# Measuring effective porosity using Frequency Domain Reflectometry with Vector Network Analyzer Systems

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**Abstract**

Effective porosity is one of the most important physical properties of porous media that affect the flow of groundwater and contaminants. However, its determination is a very difficult under both laboratory and field conditions. It takes quite an effort to classically determine it. This paper proposes a new method, the Frequency Domain Reflectometry with Vector Network Analyzer Systems (FDR-V), that instantaneously measures the real part of the complex dielectric constant of the medium effective porosity of a medium, from which the effective porosity is derived by a simple calculation. The determined range of effective porosities is from 0.381 to 0.389 for saturated standard sand samples. These compare well with 0.36, a value obtained from an empirical equation.

## 1. Introduction

Nowadays, environmental considerations are very important in the management of both surface and groundwater. Contaminations caused by human activities continually infiltrate into the soil and finally reach the groundwater. To contribute to the prevention of contaminations underground, a number of researchers are studying the mechanisms of contamination pathways and the prevention techniques to be adopted. The pathway of these contaminations is affected by several physical and chemical properties of the ground material, of which the effective porosity of the ground material is an important intrinsic parameter.

The effective porosity, $n_e$, is the volume of pore space through which fluid can effectively take place. The effective porosity is commonly used because some of the pores within a porous media may be isolated, which will not contribute to the ability of the medium to transmit water or other fluids. The relationship between effective porosity and total porosity depends on the size, shape and packing arrangement of the grains of the porous media.

Current methods of measuring effective porosity are tedious and time consuming. So, generally, it is simply calculated as 90 % of the porosity. There is therefore the need to develop methods that would directly measure effective porosity of materials. This paper describes a method that has been developed to measure the effective porosity ($n_e$) and the total porosity ($n$) of some standard sands in the laboratory, using the real part of the complex dielectric constant of the material. The real part of the dielectric constant is determined instantaneously by means of a *Frequency Domain Reflectometry with Vector Network Analyzer Systems (FDR-V).*

## 2. Frequency Domain Reflectometry with Vector network analyzer (FDR-V) systems

In this study, one type of the permittivity method in which frequency domain reflectometry with vector network analyzer systems (FDR-V) is used to measure the dielectric constant of a medium. The FDR-V systems consist of two sets of machines, namely FDR-V 1 and FDR-V 2 (Figure 1A). The FDR-V 1 utilizes a microwave frequency range of 1 – 18 GHz (Nishigaki & Komatsu, 2000). FDR-V 2 utilizes microwave frequency range from 100 MHz to 3 GHz.

The coaxial probe is 18 cm long and 0.36 cm in diameter. The microwave frequency is emitted from the central core of the coaxial probe within a diameter of 0.1cm. The coaxial probe is tied to a plastic tube through which ethanol (99.5 %) could be injected, with an allowance of 0.5 cm interval between the bottom tips of the two (Figure 1B). These are then lowered into the sample column, 2.5 cm from the bottom. Then, 20 ml of ethanol (99.5%) is slowly injected into the prepared standard sand sample column. Once the probe is lowered and the injection of the ethanol starts, the FDR-V systems measures the real part of the dielectric constants of mixtures of sand and water and, sand and ethanol at 2-second intervals till the injection of the ethanol is completed. The measured dielectric constants are stored in a data logger in a laptop computer, which also controls the FDR-V systems. A plot of the variations of a measuring dielectric constant as time passed is simultaneously displayed on the monitor of the systems.

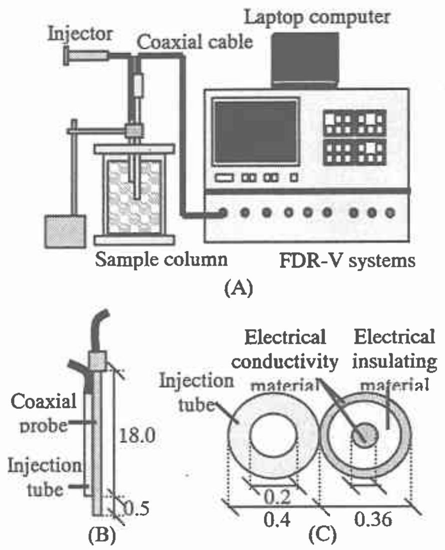


Figure 1. Schematic diagram of FDR-V systems, (A) Set-up, (B) Measuring probe, (C) Cross-section of measuring probe, [Unit: cm]

## 3. Applied mixing model of the relative complex dielectric constant

To calculate the effective porosity from the real part of the dielectric constants, the following mixing models are used:

$$\varepsilon_0 = \varepsilon_s(1-n) + \varepsilon_w \cdot n \qquad (1)$$

$$\varepsilon_1 = \varepsilon_s(1-n) + \varepsilon_w(n-n_e) + \varepsilon_{eth} \cdot n_e \qquad (2)$$

where, $\varepsilon_s$, $\varepsilon_w$, and $\varepsilon_{eth}$ are the complex dielectric constants of soil, water, and ethanol, respectively; $n$ and $n_e$ are the porosity and effective porosity, respectively, of the material understudy, which is standard sand in this study.

## 4. Effective porosity measurement of fully saturated standard sand

The sample material used in this study was standard sand, whose specific gravity and porosity were 2.65 and 0.4, respectively. Twenty-two (22) sand samples were prepared for the determinations. Each sample was put in cylindrical acrylic containers of 5 cm diameter and 6 cm deep. A 1-cm margin was left on top of the sand so that standing water could be left over the sand after fully saturating it with water. The real part of the dielectric constants of the fully saturated sand columns were then determined using the FDR-V 1 and FDR-V 2 systems. The set-up was as shown in Figure 1A. The measuring frequency range used was 1 GHz, which falls within the overlapping frequency range of 1 – 3 GHz for both the FDR-V1 and FDR-V2 systems.

## 5. Results & Discussions

The results of the determinations are shown in Figures 2 and 3, and Tables 1 and 2. Figures 2 and 3 are plots of the dielectric constants with time. Tables 1 and 2 show the measured dielectric constant and effective porosity compared to literature values. The determined effective porosities, using the FDR systems, range from 0.381 to 0.389. The results from the study compare favorably with the effective porosity calculated from the empirical formula. The porosity of the standard sand used in this study was 0.4. This means that its effective porosity is 0.36, according to the classical empirical calculation. Considering the effort that one has to make before the porosity of a medium can be determined classically and after which the effective porosity is calculated from the formula, the FDR-V systems offer a fast, easy and reliable means of determining the effective porosity of a medium in the laboratory.

## 6. Conclusions

This study describes a new permittivity technique for determining the effective porosity of a medium in the laboratory. The method, Frequency Domain Reflectometry with Vector Network Analyzer systems (FDR-V 1 and FDR-V 2) instantaneously determine the real part of the dielectric constant of the material, from which the effective porosity is calculated. The effective porosity determined with the systems compare favorably with known procedures. The determinations are rapid, fast and reliable. The FDR-V systems place, at the disposal of scientists, an additional tool in the effort to deal with geo-environmental problems.

Further work shall be carried out in the field to study how well the FDR-V systems determine the effective porosities of contaminated sites, using tracers. It is hoped that a variety of measured data, from the field and laboratory, shall be available for detailed analysis as to the effectiveness, reliability and suitability of the FDR-V systems for effective porosity determinations.

Table 1. Dielectric constants

| Pure Materials | Complex Dielectric Constant | | | |
|---|---|---|---|---|
| | FDR-V1 system | | FDR-V2 system | |
| | Literature Value* | Measured Value | Literature Value* | Measured Value |
| Soil ($\varepsilon_s$) | 2~3 (3**) | 1.85 | 2~3 (3**) | 1.65 |
| Water ($\varepsilon_w$) | 80~81 (81**) | 80.78 | 80~81 (81**) | 80.48 |
| Ethanol ($\varepsilon_{eth}$) | - | 12.98 | - | 12.42 |

Source: * Ulaby (1990)
** Nishigaki & Komatsu (2000)

Table 2. Effective porosities

| System | Effective Porosity ($n_e$) | | |
|---|---|---|---|
| | Literature Value | Measured Value | Remark |
| FDR-V1 | 0.381 | 0.382 | 0.36# |
| FDR-V2 | 0.389 | 0.385 | |

Notation: * $0.9 \times n$.
Established porosity = 0.4

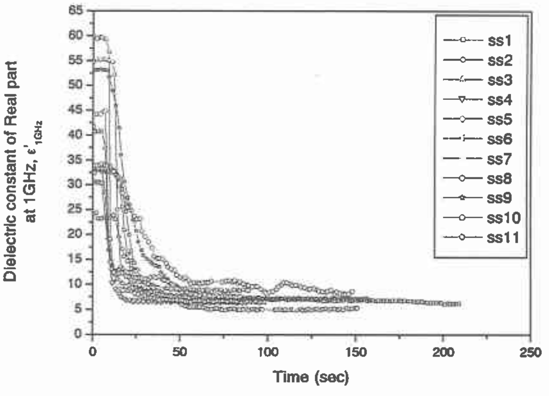


Figure 2. Graph of real part of dielectric constant with time using FDR-V1

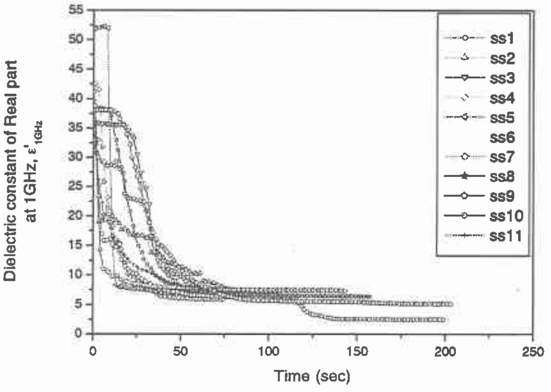


Figure 3. Graph of real part of dielectric constant with time using FDR-V2

## References:

1) Domenico, P.A., and Schwartz, F.W., 1990, Physical and Chemical Hydrogeoleogy, John Wiley & Sons, pp24-28.

2) Nishigaki, M. & M. Komatsu, 2000, Study on Measuring System of Subsurface Contamination using Frequency Domain Reflectometry with Vector Network Analyzer, In: Garnier, J., Thorel, L. & Haza, E. (ed.), *Physical Modeling and Testing in Environmental Geotechnics.; Int. Symp., La Baule, France, 15-17 May 2000*, France: LCPC : pp43-49.

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