# RELATIONSHIPS BETWEEN MOISTURE CONTENT AND DIELECTRIC CONSTANT FOR SUBGRADE AND SUBBASE OF PAVEMENT COURSES

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# ABSTRACT

Soil is used as bedding or support for all types of heavy structures, including roads, highways, and structural foundations. The strength parameter, California Bearing Ratio (CBR) is a vital consideration during the design stage of pavement and other superstructure. Moisture content in soil also plays an important role for values of CBR. In conventional methods, soil samples are taken from the field to the laboratory and moisture content is determined by standard oven drying method. These methods are laborious, time-consuming, and require excessive care and accuracy. In the presence of water, the soil shows strong dielectric performance. Microwave frequency can exploit the large contrast between the dielectric constant of free water and soil. The dielectric constant of the soil is directly correlated to soil moisture content. The dielectric constant of the soil varies with proportion of water substrate present in it. This research focused on using microwave techniques by considering frequency domain to determine moisture content of subgrade and subbase. Three samples were tested in this research: soil subgrade, sand subbase and blended subbase. Several laboratory tests such as determination of moisture content by conventional method, grain size analysis and Modified Proctor test were performed. The dielectric data measurements were taken for the three samples at operating frequency range from 1 MHz to 20 GHz. The values of dielectric constant, loss factor and conductivity of the samples were determined independently. The relation between dielectric constant, $\varepsilon_r'$ and moisture content was established in polynomial formulation in this research. The dielectric constant of soil subgrade rose rapidly with the increase of moisture content. However for sand subbase, the dielectric constant rose slowly with the increase of moisture content. The conductivity of soil sample increased more rapidly with moisture changes than sand sample. It was observed that the soil sample was highly conductive while the sand sample had poor conductivity. This study was the first of its kind to apply microwave techniques for considering frequency domain in determining moisture content of pavement layers.

# ABSTRAK

Tanah digunakan sebagai asas atau penyokong untuk semua jenis struktur berat, termasuk jalan raya, lebuh raya, dan struktur asas. Parameter kekuatan tanah, iaitu Nisbah Galas California (CBR) adalah sangat penting untuk diambil kira semasa peringkat reka bentuk turapan dan juga *super* struktur lain. Kandungan lembapan dalam tanah juga memainkan peranan penting untuk nilai-nilai CBR. Dalam kaedah konvensional, sampel tanah diambil dari tapak ke makmal dan kandungan lembapan ditentukan dengan kaedah *standard* pengeringan oven. Kaedah ini agak sukar, mongambil masa, dan memerlukan penjagaan yang rapi serta tepat. Dengan kehadiran air, tanah menunjukkan kekuatan dielektrik. Frekuensi gelombang mikro boleh mengekploitasi perbezaan yang ketara antara pemalar dielektik air dan tanah. Pemalar dielektrik tanah dikaitkan secara langsung dengan kandungan lembapan tanah. Pemalar dielektrik tanah berubah mengikut kadar air yang terdapat di dalamnya. Kajian ini memberi tumpuan kepada penggunaan teknik gelombang mikro yang mempertimbangkan domain frekuensi dalam menentukan kandungan lembapan subgred dan subtapak. Tiga sampel telah diuji dalam kajian ini iaitu; tanah subgred, pasir subtapak dan subtapak campuran. Beberapa ujian makmal seperti penentuan kandungan kelembapan dengan kaedah konvensional, analisis saiz bijirin dan ujian *Modified Proctor* telah dilakukan. Pengukuran data dielektrik telah diambil untuk ketiga-tiga sampel pada julat frekuensi operasi dari 1 MHz hingga 20 GHz. Nilai pemalar dielektrik, faktor kehilangan dan kekonduksian sampel telah ditentukan secara berasingan. Hubungan antara pemalar dielektrik, $\varepsilon_r'$ dan kandungan lembapan telah dihasilkan melalui formulasi polinomial dalam kajian ini. Pemalar dielektrik tanah subgred meningkat dengan cepat dengan peningkatan kandungan lembapan. Namun, bagi pasir subtapak, pemalar dielektrik meningkat secara perlahan dengan peningkatan kandungan lembapan. Kekonduksian sampel tanah meningkat dengan lebih cepat dengan perubahan kelembapan berbanding sampel pasir. Adalah diperhatikan bahawa sampel tanah sangat konduktif manakala sampel pasir mempunyai kekonduksian yang rendah. Kajian ini adalah yang pertama seumpamanya dengan menggunakan teknik gelombang mikro yang mempertimbangkan domain frekuensi dalam menentukan kandungan kelembapan lapisan turapan.

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# ABBREVIATIONS

| | |
|---|---|
| **ACI** | American Concrete Institute |
| **ASTM** | American Society for Testing and Materials |
| **AASHTO** | American Association of State Highway and Transportation Officials |
| **FDR** | Frequency Domain Reflectometer |
| **HMA** | Hot Mix Asphalt |
| **ISM** | Industrial, Scientific and Medical |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **MUT** | Material Under Test |
| ***mc*** | Moisture Content |
| **NDG** | Nuclear Density Gauge |
| **NDT** | Non-Destructive Test |
| **OCP** | Open Ended Coaxial Probe |
| **RF** | Radio Frequency |
| **SMCV** | Volumetric Soil Moisture Content |
| **TDR** | Time Domain Reflectometer |
| **TEM** | Transverse Electromagnetic Mode |
| **VNA** | Vector Network Analyzer |
| **VSWR** | Voltage Standings Wave Ratio |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $\varepsilon_r'$ | - | Dielectric Constant |
| $\varepsilon_r''$ | - | Loss Factor |
| $\sigma$ | - | Conductivity |
| $\pi$ | - | Pi |
| $f$ | - | Frequency |
| $\omega$ | - | Angular Frequency |
| $\lambda$ | - | Wavelength |
| $\eta$ (or $Z_0$) | - | Impedance of the Free-Space |
| $\mu_0$ | - | Permeability of the Free-Space |
| c | - | Velocity of Light in Vacuum |
| V | - | Velocity of Wave in a Medium |
| $\gamma$ | - | Complex Propagation Constant of the Medium |
| $\alpha$ | - | Rate of Decay with Distance, i.e. Attenuation Constant or Wave Absorption Coefficient |
| $\beta$ | - | Phase Information for Electromagnetic Wave of Incidence |
| $Y_L$ | - | Admittance of the Line |
| $C_0$ | - | Electrical Capacitance of the Air |
| $\tilde{Y}$ | - | Normalized Admittance |
| $s_{11}^*$ | - | Reflection Coefficients |
| $C_f$ | - | Fringe Field Capacitance |
| T | - | Measured Transmission |
| $\Gamma$ | - | Reflection Coefficient |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The strength of pavement depends mainly on the strength of subgrade in a pavement structure. If the subgrade is weak the pavement top surface layer can be completely torn down even it is strong. The compacted subgrade strength depends on its moisture content which varies due to capillary action, flood, changes of water table and precipitation. The dry unit weight of the soil increases as moisture content increases in a certain limit, and beyond the limit, moisture content increase tends to reduce the dry unit weight.

The gravimetric method, nuclear method and time domain reflectometer (TDR) are currently available to monitor the moisture content (*mc*) of paving materials [1]. In gravimetric method, samples of soil are collected from field and their moisture content is determined in the laboratory by finding the weight loss after oven drying. These methods are laborious, slow and require more care for accuracy [2].

Traditionally, bulk density of compacted soil is measured by the sand replacement method and core cutter method. Recently the nuclear density gauge (NDG) is used to measure both dry density and moisture content of compacted subbase and subgrade at the field. The nuclear density gauge cannot directly find the percentage of compaction of the pavement layers. The percentage of compaction is specified as ratio of dry density at field to maximum dry density at laboratory. The nuclear gauge is also expensive and very costly to repair because it contains the nuclear source. The nuclear density gauge also has radiation hazard and regulation limitation for its radioactive sources. For that reason, researchers seek alternative safe procedure to measured moisture content *(mc)* and density of the pavement layers [3].

Agricultural researchers have been using time domain reflectometer (TDR) techniques effectively to find soil moisture in irrigation sector since 1970. The civil engineers began their own research as they recognized the possible benefits of use microwave technologies. Diefenderfer et al. used two TDR probes to monitor moisture content *(mc)* in flexible pavement construction and pointed out that accurate moisture content (*mc*) of different materials in the field can be measured after preliminary laboratory calibration [1]. Xiong Yu et al. developed TDR method over ASTM D6780 for in situ determination of moisture content and density of subgrade soil [4]. The time domain reflectometer has limited probe length and needs calibration before using the results [5].

Kirandeep Kaur et al. discussed in their review paper about various latest soil moisture measurement techniques as shown in Table1.1 and mentioned that the frequency domain reflectometer sensor is more accurate and cheaper than TDR [6].

**Table 1.1:** List of Various Soil Moisture Measurement Techniques [6]

| Method | Advantage | Disadvantage |
|---|---|---|
| Gravimetric Method | - Precise, simple and low cost. | -Destructive test.<br>- Slow and laborious. |
| Time Domain Reflectometer (TDR) | - Precise and nonstop data collection.<br>- Initial calibration not required. | -Compound electronic kit.<br>- Expensive system. |
| Frequency Domain Reflectometer (FDR) | - More precise than TDR.<br>- The probe is flexible.<br>- Less expensive compare to other methods. | -Need extensive care.<br>-Air gaps can make error in readings. |
| Nuclear Density Gauge | - Rapid and dependable data.<br>- Recurrent readings of soil. | - It contains radioactive element.<br>- Extensive care to operate. |

To increase road strength and decrease pavement thickness, subgrade material needs optimum compaction in road construction. The optimum compaction of soil is determined by the laboratory test. However, sometimes it is difficult to transfer the optimal compaction and moisture content data from laboratory to the field. There is a necessity for developing new testing method other than the conventional testing of highway materials [7]. The microwave techniques considering frequency domain are attractive alternative for determining soil moisture content *(mc)*. In presence of water, the soil shows strong dielectric performance. Microwave frequency can exploit the large contrast between the dielectric constant of free water and soil. The dielectric properties of materials depend on microwave frequency, moisture content, bulk density and temperature [8].

The excessive water in pavement structure is one of the main reasons for the deterioration of existing pavement [1]. The United States of America expended 45 percent of its transportation cost on existing road repairs between 2009 and 2011, and 55 percent in new road construction [9]. The Malaysian road repair budget is 174 percent higher than the budget allocated for construction of new roads [7]. Therefore, determining and predicting of moisture content within the pavement system is very dominant.

The researchers established several empirical and semi-empirical formulas to investigate relation among dielectric constant and soil moisture content [10-16]. By using those models and formulas, the moisture content of the soil can be determined from dielectric constant with laboratory calibration.

## 1.2 Problem Statement

In pavement construction, compaction is a function of moisture content *(mc)* of the soil. Water aids the subgrade and subbase materials in creating a strongly packed system during the compaction process. The Standard Proctor compaction test is performed at laboratory to determine optimum moisture content at which maximum dry unit weight is attained. The test uses a single identical compactive effort from hammer drops for all soil types. But different soil types need different degree of compactive effort and the test sometimes does not produce the optimum density and its related moisture content (*mc*) [3]. This procedure is laborious, time-consuming, and requires excessive care and accuracy. Another challenge is transferring the optimal compaction and moisture content results from laboratory testing to the field. The nuclear density gauge (NDG) and time domain reflectometer (TDR) can provide maximum density and moisture content of the pavement layers at field. The nuclear density gauge (NDG) is very costly to repair because it contains the nuclear source and regulation limitations for its radioactive sources. The time domain reflectometer (TDR) gives less accurate test result and it is more expensive than frequency domain reflectometer (FDR).

## 1.3 Objective

The main objective of this study is to develop a laboratory based calibration equation for monitoring moisture content in subbase and subgrade layers by using microwave techniques. The study concentrates on the following objectives:

i. Develop a relation between dielectric constant, $\varepsilon_r'$ and moisture content (*mc*) of subgrade and subbase for correlation.

ii. Compare the measured value of dielectric constant, $\varepsilon_r'$ at field for the blended subbase sample with the established relation between dielectric constant, $\varepsilon_r'$ and moisture content (*mc*).

iii. Determine the conductivity, $\sigma$ of subbase sand and subgrade soil sample independently and evaluate the effect on texture of subbase and subgrade sample.

## 1.4 Scope of Research

To achieve the objectives of this study, the research emphasized the use of microwave techniques to determine the moisture content of the pavement layers. The nuclear density gauge was used in newly constructed road to find moisture content and dry density of the compacted blended subbase and the sample was collected. The soil subgrade and sand subbase compacted samples were prepared at laboratory. Several laboratory tests such as determination of moisture content by conventional method, grain size analysis and Modified Proctor test were carried out at geotechnical laboratory in Faculty of Civil Engineering, Universiti Teknologi Malaysia (UTM), Malaysia.The dielectric data measurement was taken for these three pavement layers at microwave laboratory in the Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM), Malaysia.

Chapter 2 presents details on pavement structure, pavement compaction, dielectric performance of the subgrade soil, characteristics of microwaves, microwave measurement system for testing, interaction of microwaves with materials, propagation of microwave in materials and details of open ended coaxial probe method. Chapter 3 describes samples preparation, experimental set-up and various test procedures. Chapter 4 offers the presentation of data and its subsequent analysis. Chapter 5 presents the conclusion of the research and recommendation for further study.

## 1.5 Significance of the Study

The dialectic based method can predict pavement performance in moisture change and provide data for various researches. Many researchers from other industries such as agriculture, food, chemical, and mining use microwave technique to determine the moisture content of different materials. Further research is needed in civil engineering field for significance in the sense that it will:-

i. Be an efficient and effective way to determine in- situ moisture content of the subgrade, subbase, and road-base.
ii. Be fast and non-destructive test.
iii. Minimize the need for sample preparation and laboratory process.
iv. It is a multidisciplinary topic encompassing microwave and civil engineering.
v. Be a suitable and low-cost measuring device for determination of moisture content for pavement courses, working in the frequency domain.

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