILEM, "New-technology roofing, Elastomeric, thermoplastic and polymer-modified bitumen membranes," *Batim. Int. Build. Res. Pract.*, vol. 15, no. 1–6, pp. 146–156, 1987.

[9] W. Allen, "The pathology of modern building," *Build. Res. Inf.*, vol. 23, no. 3, pp. 139–146, May 1995.

[10] W. P. S. Dias and A. D. C. Jayanandana, "Condition Assessment of a Deteriorated Cement Works," *J. Perform. Constr. Facil.*, no. November, pp. 188–196, 2003.

[11] M. A. M. Yunus and S. C. Mukhopadhyay, “Novel Planar Electromagnetic Sensors for Detection of Nitrates and Contamination in,” vol. 11, no. 6, pp. 1440–1447, 2011.

[12] O. Korostynska, a. Mason, and a. Al-Shamma’a, “Microwave sensors for the non-invasive monitoring of industrial and medical applications,” *Sens. Rev.*, vol. 34, no. 2, pp. 182–191, Mar. 2014.

[13] V. . Sarwate, *Electromagnetic fields and waves*. India: New Age International, 1993.

[14] R. Sorrentino and G. Bianchi, *Microwave and RF Engineering*. Singapure: John Wiley & Sons, 2010.

[15] C. /lawrence, J. Van der Veen, and J. Arballo, “Jet Propulsion Laboratory, California Institute of Technology,” 2012. [Online]. Available: http://planck.caltech.edu/epo/epo-cmbDiscovery3.html. [Accessed: 05-Dec-2014].

[16] C. . Balanis, *Antenna Theory. Analysis and design,* Third. New Jersey: John Wiley & Sons, 2005.

[17] K. Vijayakumar, S. R. Wylie, J. D. Cullen, C. C. Wright, and a I. Ai-Shamma’a, “Non invasive rail track detection system using microwave sensor,” *J. Phys. Conf. Ser.*, vol. 178, Jul. 2009.

[18] O. Buyukozturk, T.-Y. Yu, and J. A. Ortega, “A methodology for determining complex permittivity of construction materials based on transmission-only coherent, wide-bandwidth free-space measurements,” *Cem. Concr. Compos.*, no. 28, pp. 349–359, 2006.

[19] E. C. Fear, X. Li, S. C. Hagness, and M. A. Stuchly, “Confocal microwave imaging for breast cancer detection: localization of tumors in three dimensions.,” *IEEE Trans. Biomed. Eng.*, vol. 49, no. 8, pp. 812–22, Aug. 2002.

[20] Y. Li, N. Bowler, and D. B. Johnson, “A Resonant Microwave Patch Sensor for Detection of Layer Thickness or Permittivity Variations in Multilayered Dielectric Structures,” *IEEE Sens. J.*, vol. 11, no. 1, pp. 5–15, 2011.

[21] T. Meissner and F. J. Wentz, “The complex dielectric constant of pure and sea water from microwave satellite observations,” *IEEE Trans. Geosci. Remote Sens.*, vol. 42, no. 9, pp. 1836–1849, Sep. 2004.

[22] D. H. Gadani, V. A. Rana, S. P. Bhatnagar, A. N. Prajapati, and A. D. Vyas, “Effect of salinity on the dielectric properties of water,” *Indian J. Pure Appl. Phys.*, vol. 50, pp. 405–410, 2012.

[23] R. Buchner, J. Barthel, and J. Stauber, “The dielectric relaxation of water between 0C and 35C,” vol. 2, no. June, pp. 57–63, 1999.

[24] C. A. Grosvenor, R. T. Johnk, J. Baker-Jarvis, M. D. Janezic, and B. Riddle, “Time-Domain Free-Field Measurements of the Relative Permittivity of Building Materials,” *IEEE Trans. Instrum. Meas.*, vol. 58, no. 7, pp. 2275– 2282, 2009.

[25] F. . Wittmann, P. Zhang, T. Zhao, E. Lehmann, and P. Vontobel, “Neutron Radiography, A Powerful Method for Investigating Water Penetration Into Concrete,” *Adv. Civ. Eng. Mater.*, pp. 61–70, 2008.

[26] R. Vijayakumar, L. Rajasekaran, and N. Ramamurhy, “Determining the Moisture content in Limestone Concrete by Gamma Scattering Method: A Feasibility Study,” no. 1, pp. 1–10, 2002.

[27] M. Phillipson, P. Baker, M. Davies, Z. Ye, G. Galbraith, and R. McLean, “Suitability of time domain reflectometry for monitoring moisture in building materials,” *Build. Serv. Eng. Res. Technol.*, vol. 29, no. 3, pp. 261–272, Aug. 2008.

[28] E. Grinzato, P. G. Bison, and S. Marinetti, “Monitoring of ancient buildings by the thermal method,” *J. Cult. Herit.*, vol. 3, no. 1, pp. 21–29, Apr. 2002.

[29] M. Davies and Z. Ye, “A ‘ pad ’ sensor for measuring the moisture content of building materials,” vol. 3, no. 30, pp. 263–270, 2009.

[30] E. a McCullough, M. Kwon, and H. Shim, “A comparison of standard methods for measuring water vapour permeability of fabrics,” *Meas. Sci. Technol.*, vol. 14, no. 8, pp. 1402–1408, Aug. 2003.