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

3 P. Kot¹, A. Shaw¹, M. Riley¹, A.S. Ali ^{2*} and A. Cotgrave¹

4
5 ¹Built Environment and Sustainable Technologies (BEST) Research Institute

6 School of Built Environment

7 Liverpool John Moores University

8 Liverpool, UK

9 P.Kot@ljmu.ac.uk

10
11 ² Center for Construction, Building and Urban Studies (CeBUS)

12 Faculty of Built Environment

13 University of Malaya, Kuala Lumpur, Malaysia

14 Tel: +603 7967 4494 Fax: +603 7967 5713

15 email: asafab@um.edu.my

16 *corresponding author

17
18 ***Abstract***

19 Concrete flat roof defects such as water leakage present a significant and common problem in
20 large buildings, particularly in tropical countries, where rainfall is high. To monitor this
21 condition, effective non-destructive test methods are required to detect problems at an early
22 stage, especially hidden defects within the concrete roof, which are critical. This paper
23 presents the potential use of electromagnetic (EM) waves for determining possible leakage of
24 the concrete flat roof as a result of failure of the waterproof membrane layer. This study was
25 assessed, experimentally by investigation of the propagation of EM waves through the roof
26 and their interaction with water. Novel Microwave sensors described in the paper operate in
27 the 6 GHz to 12 GHz frequency range using a Marconi 6200A microwave test set. A range of

28 existing methods was reviewed and analysed. Results of experimental tests confirmed that
29 microwaves could be used as an alternative non-destructive method for identifying water
30 ingress caused by membrane failure into the concrete roof surface.

31

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

33 *Membrane*

34

35 **1.0 INTRODUCTION**

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

50

51 Porous building materials such as concrete, bricks, wood, mortar and rock wool insulation are
52 susceptible to moisture both from the air and other sources. [Investigation of the moisture](#)

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

62

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

78 **2.0 RESEARCH BACKGROUND**

79 2.1 Building Fabric

80 Common defects in concrete roof construction include roof parapet wall cracks and damage
81 to the waterproof membrane [6]. Investigations by De Silva and Ranasinghe [7] on
82 maintainability of concrete flat roofs found that the main causes of defects were design,
83 construction, maintenance and environment. Through a condition survey, the study observed
84 50 multi-story buildings of between 5 and 25 years of age, comprising a proportion of
85 residential (46%), commercial (30%), and office buildings (24%) [7].

86

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

93

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

103 surface of concrete structures.

104

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

114

115 2.2 Current Methods

116 2.2.1 Radiological Measurements

117 2.2.1.1 Neutron Method

118 Neutrons interact mainly with hydrogen nuclei and give a direct measurement of water
119 content by volume. Higher energy neutrons emitted from a radioactive substances such as a
120 radium beryllium source are slowed and changed in direction by elastic collisions with
121 atomic nuclei. Thermalization refers to the process resulting in energy loss of high-energy
122 neutrons through kinetic collisions with surrounding nuclei, the neutrons being reduced in
123 energy to about the thermal energy of atoms in a substance at room temperature. Hydrogen
124 has a nucleus of about the same size and mass; the neutron has a much greater thermalizing
125 effect than any other element. A measurement of the thermal neutron density in the vicinity of
126 a neutron source will be a measure of the concentration of hydrogen nuclei on a volume
127 basis, and thus a measure of the water concentration. The source and detector are placed in a

128 probe, the neutron source mounted in a lead shield at the bottom of the gas filled detector
129 tube. The unit is constructed to be set over an access hole in the porous material, and the
130 probe lowered through the bottom of the shield into the hole. The resolution of probe is
131 limited. It is impossible to measure accurately the water content within 150 mm of the surface
132 [25].

133

134 [2.2.1.2 Gamma Scattering Method](#)

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

149

150 [2.2.2 Electrical Measurements](#)

151 [2.2.2.1 Electrical resistance measurement](#)

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

162

163 [2.2.2.2 LTCC sensor](#)

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

176

177 2.2.2.3 Time Domain Reflectometry (TDR)

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

183

184 2.2.3 Mechanical Property Measurements

185 2.2.3.1 Thermal method

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

194

195 One drawback of the thermal conductivity method is the difficulty in obtaining reproducible
196 calibration curves, and each calibration curve is only valid for a specific density of the
197 material. IR Thermography can be used to monitor moisture content of the buildings. This
198 method requires scanning all the surface of building and comparing it to the image of the
199 subject area. The identification of the damp areas is achieved by the comparison between the
200 temperature of the dry and moist surfaces [28]. One of the thermal techniques is a ‘pad’
201 Sensor [29]. The inventors of this sensor demonstrated a non-destructive technique for the

202 measurement of moisture content within a material using thermal diffusion wherein heat is
203 delivered into a surface and the resulting temperature increase is detected at a distance from
204 the injection point. In a ‘pad’ sensor method the heater and temperature sensor are fixed at
205 the surface of a thermal insulation material block (the ‘pad’). The device offers the benefits
206 of the traditional dual probe, but with the important advantage that no holes are required to be
207 drilled in the material of interest [29].

208

209 [2.2.3.2 Vapour pressure](#)

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

216

217 **3.0 MICROWAVES**

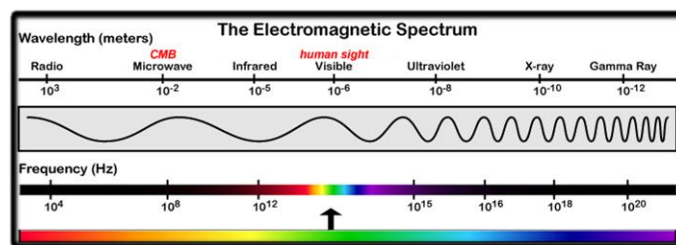
218 The use of electromagnetic waves for the purpose of detecting anomalies for some objects is
219 an approach that is being actively investigated [11]. This is because this approach has great
220 potential to be commercialised and applied to several industrial sectors. Microwave is a
221 technology that uses waves that are not harmful to the user and this technology has been
222 successfully applied in several industries such as monitoring environmental pollution,
223 wastewater quality , moisture content of materials and carbon emissions levels as well as for
224 the purpose of monitoring human health and so forth [12]. The advantage of this method is
225 it’s ability to effect real time monitoring using microwaves based on the interaction of
226 electromagnetic waves with the object tested. Signal velocity changes indicated by the

227 application of the microwave test illustrate the composition and texture of the object.
228 Individual changes in the electromagnetic frequency, transmitted in real time, can be linked
229 to changes in the composition and texture of the materials tested. Changes detected in the
230 electromagnetic frequency sent discretely is important as it will give an indication of changes
231 that can be linked with the composition of the texture of the materials tested.

232

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

236



237

Figure 1: The electromagnetic spectrum

238

Source:[15].

239

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

242

243 3.1.1 Wire Antennas

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

247

248 3.1.2 Aperture Antennas

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

255

256 3.1.3 Microstrip Antennas

257 These antennae consist of a metallic patch on a grounded substrate. The metallic patch can
258 take different configurations. The Microstrip antennae are low profile, comfortable to planar
259 and non-planar surfaces, simple and inexpensive to fabricate using printed-circuit technology
260 [16].

261

262 3.2 Dielectrics Properties of Building Fabric at Microwave Frequency

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

274

$$275 \quad \varepsilon_e^* = \varepsilon_e' - j\varepsilon_e'' = \varepsilon^* + \frac{\sigma''}{j\omega} = \left(\varepsilon' + \frac{\sigma''}{\omega} \right) - j \left(\varepsilon'' + \frac{\sigma'}{\omega} \right) [18]$$

276

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

282

283 The materials used in this research have different dielectric properties at microwave
284 frequency. This allows transmission of the microwave signal, which can then be analysed by
285 collected reflection from the material as all materials will absorb signal at a different level
286 [20]. In order to provide the most accurate results, it is essential to estimate the value of
287 dielectric constant. It is important to use the Double Debye Relaxation equation to calculate
288 the dielectric constant of water [21].

289

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

298 building materials will allow determination of the condition of the building structure or fabric
299 by analysing changes, which occur in wave amplitude.

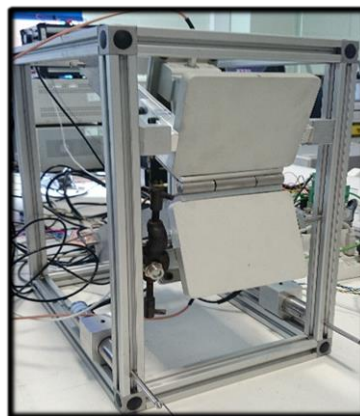
300

301 **4.0 METHODOLOGY**

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

307

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



315

316

Figure 2: Sensor Design

317 A preliminary roof structure for testing is made from a pre-cast concrete paving slab
318 (600x600x50mm), grade 20 without any reinforcement bar and with an applied rubber
319 membrane. A paving slab has been placed on a metal frame 620mm high as indicated in
320 Figure 3. This height is to ensure easy access for the sensor antenna during the experiment.



321

Figure 3: Concrete Paving Slab on Metal Structure

322

323

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



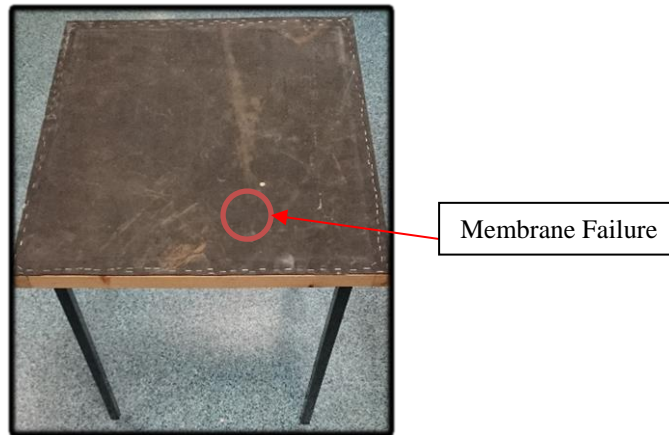
327

Figure 4: Concrete Paving Slab with a Membrane Layer

328

329

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



333

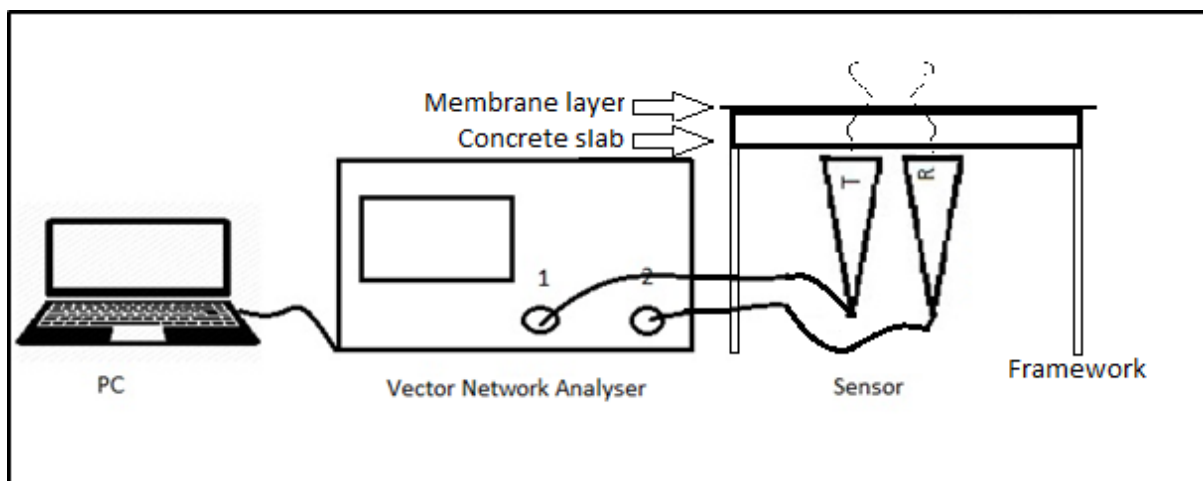
334

Figure 5: Membrane with a Fault

335

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

340



341

342

Figure 6. Schematic Diagram of the Test Setup

343

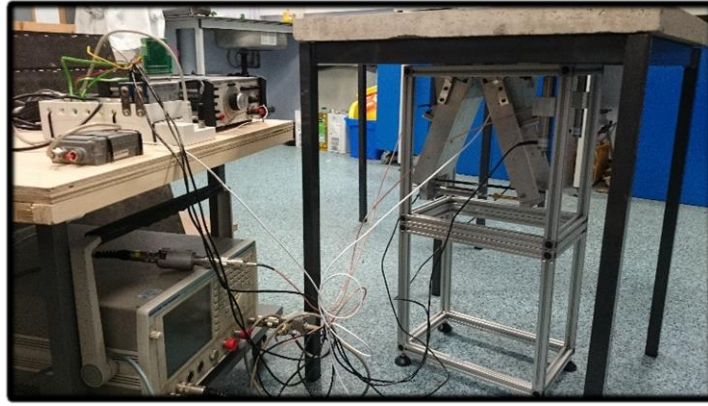


Figure 7: Preliminary Experiment Setup

344

345

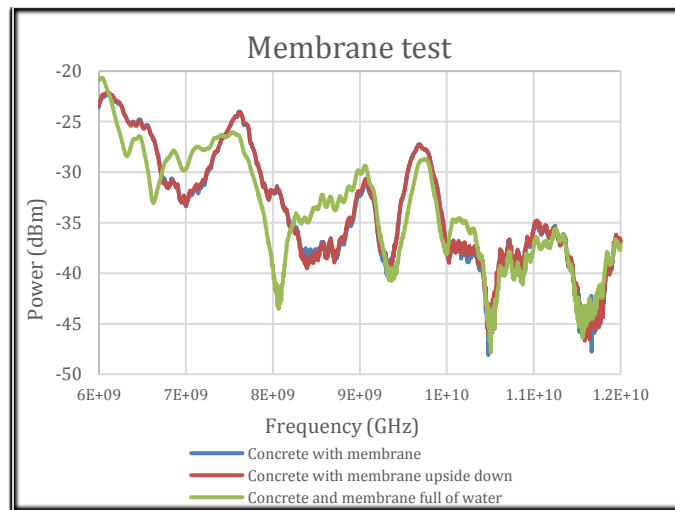
346

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

350

351

352 5.0 RESULT



353

354 Figure 8: Membrane position experiment results

355 Figure 8 shows that the position of the membrane does not affect the results of experiment.

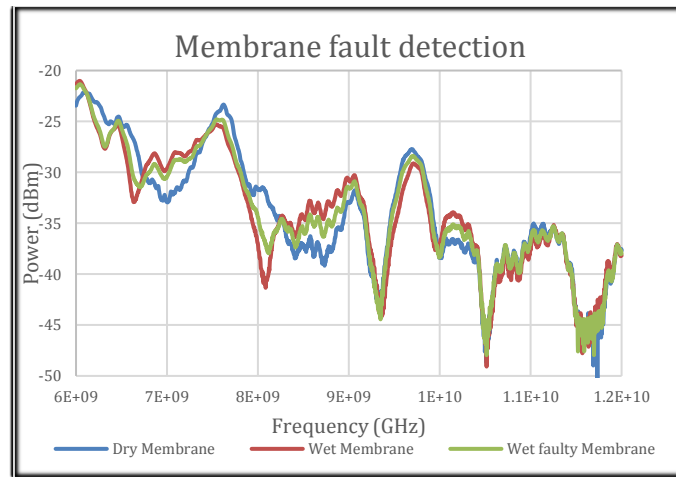
356 Noticeable changes appeared after applying water on the top of the membrane, especially

357 around 8GHz frequency range. Water absorbs electromagnetic waves very well because of

358 its dielectric properties, which enabled observation of changes in microwave spectrum. Data
359 analysis allows identification of the location of the water content.

360

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



363

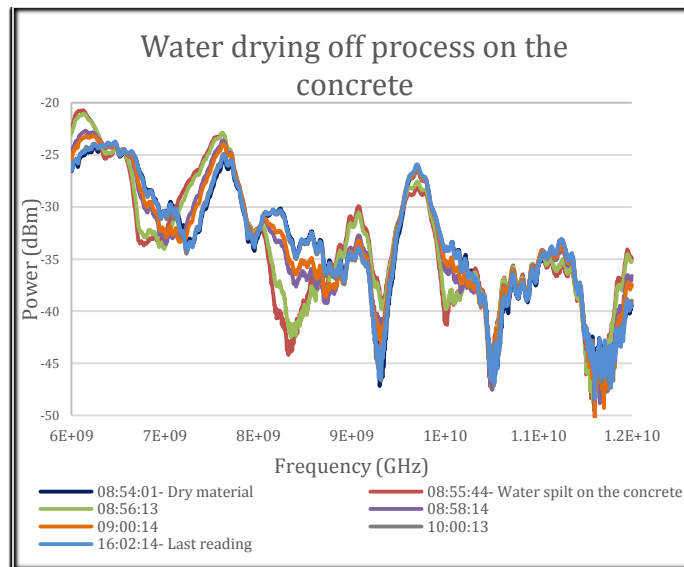
364 Figure 9: Membrane Fault Detection Experiment Results

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

368

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

372



373

374

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

375

376

Results from the third experiment, as shown in Figure 10, enabled mapping of the drying off

377

process at the range of frequency between 8 GHz to 9 GHz. Changes in the spectrum were

378

caused by dielectric properties of the water, the reducing amount of water absorbs less EM

379

energy, which enabled identifying the stage of the water drying process. Data analysis

380

applied to the results can be used to identify the precise stage of the water drying process.

381

382 6.0 CONCLUSION

383

In conclusion, preliminary experiments prove that electromagnetic waves at the frequency

384

ranges between 6GHz to 12GHz can be used to identify damage to concrete caused by water

385

ingress arising from membrane failure in real time measurements and in a non-destructive

386

manner. Further sensor development can be used for identifying damage in flat roof

387

structures in differing environmental conditions.

388

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393

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