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ROAD PAVEMENT DENSITY ANALYSIS USING A NEW NON-DESTRUCTIVE GROUND PENETRATING RADAR SYSTEM

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Abstract—Density is an important parameter to determine the strength of road, and it will ensure the safety of the use as well as maintaining the quality of road pavement. In this paper, the validation of GPR mixture model based on the microwave nondestructive free space method to determine the density of road pavement typed Hot Mix Asphalt (HMA) will be presented. The frequency range of operation used is 1.7–2.6 GHz. The attenuation is a major factor for gathering the density of road pavement predictably. The existing mixture model has been used to produce simulation data for determining the predicted complex permittivity and attenuation due to various densities of road pavement. The GPR laboratory measurement is performed where the measured attenuation due to various densities was obtained. The comparison results between measurement and simulation were investigated, and the relative errors

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in between were calculated to see the performance of the model. The best performance of mixture model was selected due to the smallest mean error using the optimization technique. An improved attenuation formula or optimized mixture model was obtained from the optimization technique to produce the better model. 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 mixture model. The optimized mixture model is introduced as GPR mixture model in this work. The validation process at field test had been conducted to evaluate the performance of optimized GPR model and produce the error range from 3.3% and 4.7%. At the end of this project, the GPR mixture model can be used as a calibration curve where the values of predicted density of a given real road pavement can be read directly once the attenuation values are known.

1. INTRODUCTION

Road condition assessment and monitoring using traditional methods such as visual inspection are labor intensive, slow and expensive [1]. More efficient and automated methodology for road pavement inspection by using ground penetrating radar (GPR) is proposed to identify the cause of existing problems and define optimal strategies for repair and rehabilitation [2]. Furthermore, this will ensure the safety of the use of road as well as maintaining the quality [3].

GPR has been used extensively in the road pavement for quite some time and was performed in early 1980s [4]. Most of the research and development works in road application have been performed with low frequency (1000–5000 MHz) to evaluate and survey the road pavement layers condition [5].

The known pavement density measurements are coring sample method [6], nuclear-sourced device [7], and rolled density gauge [8]. All these approaches were widely used for this purpose but these techniques are found to have drawbacks and limitations. Thus, people were motivated to find 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 objective, analytical analysis, laboratory scale experimentation and field test validation were performed in this paper to develop a new GPR system. Using this method, it takes shorter time and is more efficient compared to other conventional methods. The GPR measurement can be done using free space technique, or in other words, sample and detector are 'not in touch'.

A typical GPR system is composed of several parts such as a signal generator. This device would produce the electromagnetic wave that will propagate through the pavement slab to measure its density. The wave will be transmitted by the antennae and reflected by the pavement slab sample. The spectrum analyzer is used to collect the received signal strength or power data and will be converted into attenuation. The density of road pavement is linearly related to a measured returned signal in power, and it can be determined by comparing the measured attenuation from the laboratory. In order to compare the measured attenuation, a mixture model is used to determine the predicted attenuation from a particular road pavement density as well as the predicted density of the road pavement. The main objective of this project is to optimize the selected or best mixture model with the lowest mean relative error then to validate the optimized model at field test real condition.

2. SIMULATION RESULTS

A mixture model is a model in which the independent variables are measured as fractions of a total. An effective permittivity of such heterogeneous mixtures can be approximated from the permittivity of constituents by using mixing formulas found at [9, 10].

In result and discussion part, a comparison of attenuations between measurement and three mixture models for nine road pavement slabs at four frequencies will be discussed. The three mixture models used are Nelson, Landau and Lichtenecker mixture models. The best mixture model with the lowest mean errors can be selected for further optimization technique. The models are as follows:

Nelson mixture model by A. Sihvola, E. Nyfors, and M. Tiuri:

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

Landau mixture model by H. Looyenga:

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

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

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

These mixture models represent the complex permittivity of the particular road pavement density where high density is found to give a high complex permittivity. v_1, v_2 and v_n are the fractional volume of the respective components, where $v_1 + v_2 + \ldots + v_n = 1$. The fractional volume of the respective components, v_n, is calculated based on Equation (4) [9].

$$\text{Fractional volume, } v_n = \left|\frac{m}{d}\right| \times 100 \tag{4}$$

In Equation (4), m is a weight of each material, and d is a density of road pavement. In Equations (1) to (3), $n = 11$ is used since the road pavement is made up of 1 asphalt and 9 aggregates of medium. The air void content is also considered in the model [11]. For both asphalts and aggregates, a typical relative dielectric permittivity lies in the range of 2 to 6 whereas 1 for air void content [12]. Asphalt is a sticky, black and highly viscous liquid whereas aggregate is applied to all particles with diameter below 20 mm [1]. These two types of parameters were used in this work. Then, an attenuation Equations (5) and (6) will be used for attenuation prediction due to different densities of road pavement [9].

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

where

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

In Equations (5) and (6), α is an attenuation constant, and 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 $\mu = 1 \times 10^{-6}$ [13], ε'' and ε' are dielectric constant and loss factor respectively that are obtained from complex permittivity, ε of mixture model. A is a 'predicted attenuation', and t is a fixed thickness of road pavement as suggested by Public Works Department (PWD) where $t = 0.05$ m.

The mixture model in simulation developed is based on the volume, v, and permittivity, ε, of road pavement material. Since the road pavement is one of the mixture samples, the mixing formula is most suitable. The volume and permittivity for each material inside the real road sample is determined before the real GPR measurement is done. The techniques for developing the road sample at the outside real road pavement are practiced in lab for road sample preparation as well as GPR measurement. Other than volume and permittivity, frequency used in the real experimental is also used in the mixture model of simulation. Fig. 1 shows the phenomenon of using this model in GPR environment.

In Fig. 1, assuming that the reflection 1 is due to the surface layer while reflection 2 is due to the bottom layer. The reflection occurs when the signals encounter a different permittivity of layer. The power received is found decreasing with the increasing of depth. Both the measurement and simulation use the microwave techniques. The free space method and reflection technique are used as the microwave techniques. The power received at any instant time is due to the average reflection from surface and bottom layers of the road pavement volume. In simulation, the attenuation model is considered the loss due to the whole volume of samples since it involves the volume of a sample.

For the first testing, Equations (3), (5) and (6) can be used to see the relationship between attenuation, A, and thickness, t, for various frequencies. Fig. 2 shows the relationship between attenuation and thickness for various frequencies which are from 1.7 GHz to 2.6 GHz. From the graph, we can see that the higher frequency produces the higher attenuation, and when the thickness of the sample increases, the attenuation also increases. This happens because the electromagnetic signal can provide a good penetration at the upper layer (low thickness)

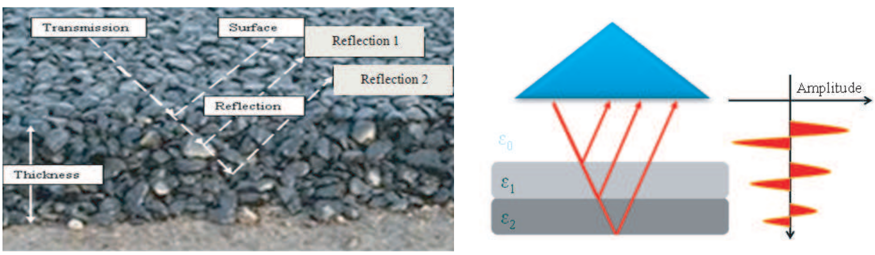

Figure 1. Typical GPR reflections from a road pavement slab in mixture model.

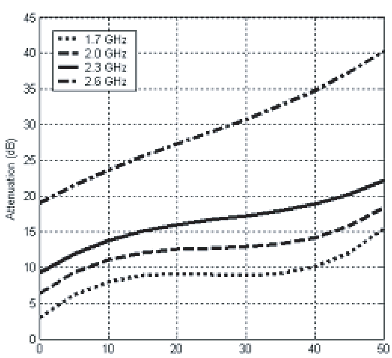

Figure 2. Relationship between attenuation and thickness for various frequencies.

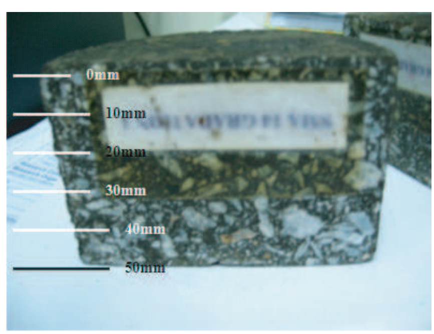

Figure 3. Core road pavement sample with thickness sign.

of pavement sample that can cause low attenuation. Thus, thickness also can give a higher effect for attenuation other than the density and frequency.

The attenuation is also affected by the thickness of the sample as expressed in Equation (5) where the attenuation is proportional to thickness as shown in Fig. 2. The figure also shows that the attenuation is increased with thickness of the road pavement sample. Moreover, when the density of road pavement is increase, it can also cause a high attenuation drastically. Fig. 3 shows the core of road pavement sample with thickness that equivalent to that in Fig. 2. In this project, the 50 mm of thickness of road pavement is most suitable for examining the road pavement characteristics such as density and avoiding errors, which is suggested by Public Works Department (PWD).

From Fig. 2, the non-linear results show that the signal penetration power is dependent on wavelength or frequency and that the layer of road pavement will not affect the signal penetration power as proved in Equation (5). Equations (1)–(3) will contribute to the permittivity, ε, and it will be used for real part, ε', and imaginary part, ε'', of Equation (6) for attenuation constant value. Then, it will used for equation (5). Equations (5)–(6), which consist of log and exponent term, show that the high frequency can cause a high attenuation. It is can be proved that the signal has a high resistance when using high frequency. The high resistance causes the signal difficult to penetrate, and more power will lose, which can cause high attenuation.

3. MATERIAL AND SAMPLE PREPARATION

This work begins with preparation of pavement slab sample with different densities. The density calculation is based on the ASTM standard [11].

$$\text{Bulk density, } d = (1 - \text{OAC}/\text{TMD}) \times 100\% \qquad (7)$$

In Equation (7), OAC is an Optimum Asphalt Density, and TMD is Theoretical Maximum Density. These two values are obtained from standard superpave and rice method at Traffic and Highway laboratory. There are three types of HMA gradations which are lower, middle and upper boundaries. The purpose is to see the performance of proposed GPR system at various boundaries of HMA gradation. For middle boundary gradation, there are nine pavement slabs with different densities developed. The road pavement slab samples were made according to the suitable proportion according to Public Works Department (PWD). For middle boundary, the road pavement slab samples used in this measurement consists of 5% of air void and 95%

of solid whereby the solid consists of 5% OAC and 95% aggregates as suggested by PWD [11]. For each upper and lower boundary, there are five road pavement slabs respectively. For each gradation, there are 2%, 4%, 6%, 8% and 10% of air void content inside the road pavement. Table 1 shows the example of calculation for slab 1.

In Table 1, the 'weight' in kg is the weight of each aggregate or material of the road pavement whereas the 'total weight' is a weight of road pavement. The total weight will be different among the various road pavement slabs densities. Besides, the total fractional volume is found to be equal to 1, where $v_1 + v_2 + \ldots + v_n = 1$. It shows that one new sample is formed by n different materials. The values of v_n and ε_n will be used as input parameters in mixture model as in Equations (1), (2) and (3) in order to determine the 'predicted attenuation' value. Thus, there are nine 'predicted attenuation' values due to the nine road pavement slab samples for middle boundary. The procedure is also used for the upper and lower boundaries. In material mixing process, the paving and compaction are implemented in Turamachine with similar volume for all road pavement slabs but different weights. The density calculation is based on the ASTM standard [11].

Table 1. Weight of aggregate retain for slab 1.

Weight of aggregate retain for Slab 1					
Sieve Size/ material	**% Passing**	**% Retained**	**Weight (kg)**	**Fractional volume,** v_n	**Permittivity,** ε_n
14	87.5	12.5	1.93	0.12	5.01
10	79	8.5	1.31	0.08	5.03
5	62	17	2.63	0.16	5.05
1.18	53.5	8.5	1.31	0.08	5.15
3.35	37.5	16	2.47	0.15	5.42
0.425	23.5	15	2.32	0.14	5.62
0.15	11.5	13	2.01	0.12	5.68
0.075	7	5.5	0.85	0.05	5.86
PAN	0	4	0.61	0.03	5.99
Asphalt			0.81	0.05	2.0
Air void				0.05	1.00
		Total weight:	16.3094825	1.00	

4. INDOOR MEASUREMENT SETUP AND PROCEDURE

The GPR measurement set up as shown in Fig. 4. From the figure, the distance between horn antenna and road pavement sample is fixed, about 0.3 m height. This height also will be used for field test work in order to make sure the volume or size of the road pavement density under test is consistent. The model of this antenna is WR430 with frequency ranging from 1.7 GHz to 2.6 GHz, and the nominal gain is 20 dB.

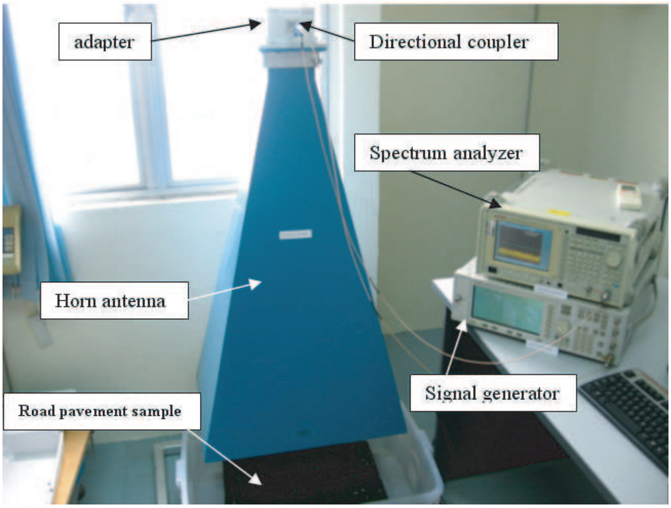

Figure 4. GPR measurement setup.

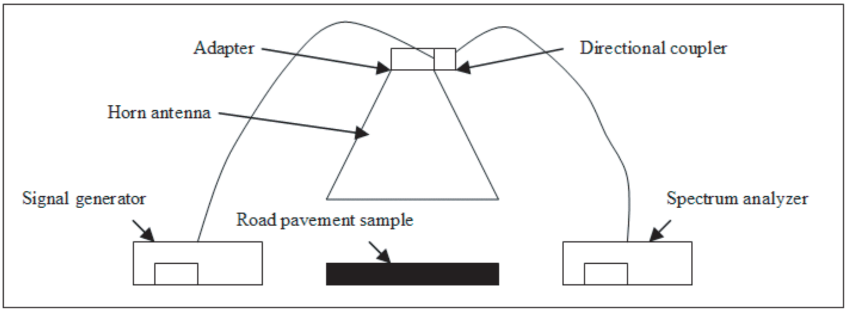

Figure 5. Environmental setup block diagram.

In this testing, continuous wave is used since this wave will penetrate the whole body of the pavement sample. The purpose is to determine the permittivity of road pavement as well as predict the density based on the whole body of road pavement but not based on particular thickness. As known before, the pulse wave is used for particular thickness or thickness determination purpose as done by previous researchers [6]. Figs. 4 and 5 show the GPR measurement system setup and environmental setup block diagram respectively.

In GPR data collection, for each GPR transmission and reflection to the pavement slab sample with specific density, there are fifty data were taken for each of four frequencies. For each road pavement slab, the fifty data were taken in 100 minutes where 2 minutes for each datum. During the measurement, the correct reading of received signal strength is obtained only when the reading of the measured slab sample is kept constant at the spectrum analyzer. The measurement setup has been based on the reflection due to whole volume of sample since the signal strength was taken on every 2 minutes. At any instant time, the signal strength data taken are an average due to the reflection from upper to the bottom layers of the sample. The losses due to the container and antenna are also considered in the calculation of path loss.

The thickness being tested is up to 5 cm, and it is proved that the high thickness will cause high attenuation. The maximum thickness tested is proved by the PWD. During the measurement, the flatness of the sample is kept constant in order to make sure the measurement done is consistent, where the slab is properly developed using standard Turamachine.

For comparison, the purpose of GPR measurement is to determine the 'measured attenuation' whereas the purpose of using mixture formulas is to determine 'predicted attenuation' for particular density. The road pavement is known as a mixture sample that is composed of different permittivitoes and fractional volumes of materials. According to Equation (6), the real and imaginary parts of permittivity can contribute to the specific permittivity for particular density. The equation also shows that the permittivity is dependent on frequency used during measurement. The frequency used is in the range of GPR frequency bandwidth.

5. MEASUREMENT RESULTS AND DISCUSSION

Figure 6 shows the relationship between the received signal strength and number of GPR reading that collected from the laboratory experimentation. It was observed that the different densities of road pavement produce different results of received signal strength. The received signal strength is an average signal based on both the surface and base layers of road pavement. It is found that the highest density of road pavement slab causes the lowest received signal strength compared with the other lower density of slab samples. This may be because the highest density of slab absorbs more energy of electromagnetic from the horn antenna than the lower density. These kinds of results are also found at other frequencies which are 2.0 GHz, 2.3 GHz and 2.6 GHz.

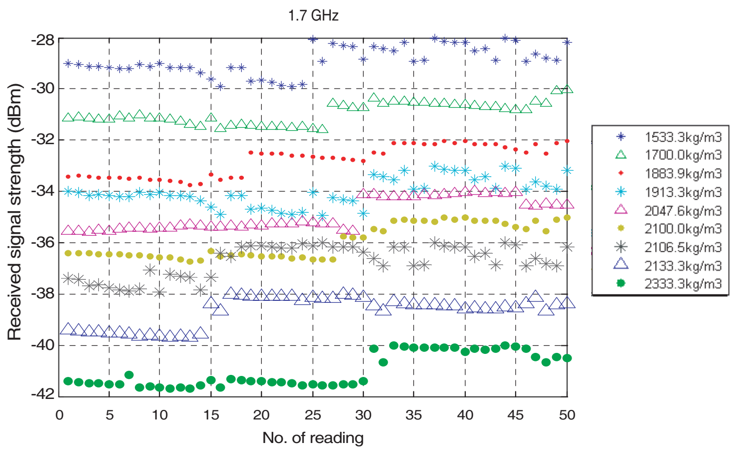

Figure 6. Received signal strength (dBm) versus number of reading of GPR data for nine road pavement slabs (middle boundary).

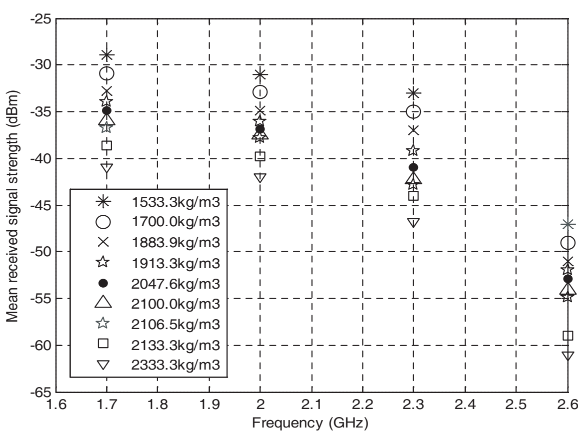

Figure 7. Mean received signal strength (dBm) versus four different frequencies of GPR data for nine road pavement slabs.

In addition, the different results among four frequencies were also observed as shown in Fig. 7. It can be found that the highest frequency produces the lowest range value of mean received signal strength compared with the other lower frequencies. The lower value of received signal strength produces higher attenuation. It is interesting to note that higher frequency causes higher attenuation because there was the possibility that the higher frequency of signal consisting of short wavelength can cause it travel in a very short distance. This causes a scattering on the road pavement [6].

Initially, there is one attenuation value for each road pavement slab sample at each frequency. In this analysis, there are four attenuation values for each road pavement slab sample due to 3 mixture models and 1 measurement datu, which are compared as can be seen in Fig. 8. In addition, the effect of the container, 4 dB, and antenna, 3.46 dB, [14] will be considered by addition to the measured signal attenuation since it was used during the laboratory experimentation. Then, the comparison of attenuation between measurement and three mixture models for nine road pavement slabs at four frequencies has been done. In Fig. 8, the measured attenuation is obtained from laboratory experiment, and the predicted attenuation is obtained from simulation analysis by using three mixture models. The three mixture models used are Nelson, Landau and Lichtenecker mixture models as mentioned in detail previously.

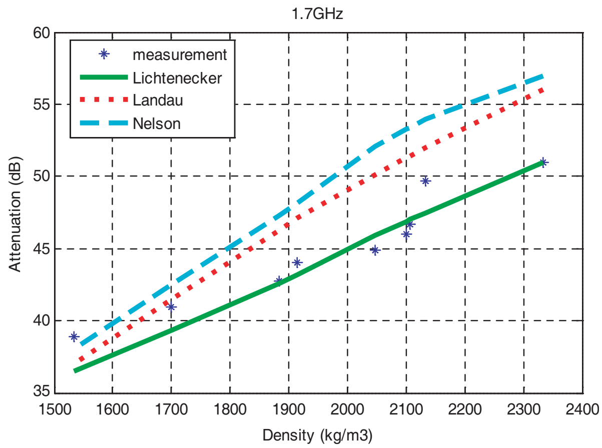

Figure 8. Comparison of attenuation between measurement and three mixture models for nine road pavement slabs at four different frequencies.

Table 2. Mean relative error of attenuation between measurement and three mixture models.

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

Figure 8 clearly shows that the different mixture models produce different results. From these results, Lichtenecker mixture model looks very close to the measurement of other models, and the Landau mixture model looks better than Nelson mixture model. The comparison between the attenuation values of the Lichtenecker mixture model and the measurement shows the lowest relative error between measurement and simulation. The three mixture models increase with the increasing of density. In other words, high density produces high attenuation. This is due to the fact that more electromagnetic energy will be absorbed by the molecules of the road pavement with high density compared to lower density. The increasing frequency would also produce high attenuation. This kind of result is also valid at the other three frequencies. Then, the relative error between measurement and these three models has been measured to show the performance of each model.

From Table 2, the mean relative error for Lichtenecker mixture model is found smallest among Landau and Nelson mixture models. The value is around 1.5% and 2.8%. The four frequencies also show that the Lichtenecker mixture model produces the lowest value than the other two mixture models. The lowest error value is due to the good agreement between measured and predicted attenuation results. From the results, it can be concluded that the Lichtenecker mixture model shows the greatest results and can be used for optimization process. The best mixture model with the lowest mean errors will be selected for further optimization process. The optimization is performed in order to fit the measurement results for the simulation ones. The purpose is to develop a new optimized model more accurate than the existing one.

5.1. Optimization Technique

According to Equations (5) and (3), the equation of attenuation can be more accurate if the equation is optimized using suitable optimization technique.

In order to determine which variable is suitable, the sensitivity analysis is proposed, and attenuation constant, α, is found suitable since this variable is affected by density. During measurement, the thickness of road pavement sample, t, was fixed at 0.05 m. Therefore, the relationship between attenuation and thickness is not important in this case. Thus, the variable α, is most suitable for getting the new attenuation data. Using this optimization technique, it is found that one new parameter has been added to attenuation constant.

$$A = 10 \log \left(e^{-2(x_1+\alpha)\cdot t} \right) \tag{8}$$

or

$$x1 = \frac{\ln \left(10^{\frac{A}{10}} \right)}{-2t} - \alpha \tag{9}$$

where A, t and x_1 are measured attenuation, thickness of road pavement sample and additional constant, respectively. The value x_1 is introduced into Equation (8) to get a new set of data of attenuations, A. Then, it will be compared to the set of data before optimization.

Additionally, a least square curve fitting approach was carried out to produce the best fitting line through the measured data with Lichtenecker mixture model. Based on the optimization, the Lichtenecker mixture model is improved by introducing new constant parameters x_2 and x_3 as follows;

$$\ln \varepsilon = v_1 \ln \varepsilon_1 + v_2 \ln \varepsilon_2 + v_3 \ln \varepsilon_3 + x_2 \ln x_3 \tag{10}$$

From the above equation, the parameters, x_2 and x_3, are new variabls that were found by using MATLAB software. The calculation was realized using the MATLAB *lsqcurvefit* command [15].

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 parameters x_1, x_2 and x_3 are introduced as Attenuation, Volume and Permittivity factors in this project. Similarly, substitution values of x_1, x_2 and x_3 into Equations (8) and (10) give

$$A = 10 \log \left(e^{-2(-4.1628+\alpha)d} \right) \tag{11}$$

$$\ln \varepsilon = v_1 \ln \varepsilon_1 + v_2 \ln \varepsilon_2 + v_3 \ln \varepsilon_3 + 0.8088 \tag{12}$$

Besides, the concrete attenuation, 7 dB, [14] is considered as an input to this optimization for future real test purpose. From Equation (12), the value 0.8088 can be explained by physical justification. It is shown that there exists unknown material inside the road pavement other than asphalt and aggregates. The unknown

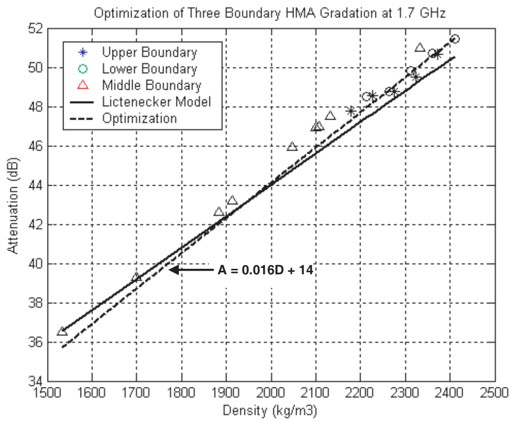

Figure 9. Comparison results among measurement, mixture model and optimization.

material produces the Attenuation, Volume and Permittivity factors inside the road pavement. Then, the comparison and relative error of attenuation before optimization (Lichtenecker mixture model) and after optimization (optimized mixture model) is done and shown in Fig. 9. The optimized mixture model is introduced as GPR mixture model in this work.

The comparison of attenuation between optimized mixture model and the three boundaries (middle, upper and lower) were made in Fig. 9 in order to see the performance of the optimized mixture model that is developed to all the boundaries of HMA pavement. From the results, it can be seen clearly that the optimization technique produces better results than the original simulation results, Lichtenecker mixture model. The value after optimization looks very close to the measurement data better than the old mixture model before optimization. This is because the mixture model was improved successfully by using suitable optimization technique to produce the best optimized mixture model. This kind of result is found valid when using other three frequencies. Besides, the best optimization fitting equations obtained from the graph (dotted line) can be used as a calibration curve. It involved A and D where A represents the 'predicted attenuation', and D represents the 'predicted density' of road pavement.

Again, the relative error value is also analyzed to see the performance before and after optimization of the mixture model. The results show that the relative error values for all samples give expected results where the mean relative error after optimization is smaller than before the optimization. The range is from 0.68% to 1.79%

whereas 1.5% and 2.8% for those before optimization. In the next process, the optimized model will be validated in reliability analysis in real field test work. It will be used as a calibration curve where the values of predicted density of a given real road pavement can be read directly once the attenuation value is known. The validation process or reliability analysis has been conducted randomly at nine different measured points of outdoor real road pavement of Faculty of Engineering, University Putra Malaysia (UPM). Those measured points had been drilled out, and its real density was measured in the lab. The outdoor GPR measurement setup is shown in Fig. 10.

The outdoor GPR measurement at each point have been conducted three times at different days within three weeks. All the conditions used are similar to the lab measurement to make sure the density measurement is consistent. The results for all measured points of 4 different frequencies are shown in Fig. 11.

Figure 11 shows the relationship between the mean of received signal strength and frequency for nine measured points of field test. It can be found from the results that the mean of received signal strength decreases with the increasing frequency. The mean of received signal strength is found lower for the higher density of road pavement. This fact is because there will be more losses when using high frequency and high density of road pavement. These results show that the high density of road pavement and high frequency can cause high attenuation. The direct comparison between predicted and measured densities is shown below.

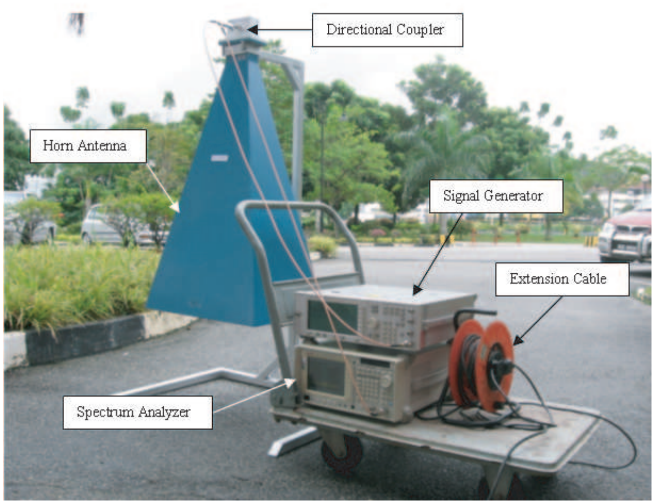

Figure 10. Outdoor GPR measurement system.

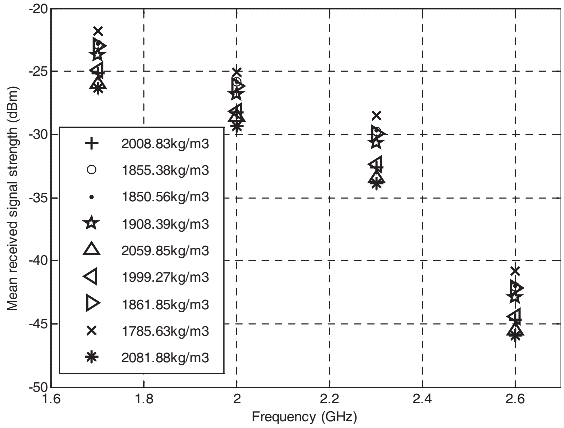

Figure 11. Mean received signal strength for fifty data for nine measured points at four frequencies (outdoor).

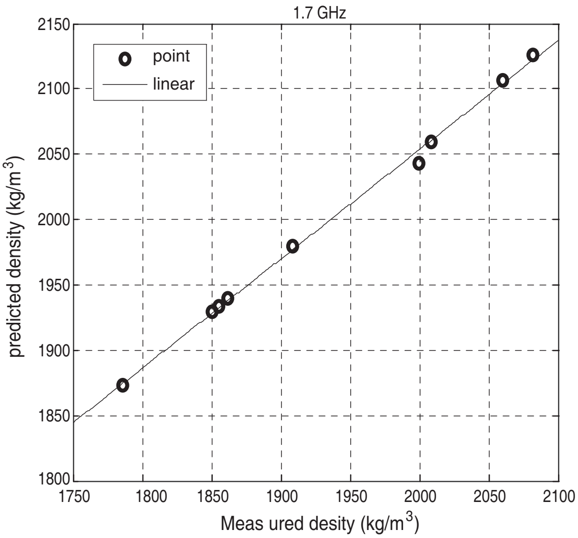

Figure 12. Direct comparison between predicted and measured density at four frequencies.

In Fig. 12, it can be seen that the results are very close among each other at each measured point. When the four frequencies are compared, the density at 1.7 GHz looks most closely with the actual density and lower error than the other frequencies as proved in Table 3. The mean of relative error has been calculated to analyze the overall relative error as in Table 3. The highest mean of relative error can be found at the highest frequency, 2.6 GHz with value 4.72% whereas the lowest comes from the lowest frequency, 1.7 GHz with 3.37%. Thus, it can be found that the highest frequency produces the highest mean of relative errors and vice versa. This is may be due to the fact that higher frequency causes higher loss of the GPR signal power and poorer penetration. Based on the finding, it is interesting to note that higher frequency is found to have poorer penetration as proved before in the simulation path. The lowest frequency, 1.7 GHz, is more suitable to be used to predict the density of the road pavement. Based on the results above, it can also be concluded that this microwave technique and GPR mixture model is found valid and can be used to predict the density for various road pavements.

In this investigation, the received signal at any instant time is found to be an average of the bottom and surface reflections. The average received signal strength obtained is found has no contrast effects with frequency since the average signal is based on the mixture sample, not separate samples. Especially the real road pavement is found as a mixture sample type. This is proved after the real outside measurement is done. The relative error of the modeling at some points of real road pavement is found lower, and it is shown that the measurement technique is found valid. The approach of GPR measurement techniques used in the lab is practiced in the real road pavement. In GPR, there is a valid frequency range which is from 1.7 to 2.6 GHz, whereas the other wider bands of frequency are not used

Table 3. Relative error between measured and predicted density at four frequencies.

Point No.	**Measured Density (kg/m^3)**	**Relative Error (%)**			
		2.6 GHz	**2.3 GHz**	**2.0 GHz**	**1.7 GHz**
1	2008.8388	3.83029	3.90389	3.00844	2.51475
2	1855.3859	5.52327	4.79045	4.63101	4.22088
3	1850.5667	5.04203	4.20366	4.94421	4.26503
4	1908.3969	4.65182	4.54208	4.68585	3.74973
5	2059.8570	3.84289	3.76357	1.34234	2.26753
6	1999.2729	5.08373	3.89252	3.38787	2.16655
7	1861.8506	5.00705	4.17389	5.39151	4.16198
8	1785.6345	5.47968	4.36498	6.5582	4.88338
9	2081.8875	4.05602	4.00997	2.34644	2.10873
Mean Relative Error (%)		4.724087	4.182777	4.032875	3.370951

as proved by literature review.

Additionally, this work is more to electromagnetics field where it involves all the propagation mechanisms such as transmission, reflection, scattering of the electromagnetics signal from the horn antenna to the sample. All the equations involved are also under EM study such as permittivity, permeability and conductivity.

6. CONCLUSION

In conclusion, this project has been successfully developed and introduces a GPR mixture model based on microwave technique of free space measurement in determination of the density of road pavement. The work consists of attenuation measurement using reflection technique on the road pavement sample. The Lichtenecker Mixture Model was chosen as the best model to predict the complex permittivity and attenuation for different road pavement densities. Optimization technique to improve the result according to attenuation formula has been done successfully, and the error between measurement and simulation is smaller than that before optimization. The GPR mixture model was validated by the reliability analysis and gave error within 3.37% and 4.72%. The lower frequency, 1.7 GHz, is found most suitable to determine the density of HMA road pavement over the frequency range of operation. At the end of this project, the calibration curve that obtained can be used to predict the density of any real HMA road pavement. In future development, the GPR mixture model from this work can be used for further GPR research that is capable of characterizing more properties of road pavement sample.

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