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Road Pavement Density Measurement by Using Non-Destructive Ground Penetrating Radar System

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Abstract

This paper presents the development of Ground Penetrating Radar (GPR) system based on the electromagnetic wave reflection in order to determine the density of road pavement**.** The proposed method is simple, fast, non-destructive and within an acceptable accuracy of determining the road pavement density. The predicted signal attenuation from the theoretical analysis is compared with the signal attenuation measured from the laboratory experimentation. The comparison produces the relative error between these two results and it is used in the optimization. The best theoretical model with smallest mean error from the three existing GPR Mixture Models (GMM) has been improved in optimization process. The finding from the optimization process suggested that three additional constant parameters which are Volume factor, Permittivity factor and Attenuation factor need to be included to improve the existing GMM model. A field test had been conducted as a reliability analysis to validate the optimized GMM model. From the field test, it shows that the proposed GPR system works well with an error range from 0.29% to 0.96 % for nine locations. Finally, a complete GPR system has been developed based on the optimized GMM attenuation curve to predict the density of a real road pavement.

Keywords: Ground Penetrating Radar, Road Pavement, Density, Attenuation, Electromagnetic

1. Introduction

Ground Penetrating Radar (GPR) has been used extensively in the road pavement evaluation for quite some time and was performed in early 1980s (Saarenketo and Maijala, 1994). The known road pavement evaluation measurements are coring sample method (Grote *et al*., 2005), nuclear-sourced device (Scmidt, 2006), and rolled density gauge (Edward *et al*., 1998). All these approaches were widely used for this purpose but these techniques are found have drawbacks and limitations. Thus, it was motivated to find the more efficient and automated methodology to overcome these limitations. In this work, microwave technique based on GPR technology is being introduced to measure the density of the road pavement. To gain this purpose, an analytical analysis, laboratory scale experimentation and field test validation were performed in this paper in order to develop a new GPR system. Using this method, it takes shorter time and more efficient compared to other conventional methods by using microwave free space technique. The main objective of this work is to optimize the selected or best GPR mixture model with lowest mean relative error and then to validate the optimized model at field test real condition by using microwave free space and reflection technique.

2. Simulation Procedure: GPR Mixture Model

In simulation analysis, the GPR mixture model is used where the complex permittivity of heterogeneous mixtures can be predicted (Sihvola *et al*., 1998). The three models used are Nelson, Landau and Lichtenecker mixture model. The models are as follows:

Nelson mixture model by Sihvola, A., E. Nyfors and M. Tiuri (Sihvola *et al*., 1998):

$$\sqrt{\varepsilon} = v_1\sqrt{\varepsilon_1} + v_2\sqrt{\varepsilon_2} + .. + v_n\sqrt{\varepsilon_n} \tag{1}$$

Landau mixture model by Looyenga, H. (Looyenga, 1965).

$$\sqrt[3]{\varepsilon} = v_1\sqrt[3]{\varepsilon_1} + v_2\sqrt[3]{\varepsilon_2} + .. + v_n\sqrt[3]{\varepsilon_n} \tag{2}$$

Lichtenecker mixture model by Sihvola, A., E. Nyfors and M. Tiuri (Sihvola, 1998):

$$\ln\varepsilon = v_1\ln\varepsilon_1 + v_2\ln\varepsilon_2 + .. + v_n\ln\varepsilon_n \tag{3}$$

The ε represents the complex permittivity of the particular road pavement density, where high density is found to give a low complex permittivity. The complex permittivity, ε is described as below equation.

$$\varepsilon = \varepsilon^{'} - j\varepsilon^{''} \tag{4}$$

where $\varepsilon^{'}$ is the dielectric constant' while $\varepsilon^{''}$ is the loss factor (Samuel, 1992). For v_1, v_2 and v_n are the fractional volume of the respective components, where $v_1 + v_2 + .. + v_n = 1$. From equation (1) to (3), n = 11 is used since the road pavement is made up of 1 asphalt and 9 aggregates of ACW14 including the air void content (J.K.R., 1998). The relative dielectric permittivity for both asphalts and aggregates are in the range of 5 to 6 whereas 1 for air void content (Shang *et al*., 1999). The attenuation equations (5) and (6) will be used for attenuation prediction due to different density of pavement (Sihvola *et al*., 1998).

$$A = 10\log_{10}(e^{-2\alpha.t}) \tag{5}$$

Where

$$\alpha = \frac{2\pi.f.\varepsilon^{''}}{2}\sqrt{\frac{\mu}{\varepsilon^{'}}} \tag{6}$$

From equations (5) and (6), α is an attenuation constant, f is a carrier frequency: 1.7 GHz, 2.0 GHz, 2.3 GHz or 2.6 GHz, μ is permeability of road pavement where $\mu = 1\times10^{-6}$ (Jerry, 1998). An A is a 'predicted attenuation' and t is a fixed thickness where t = 0.05 m. Figure 1 shows the phenomenon of using this model in GPR environment.

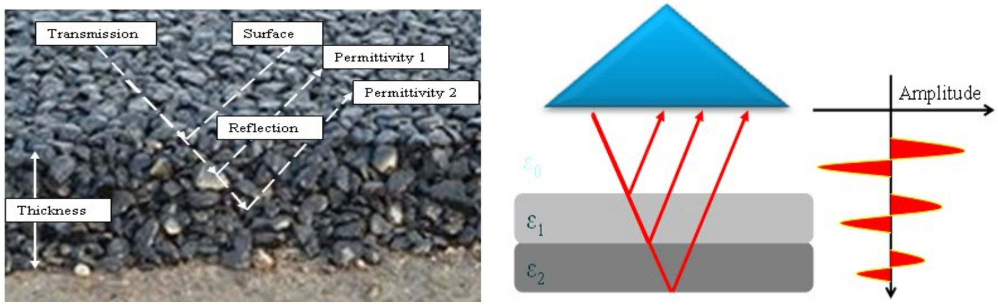


Figure 1: Typical GPR reflections from a Road Pavement Slab in GPR Mixture Model

In Figure 1, the permittivity 1 is due to road pavement whereas permittivity 2 is due to concrete. The permittivity (ε_r) contrast in layered media causes reflection of incident Electromagnetic Wave. Asphalt is a sticky, black and highly viscous liquid whereas aggregate is applied to all particles below 20 mm diameter in size (Saarenketo and Soderqvist, 1993). The microwave techniques used are free space method and reflection technique.

3. Material and Sample Preparation

In laboratory, there have nine pavement slabs with different densities. The road pavement slab samples used in this measurement consists of 5% of air void and 95% of solid whereby the solid is consists of 5% asphalt and 95 % aggregates as suggested by Public Work Department (J.K.R., 1998). In mixing process, the paving and compaction are implemented in Turamachine. The dimension of each road pavement slab sample is 0.5 m x 0.42 m x 0.05 m. The volumes are similar for all slabs but different in mass.

4. Indoor GPR Measurement Setup and Procedure

The next process is a laboratory GPR measurement setup as shown in Figure 2. From the figure, the distance between horn antenna and road pavement sample is fixed with 0.3m height. This height also will be used for field test work in order to make sure the volume of the road pavement under tested is consistent. In this testing, continuous wave is used since this wave will penetrate the whole body of the sample as well as to determine the density based on the whole body of road pavement.

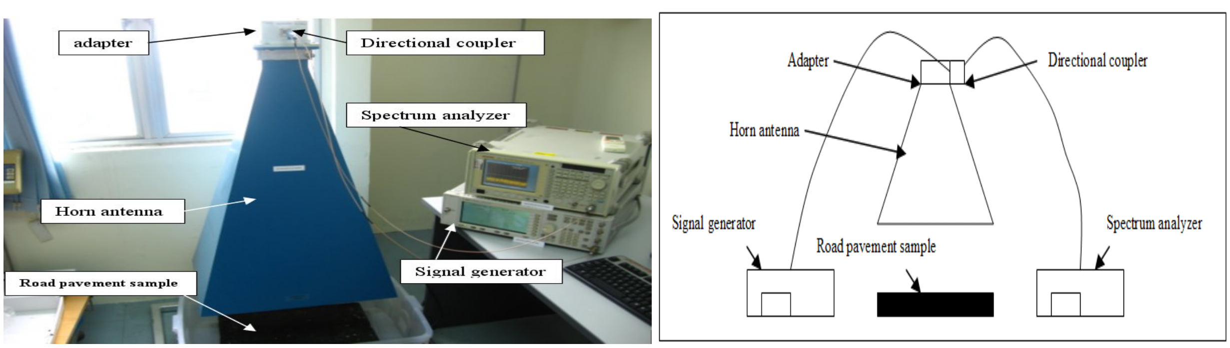


Figure 2: GPR Measurement Setup

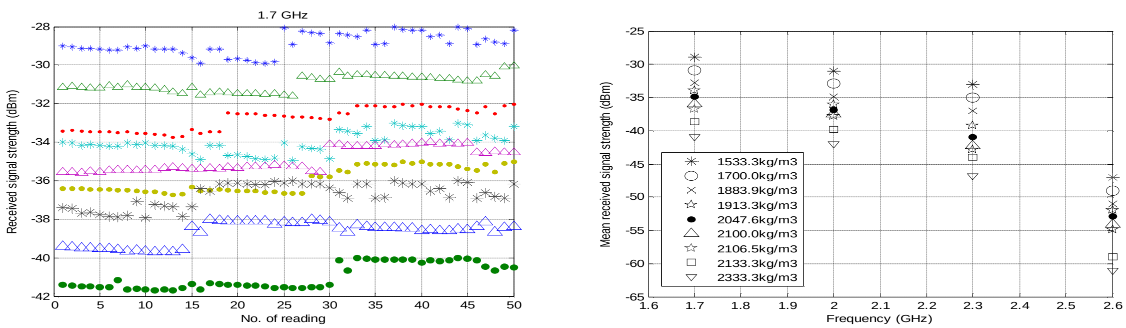
In measurement part, the fixed transmitted power used is 10 dBm. The horn antenna would sends many waves into the road pavement slab sample, then spectrum analyzer will record a received power in dBm.

In GPR data collection, for each GPR transmission, fifty data were taken for each four frequencies. For each road pavement slab, the fifty data were taken in 100 minutes where 2 minutes for each data.

5. Results and Discussion

5.1. Received Signal Strength for Nine Pavement Slabs at Four Frequencies.

Figure 3 shows the received signal strength due to nine slabs that collected from the laboratory experimentation. There is only frequency 1.7 GHz is shown since it is the most suitable frequency in this purpose. From the results, it is found that the highest density of road pavement slab causes the lowest of received signal strength at each frequency. This is due to the highest density of slab absorbs more energy from the wave. The differences among frequencies were also being observed as seen in Figure 3(b).



(a) (b)

Figure 3(a): Received Signal Strength due to Nine Road Pavement Slabs at Frequency 1.7 GHz
(b): Mean Signal Strength due to Nine Road Pavement Slabs at Four Frequencies

When we compare among four frequencies at Figure 3(b), it can be investigated that the highest frequency produces the lowest range value of received signal strength. The higher frequency had a higher resistance than the lower frequency and will causes more loses. The lower value of received signal strength produces the higher of attenuation. This is interesting to note that the higher frequency causes the higher attenuation. There was possibility that the higher frequency resulting the poor penetration.

5.2 Comparison of Attenuation between Measurement and Three GPR Mixture Models

From Figure 4, the measured attenuation is obtained from the laboratory experimentation and the predicted attenuation is obtained from the simulation analysis part by using three GPR mixture models. In addition, the effect of the container, 4 dB from (Damosso, 1999) is considered by addition of container attenuation to the measured signal attenuation since it was used during the laboratory experimentation.

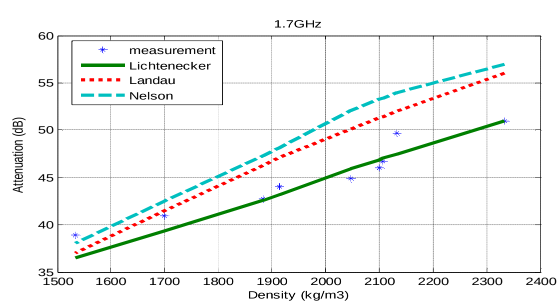


Figure 4: Comparison of Attenuation Between Measurement and Three GPR Mixture Models for Nine Road Pavement Slabs at Frequency 1.7 GHz

In Figure 4, it is clearly can be seen that the Lichtenecker mixture model looks very close to the measurement compared with the other models. The closest results show the lowest relative error. The other two models are not really close with the measurement might be the both are not really suitable for road pavement materials compared than the other heterogeneous samples such as concrete and cement. Even though, the figure still shows these three models increase with the increasing of density.

5.3 Relative Error of Attenuation between Measurement and Three GPR Mixture Models

The relative error has been done as shown in Table 1 to show the performance of each model. The best model with lowest mean errors will be selected in optimization for further. The optimization is performed in order to fit the measurement results with the simulation results.

Table 1: Mean Error of Attenuation Between Measurement and Three GPR Mixture Models

Frequency, GHz	Lichtenecker, (%)	Landau, (%)	Nelson, (%)
1.7	2.4	7.1	9.1
2.0	2.8	6.0	8.7
2.3	1.5	6.0	7.9
2.6	2.3	4.6	6.2

In Table 1, the mean relative error is considering all the results due to nine road pavement slabs. It is indicates that the mean relative error for Lichtenecker mixture model is the smallest with value is around 1.5 % and 2.8 %. at four frequencies. The lowest error value is due to the good agreement or closest data between measured and predicted attenuation results. Thus, the Lichtenecker mixture model has shown greatest results and can be used for optimization process.

5.4 Optimization Technique

The purpose of optimization technique is to produces a new mixture model that can predict more accurate the attenuation due to different density. The sensitivity analysis is a suitable method and attenuation constant, α is found most suitable to fit because this variable is affected by density as well as to get the new attenuation data. It is found that one new parameter has been added to attenuation constant.

$$A = 10\log(e^{-2(x1+\alpha).t}) \tag{7}$$

A new set of attenuations data, A will be compared to the set of data before optimization. Besides, the least square curve fitting approach was carried out to produce the best fitting line and it is found that a new constant parameter x_2 and x_3 are added and performed by using the MATLAB *lsqcurvefit* command (Chrysostosmos and Nikias, 1995).

$$\ln\varepsilon = v_1\ln\varepsilon_1 + v_2\ln\varepsilon_2 + v_3\ln\varepsilon_3 + x_2\ln x_3 \tag{8}$$

From the least squares routine, x_1, x_2 and x_3 were found to be -4.1628, -0.7569 and 0.3435 respectively. The parameter x_1, x_2 and x_3 are introduced as Attenuation factor, Volume factor and Permittivity factor in this project. Similarly, substitutions values of x_1, x_2 and x_3 into equation (7) and (8) give;

$$A = 10\log(e^{-2(4.1628+\alpha)d}) \tag{9}$$

$$\ln\varepsilon = v_1\ln\varepsilon_1 + v_2\ln\varepsilon_2 + v_3\ln\varepsilon_3 + 0.8088 \tag{10}$$

From equation (10), the value 0.8088 can be explained by physical justification. It is show that there exists unknown material inside the road pavement other than asphalt and aggregates and produces the Attenuation factor, Volume factor and Permittivity factor inside the road pavement. After this, the comparison and relative error for before and after optimization is done as shown in Figure 5 and Table 2.

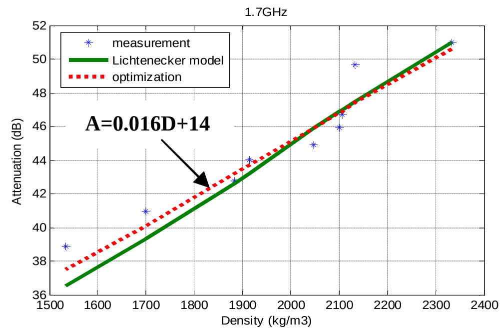


Figure 5: Attenuation Comparison between Measurement, GPR Mixture Model and Optimization

Table 2: Relative Error between Before (Lichtenecker) and After Optimization

Frequency, GHz	Lichtenecker, (%)	Optimization, (%)
1.7	2.4	1.9
2.0	2.8	1.4
2.3	1.5	1.2
2.6	2.3	1.9

From Figure 5 and Table 2, it clearly can be seen that the relative error for after optimization is less than before optimization, Lichtenecker mixture model for all samples. This is valid for all frequencies of the results. Thus, the optimization technique was successfully done and it can gives a good solution to improve the GPR mixture model. Besides, the best optimization fitting equations that obtained from the graph (dotted line) can be used as a calibration curve which involved A and D.

5.5 Field Test Validation

In this discussion, the field test validation is performed using a new real road pavement for the validation of improved GPR mixture model using a calibration curve. The validation process has been conducted at nine outdoor real road pavement of Faculty of Engineering, University Putra Malaysia. The outdoor GPR measurement setup and measurement point must be determined first before the measurement process.

5.5.1 Predicted Technique Using Optimized GPR Mixture Model

This technique is implemented by using Optimized GPR mixture model as discussed before. The purpose of this technique is to produce a predicted density of nine measured points for comparison purpose. The first step is an outdoor GPR measurement setup. In this setup, the outdoor GPR measurement equipments that used are similar with the equipments that used before in laboratory.

5.5.2 Received Signal Strength for Nine Points with Predict Density

The outdoor received signal strength measurements had been conducted at nine different points at outdoor real road pavement. From the finding, it is found that the higher density causes the lower value of received signal strength and vice versa. Besides, the range of received signal strength for the higher frequency is found lowest than the other lower frequencies. It can be concluded that the highest frequency produces the lowest of received signal strength and vice versa. This is due to the poor penetration at higher frequency when compared with the lower frequency (Okamura, 1981).

5.5.3 Comparison between Measured (Actual) and Predicted Density

In this part, the comparison between measured and predicted density has been done. The measured density is obtained by drilling out the core sample from each measured point. The results of measured and predicted densities for all measured points at four frequencies are shown in Table 3.

Table 3: Direct Comparison between Predicted and Measured Density at Four Frequencies

Point no.	Measured Density (kg/m3)	Predicted Density (kg/m3)			
		2.6 GHz	2.3 GHz	2.0 GHz	1.7 GHz
1	2008.838891	2020.2412	2015.5393	2015.4426	2011.2275
2	1855.385920	1873.0325	1872.0451	1841.7765	1860.4390
3	1850.566736	1864.1005	1861.6919	1842.7993	1855.3927
4	1908.396947	1926.4176	1922.8553	1918.4723	1915.9479
5	2059.857022	2082.4864	2081.8253	2040.1887	2067.8782
6	1999.272992	1977.4349	1982.6506	2012.365	1991.1061
7	1861.850680	1883.4785	1844.5622	1870.1730	1867.2084
8	1785.634570	1800.1569	1791.3552	1789.4331	1787.4009
9	2081.887578	2111.4079	2104.2593	2098.8583	2090.9469

In Table 3, it can be seen that the results are very close from each other at each measured point. It clearly can be seen that there are some points with good agreement and also with not really good agreement or slightly poor agreement between predicted and measured density. The poor results can be seen at frequency 2.3 GHz and 2.6 GHz compared with the result at frequency of 1.7 GHz and 2.0 GHz where there are slightly good agreements for all measured points. Base on this finding, it is interesting to note that the higher frequency is poor penetration when compared with the lower frequency as proved before.

5.5.4 Relative Error between Measured (actual) and Predicted Density

In this analysis, the relative error between measured and predicted density for each measured point had been done. The purpose is to see the performance of improved GPR mixture model at four different frequencies where the highest relative error show the poor result and vice versa as listed in Table 4.

In Table 4, it can be found that most of the lowest relative errors are come from the lowest frequency. The highest mean relative error show the density value is not really close in overall. The highest mean relative error is 0.97 % whereas the lowest is 0.29 %. Thus, it can be concluded that the low frequency is more suitable to be used to predict the density of the road pavement than the higher frequency. Base on the results above, it can also be concluded that this microwave technique and the improved version or optimized GPR mixture model can be used to predict the density for various road pavements as well.

Table 4: Relative Error between Measured and Predicted Density at Four Frequencies

Point no.	Measured Density (kg/m3)	Relative error (%)			
		2.6 GHz	2.3 GHz	2.0 GHz	1.7 GHz
1	2008.838891	0.564402	0.332439	0.327657	0.118763
2	1855.385920	0.942138	0.889893	0.738929	0.271607
3	1850.566736	0.72602	0.597583	0.421504	0.260107
4	1908.396947	0.935451	0.751923	0.525177	0.394113
5	2059.857022	1.086650	1.055243	0.964044	0.387895
6	1999.272992	1.104363	0.838390	0.650580	0.410169
7	1861.850680	1.148290	0.937266	0.445001	0.286937
8	1785.634570	0.806728	0.319348	0.212273	0.098824
9	2081.887578	1.398134	1.063165	0.808569	0.433262
Mean Relative Error (%)		0.968019	0.753917	0.565970	0.295742

6. Conclusion and Future work

As a conclusion, this project has successfully developed an optimized GPR mixture model based on microwave technique of free space measurement in determination of density of road pavement. The Lichtenecker Mixture Model was chosen as a reference since the relative error is smallest than value of the other GPR mixture models. Optimization technique to improve the result according to attenuation formula has been done successfully and the error between measurement and theoretical is smaller than before optimization. The optimized GPR mixture model was validated by the reliability analysis. At the end of this project, the calibration curve that obtained can be used to predict the density of any real road pavement sample. In future development, the optimized GPR mixture model from this work can be used for further GPR research that capable to characterize more properties of road pavement sample.

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