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Investigation on Dielectric Properties of Sludge Waste from Water Treatment Using Microwave Non-Destructive Testing (MNDT)

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Abstract: The demand for water cleanup rises in tandem with a country's requirements and development. Recovery of purified water containing nutrients and other beneficial materials is a critical opportunity that must be taken advantage of. A challenge that needs to be tackled is the necessity for large capacity and high-value management of sludge waste following the water treatment process. The pH level and microwave frequencies influence were used as a starting point for assessing the content of the sludge waste. Microwave non-destructive testing (MNDT) is a microwave measurement that can be used to determine the dielectric characteristics of materials without destroying or modifying the sample's content. The methodology employs a free-space measurement technique with a frequency range of 8 to 12 GHz (X-band). Through S-parameters acquired, a correlation analysis was done to analyze the effect of frequencies with the sludge waste. A comparative investigation with peat soil samples in establishing if the sludge has similar attributes to normal soil is used to ensure the accuracy of the sludge waste data. It can be determined that the sludge waste has a high signal correlation towards the frequency band 8 GHz to 12 GHz, which is compatible with the MNDT approach. All of the sludge samples had a pH range that is appropriate for agricultural use.

Keywords: Microwave Non-Destructive Testing (MNDT), sludge waste, X-band frequency, s-parameters

1. Introduction

Wastewater remediation and sludge treatment have also become a rising global environmental problem in the search for a green and sustainable future. The environment and public health should not be overlooked as the country progresses to higher levels of development. Several cutting-edge wastewater and sludge treatment processes have been

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developed over the last few decades. Active research is being undertaken globally to find sustainable treatment techniques, and microwave technology is gradually making a modest but promising imprint in improving the ease, speed, and effectiveness of some wastewater and sludge management treatment processes [1]-[4].

The presence of sludge waste in water treatment plants has become one of the most pressing issues that must be addressed immediately. Because sludge is by far the largest in volume, its treatment and disposal methods are of major concern [5]. The high cost of handling and the necessity for a large place for waste disposal have raised several worries among the water company and the state office (DOE). As a result, a solution is required for managing sludge waste so that it can be repurposed for other purposes, such as agriculture or even construction, which will benefit the environment and indirectly alleviate local environmental concerns, as sludge is one of Malaysia's major waste contributors. The cost of treating wastewater tends to create a financial burden for wastewater treatment companies. In addition, this will keep on increasing with the increasing population especially in the urban areas in Malaysia. The value of a clean environment far exceeds the involved in preserving it, thus no monetary value can be pinned for a clean environment. Numerous environmental and health risk-related issues associated with the disposal of sludge are also reported in which if not mitigated properly it will cause serious problems [5], [6].

Thus, this project demonstrates the potential of MNDT as a method to investigate the dielectric properties of sludge waste. The dielectric properties of the material in the sludge waste is important to identify the material suitability of the materials for any other usages. For instance, giving low permittivity for organic matter is suitable for agricultural purposes [6-8] or even in construction [9], [10]. The X-band frequency of 8 to 12 GHz is applied in determining the sludge content due to its equipment feasibility and supports the detection of smaller particles in a radar. It also operates better with small antennas and can handle high power since it has a short wavelength of 2.5 cm to 3.8 cm. Besides being fast and contactless, microwave application in MNDT has a good penetration in nonmetallic materials. Thus, this method will offer a simpler and high-speed operation in determining the contaminant of the sludge waste. A laboratory-scale using relatively small quantities of sludge, but the findings will serve as a solid base for further scaling up of the microwave-based sludge treatment technology.

2. Methodology

Two sludge waste samples were collected from two different locations: The Semenyih 2 plant and the Sungai Langat plant. Samples were obtained from those locations' processing sites and stored at room temperature. Before testing, the samples underwent three-stage measurements: weight measurement and pH measurement and followed by MNDT measurement. To ensure the stability of the sample in terms of pH level and consistency of S-parameters data received from MNDT the measurement process was done three times for each sample using identical protocols. The data was then examined with SPSS software to determine the correlation between frequencies used with the S-parameters obtained from the sludge. Finally, the same techniques and MNDT measurements were applied to peat soil samples for better understanding of the overall MNDT measurements.

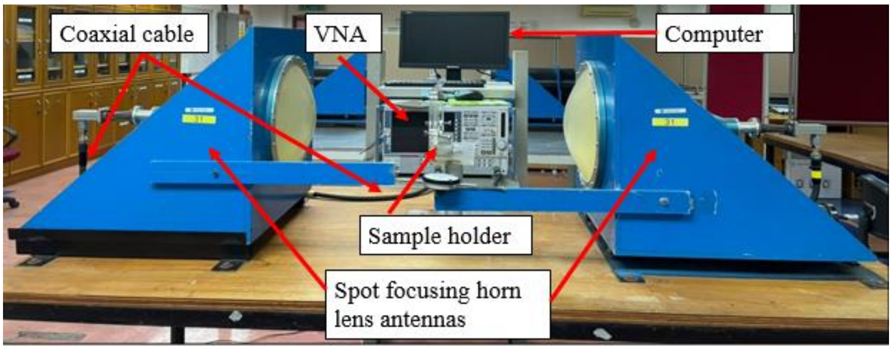


Fig. 1 - MNDT (free space) measurement setup

A fundamental laboratory free space measurement system of MNDT has been setup as shown in Fig. 1. Which consists of a vector network analyzer (VNA) and a pair of horn lens transmitters and receiver antennas that are connected with coaxial cables. The spot-focusing horn lens antenna consists of two equal plane-convex dielectric lenses mounted back-to-back in a conical horn antenna. The sludge waste sample is placed in between the transmitter and receiver antennas in an acrylic sample holder to measure electromagnetic properties of dielectrics at microwave frequencies between 8 GHz to 12 GHz (X-Band) that applies the electromagnetic free space measurement technique [11], [12]. The frequency is not fixed due to the unpredictability of which frequency will be able to give measurements on the electrical properties of the material contained in the sludge waste.

Preceding the MNDT measurement, the sludge samples underwent two processes of weight and pH measurement. For the weight measurement, first, the sample holder's weight is measured and the sludge sample is then put into the acrylic sample holder. Next, the sludge sample in the sample holder is measured and is subtracted with the weight of the sample holder to obtain the first sample weight. The first sludge sample weight is set as a reference weight for the other two Semenyih (2) samples. For the pH measurement, the pH value is measured using a soil pH meter. The soil pH meter is placed about 4cm deep into the middle of the sample holder. Lastly, the sample together with the sample holder is placed between the two antennas and the S-parameters will be extracted using MNDT measurement. All of the weight and pH measurement procedures are repeated for three sludge waste samples from Sungai Langat plant.

For three sludge samples from each plant, the first sample weight is set to a reference for other two samples since the weight is defined as a constant variable in this study and should not alter other variables such as frequency or S-parameters that could lead to different outcomes. The pH level of the sludge waste samples was tested to compare it to the appropriate pH level of soil for plant development and other agriculture applications. These processes were implemented to replicate the plant process, which involved exposing the sludge for two to four weeks before being delivered to the disposal area. The data was then sent into a post-processing process that used Pearson Correlation Analysis and SPSS software to evaluate the correlation between the X-band frequencies used and the S-parameter response. A correlation analysis is a statistical tool for determining the relationship between two variables.

The sludge samples were compared to peat soil samples to see if they might simulate soil suited for agriculture. Peat soil was used to further investigate the impacts of MNDT and to reaffirm the technique's suitability for dealing with sludge waste as an organic, non-hazardous substance. Because of its high organic matter concentration, peat soil was chosen for plants that require an acidic climate [14-16]. Peat soil samples were subjected to the same sample preparation and MNDT testing techniques as sludge waste samples. The S-parameters data [17] received from peat soil samples were also studied using the correlation analysis technique to see if the frequencies have an influence on the soil samples and how the high frequency affects the soil samples.

3. Results and Discussion

After extracting the S-parameters data from the free space measurement system using the VNA, the S-parameters response graph of S_{11} and S_{21} are visualised in terms of real and imaginary values versus the X-band frequency. Then the same data is used for Pearson Correlation Analysis with SPSS software to evaluate the link between S-parameters and X-band frequency. As previously indicated, the measurement technique is repeated about three times for each sample, resulting in two S-parameter response graphs, two scattering plots of S-parameters response, and four Pearson Correlation Analysis of S-parameters for each sample (S_{11} real, S_{11} imaginary, S_{21} real, S_{21} imaginary).

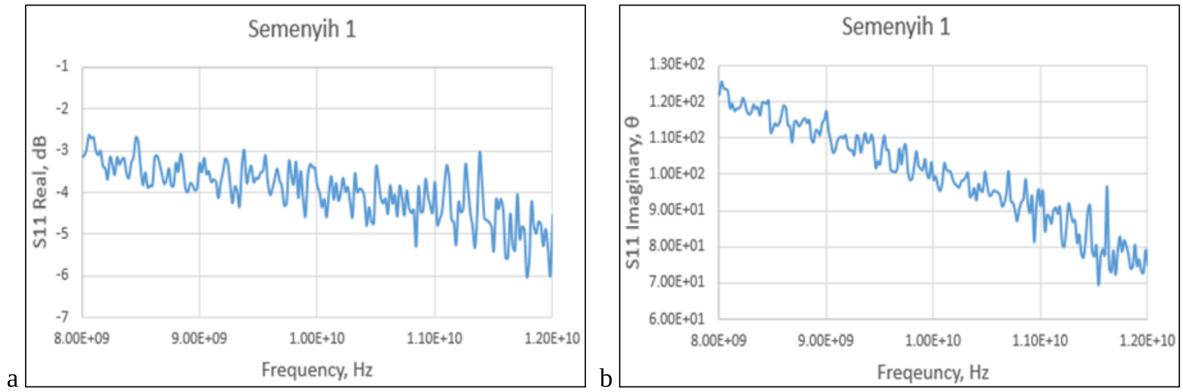


Fig. 2 - Graph of S_{11} against frequency for sample 1 from Semenyih 2 plant (a) S_{11} real; (b) S_{11} imaginary

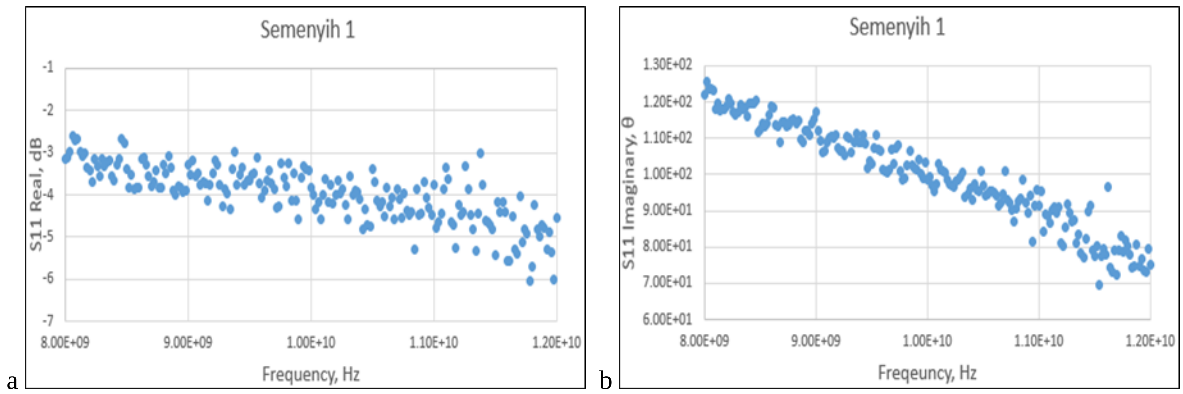


Fig. 3 - Scattering plot of S_{11} against frequency for sample 1 from Semenyih 2 plant (a) S_{11} real; (b) S_{11} imaginary

The complex value of S_{11} and S_{21} is the focus of the recovered S-parameters data from the MNDT experiment. Fig. 2 show the measured data in terms of S_{11}, while Fig. 3 show the scattering plot for amplitude value in dB and phase of the response towards the X-band frequency for sample 1 from the Semenyih 2 plant. Fig. 2 (a) and Fig. 3 (a) shows that the amplitude signal is inversely proportional with the X-band frequency and the signal is focused between -5 and -3 dB. From Fig. 2(b) and Fig. 3(b), the phase signal exhibits a significant linear similar downward pattern with better correlation than amplitude and the signal is concentrated between 60 ^{o} and 125 ^{o}, as seen in Fig. 3 and Fig. 5. To understand the relationship between the frequencies chosen, more investigation of the S-parameters was required.

Table 1 - Pearson Correlation analysis between frequency and S11 real

	Frequency	**S_{11} real**
Pearson Correlation	1	-.769**
Sig. (2-tailed)		<.001
N	201	201
Pearson Correlation	-.769**	1
Sig. (2-tailed)	<.001	
N	201	201

** Correlation is significant at the 0.01 level (2-tailed).

Table 2 - Pearson Correlation analysis between frequency and S11 imaginary

	Frequency	**S_{11} imaginary**
Pearson Correlation	1	-.966**
Sig. (2-tailed)		<.001
N	201	201
Pearson Correlation	-.966**	1
Sig. (2-tailed)	<.001	
N	201	201

** Correlation is significant at the 0.01 level (2-tailed).

The Pearson Correlation analysis using the SPSS software between the complex value of S_{11} and the X-band frequency is shown in tables 1 and 2. From Table 1 and Table 2, the Pearson Correlation value is -0.769** and -0.966** which indicates that both S_{11} real and S_{11} imaginary signal are inversely proportional and correlated at significant level of 0.01 or 99% with the X-band frequency. The reflection coefficient, or S_{11}, denotes that the signal that is reflected back to the transmitter antenna after propagating through the sample tested before reaching the receiver antenna is reflected back to the transmitter antenna.

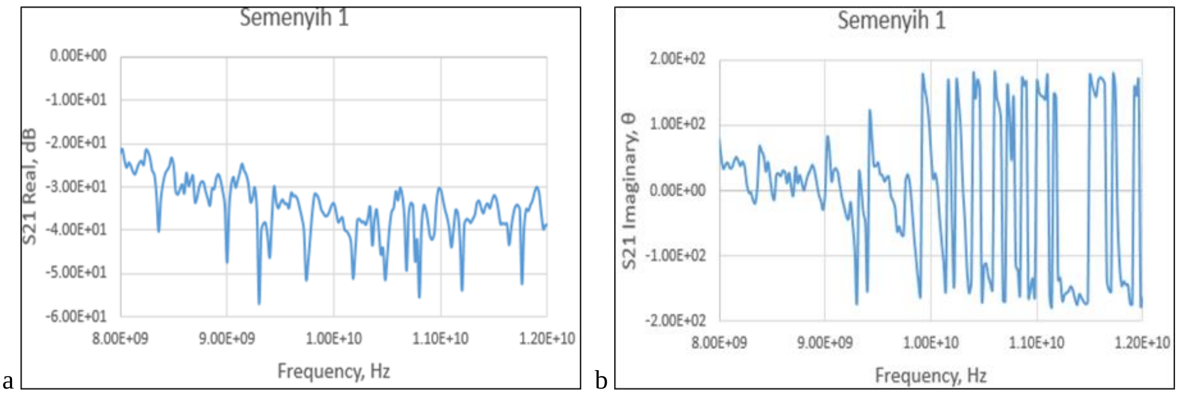
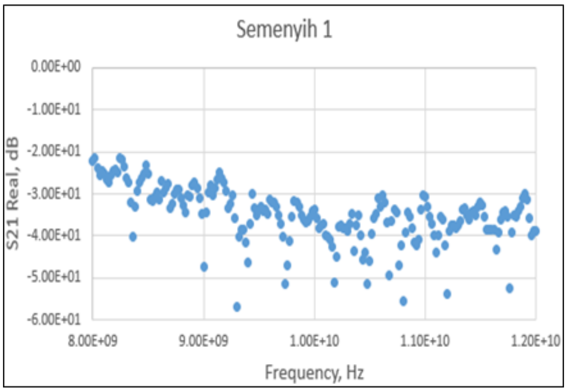


Fig. 4 - Graph of S_{21} against frequency for sample 1 from Semenyih 2 plant (a) S_{21} real; (b) S_{21} imaginary



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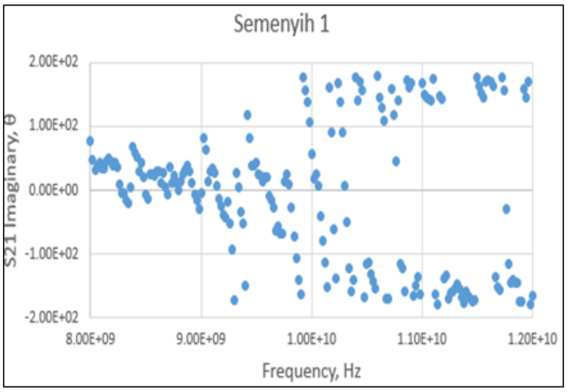

b

Fig. 5 - Scattering plot of S_{11} against frequency for sample 1 from Semenyih 2 plant (a) S_{21} real; (b) S_{21} imaginary

Fig. 4 (a) and Fig. 4(b) illustrate the S_{21} real and imaginary responses to the X-band frequency while Fig. 5(a) and Fig. 5(b) are the scattering plot in measuring sample 1 from the Semenyih 2 plant, respectively. Fig. 4 (a) and Fig. 5 (a) shows how the amplitude signal is extremely condensed between -40 dB and -20 dB, while Fig. 4 (b) and Fig. 5 (b) shows how the phase signal is spread between -100 º and 100 º. As seen from the graphs, the complex S_{21} parameter exhibits a reaction to the X-band frequency and the same downward pattern as the S_{11} amplitude and phase, even though the signal is slightly dispersed for amplitude and narrowly dispersed for phase.

Table 3 - Pearson Correlation analysis between frequency and S21 real

	Frequency	S_{11} real
Pearson Correlation	1	-.523**
Sig. (2-tailed)		<.001
N	201	201
Pearson Correlation	-.523**	1
Sig. (2-tailed)	<.001	
N	201	201

** Correlation is significant at the 0.01 level (2-tailed).

Table 4 - Pearson Correlation analysis between frequency and S21 imaginary

	Frequency	S_{21} imaginary
Pearson Correlation	1	-.162*
Sig. (2-tailed)		<.001
N	201	201
Pearson Correlation	-.162*	1
Sig. (2-tailed)	<.001	
N	201	201

* Correlation is significant at the 0.05 level (2-tailed).

Table 3 and Table 4 in the S_{21} Pearson Correlation analysis using SPSS software show the association between the complex value of S_{21} and the X-band frequency. From Table 3, the Pearson Correlation value is -0.523** which shows that the S_{21} real signal is inversely proportional and correlated at significant level of 99% with the X-band frequency. On the other hand, from table 4, the value of Pearson Correlation is -0.162*. It means that S_{21} imaginary signal is also inversely proportional to the X-band frequency but the signal is correlated at 95% significant level. The transmission coefficient, or S_{21}, indicates that the signal propagates from the transmitter antenna to the reception antenna, and then is reflected back to the transmitter antenna after passing through the samples being measured.

The results of the correlations analysis for the samples are summarised in Table 5, 6, and 7, accordingly. The signal is 99% correlated at significant levels of 0.01, while the signal is 95 % correlated for substantial levels of 0.05. The X-band frequencies were utilized to investigate the electrical properties of the samples, as can be shown. Table 5 shows that the X-band frequencies are significantly linked (99%) with all S-parameters of the sample acquired from the

Semenyih 2 plant, except the S_{21} phase of sample 1, which corresponds by 95%. Table 6 shows that the X-band frequencies are all highly associated (99%) with the S-parameters of the Sungai Langat sample. Last but not least, table 7 demonstrates that, for peat soil samples, the X-band frequencies are highly associated (99%) with the sample S-parameters, except S_{21} phase for sample 2 and sample 3, which have signal correlation of 95%.

Table 5 - Summary of correlations analysis for sludge waste samples from Semenyih 2 Plant

Samples	Semenyih 1	Semenyih 2	Semenyih 3
S_{11} Amplitude (dB)	-0.769^{**}	-0.693^{**}	-0.694^{**}
S_{11} Phase (θ)	-0.966^{**}	-0.957^{**}	-0.955^{**}
S_{21} Amplitude (dB)	-0.523^{**}	-0.602^{**}	-0.561^{**}
S_{21} Phase (θ)	-0.162^{*}	-0.355^{**}	-0.343^{**}

Note: ** (99% correlated), * (95% correlated)

Table 6 - Summary of correlations analysis for sludge waste samples from Sungai Langat Plant

Samples	Sungai Langat 1	Sungai Langat 2	Sungai Langat 3
S_{11} Amplitude (dB)	-0.825^{**}	-0.812^{**}	-0.800^{**}
S_{11} Phase (θ)	-0.972^{**}	-0.967^{**}	-0.967^{**}
S_{21} Amplitude (dB)	-0.283^{**}	-0.360^{**}	-0.340^{**}
S_{21} Phase (θ)	-0.555^{**}	-0.390^{**}	-0.438^{**}

Note: ** (99% correlated), * (95% correlated)

Table 7 - Summary of correlations analysis for peat soil samples

Samples	Gambut 1	Gambut 2	Gambut 3
S_{11} Amplitude (dB)	-0.912^{**}	-0.342^{**}	-0.934^{**}
S_{11} Phase (θ)	-0.973^{**}	-0.991^{**}	-0.969^{**}
S_{21} Amplitude (dB)	-0.541^{**}	-0.301^{**}	-0.635^{**}
S_{21} Phase (θ)	0.204^{**}	0.171^{*}	0.109^{*}

Note: ** (99% correlated), * (95% correlated)

4. Conclusion

Based on the results of the correlation and comparative analysis, it can be concluded that the MNDT (free space) measurement system can be applied to sludge waste and peat soil samples, as all of the samples tested to have a high signal correlation of reflection and transmission in the frequency band 8 GHz to 12 GHz (X-band). In terms of pH level testing, it was discovered that the sludge waste samples have a pH range that is good for agriculture, particularly for plant growth that demands an acidic environment. Despite this, more S-parameter study is required to confirm these findings and extract the dielectric characteristics of the sludge waste to determine a specific application for sludge waste reuse.

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