Reviewing methods for determination of Dielectric Constant required to Calibrate GPR Study for Asphalt Layers

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Abstract. Ground Penetrating Radar (GPR) is a non-invasive technique developed substantially in the recent years. Initially, GPR technology was applied to natural ground to explore the subsurface conditions and identify the anomalies in it. Now it has become a well-accepted technique to investigate any kind of materials such as wood, ice, concrete, asphalt etc. The calibration of GPR equipment is most important prerequisite criteria before data collection for accurate investigation of pavement subsurface features. During calibration, the velocity of radar waves will be calibrated in contrast to subjected material as whole examination is governed on the basis of it. The basic dielectric properties required as a prerequisite while using GPR system are dielectric permittivity, electrical conductivity along with magnetic permeability. The dielectric constant affects the velocity of transmitting wave as inverse proportion i.e. velocity decreases with an increase in dielectric constant and vice-versa. Considering the principle, the detailed study of pavements requires understanding and estimation of ‘bulk’ dielectric constant. The heterogeneous conditions of pavement actually obscure the straightforwardness of analysis and therefore estimation of a ‘bulk’ dielectric constant value becomes essential. There are several methods to compute the dielectric constant of asphaltic layers, which are developed by different researchers, and these are discussed briefly in this paper. The paper tries to put forward the merits and demerits of these methods and to identify the most appropriate one suiting to Indian conditions.

1. Introduction
Ground Penetrating Radar (GPR) is a non-invasive technique developed substantially in the past few years. Being non-intrusive equipment, it facilitates subsurface testing non-destructively along with providing more appropriate and reliable information. The GPR system generally consists of transmission and receiver antenna with controlling unit to generate the subsurface profile of any surface needs to be assessed. At the inception of GPR technology, it was primarily applied to natural grounds though now it is a well-accepted technique to investigate any kind of materials such as wood, ice, concrete, asphalt etc.

The application of GPR in road infrastructure having an eminent role nowadays predominantly because of its ability to conduct testing in non-destructive manner. Furthermore, the data collected by this NDT equipment can be collected in an abundant amount which will be never feasible with traditional destructive testing due to several limitation including cost and time consumption. Therefore, the GPR technology is an inevitable activity which would not only collect data at faster rate but also avoids the post data collection consequences which will definitely diminishes the structural integrity and reduces an overall pavement performance. In case of flexible pavement, nowadays GPR is generally used to collect layer thickness, presence of moisture or air voids, subsurface cracking, subsidence prone area,
quality assurance of pavement constructions or any other kind of anomalies needs to be detected. It can also be used to detect the slab thickness, depth to dowel bars and their orientation, moisture content etc. in rigid pavement structures.

GPR application is entirely based on the medium characteristics or particularly the dielectric properties of the medium through which radar waves will transmit. The basic dielectric properties prerequisite to be considered while using GPR system are dielectric permittivity, conductivity along with magnetic permeability [1]. As most of the pavement materials are non-magnetic, the latter property can be neglected. Therefore, the electric property of the material is the only decisive parameter, which will affect the path of transmitted waves. Whenever a change in dielectric constant appears into the path of radar wave, a part of it will be reflected back which is of our interest. This reflected energy will be captured by receiver antenna and helps to generate the subsurface profile depending on its amplitude. Nevertheless, GPR is predominantly used in low electric loss material due to its susceptibility of signal attenuation when encounters with highly electrical conductive material like clays, water etc.

As abovementioned, the whole GPR practice governed by the change in dielectric constant or dielectric contrast. Though sufficient amount of radar signal reached at subgrade, the low dielectric contrast (due to contamination of base layer from migration of subgrade fine particles) between subsequent layers resulted in difficulty to distinguish layer interfaces [2]. The dielectric constant of different pavement materials reported to be in close range as mentioned in table 1 [3].

| Material         | Dielectric constant | Velocity (mm/ns) |
|------------------|---------------------|------------------|
| Air              | 1                   | 300              |
| Asphalt mixture  | 4-10                | 90-160           |
| Concrete         | 5-9                 | 100-130          |
| Aggregate        | 6-18                | 70-120           |
| Water            | 81                  | 33               |

From table 1 it can be concluded that the dielectric constant is directly affecting velocity of transmitting wave since velocity decreases with increase in dielectric constant. Since any pavement is a layered structure lying on naturally available or compacted subgrade and consists of combination of various materials mentioned above which makes it a heterogeneous medium. These heterogeneous conditions further obscure the analysis straightforwardness and therefore a ‘bulk’ dielectric constant value essential to be computed which will be used to investigate pavement characteristics accurately. The bulk dielectric constant of any pavement material relies on its material constituents (asphalt, aggregate etc.) and material conditions (like moisture content, air voids etc.). There are several methods developed by many researchers to compute the dielectric constant of pavement materials and will be discussed briefly in subsequent sections.

2. Need of GPR calibration
The calibration of GPR equipment is prerequisite before data collection for accurate investigation of road subsurface features. During calibration, the velocity of radar waves must be calibrated in contrast to subjected material as whole examination is governed on the basis of it. As explained in previous section, the effective dielectric property of heterogeneous materials (like layered pavement structure) needs to be computed as the different proportions of varying material characteristics influences the geometric features of any considered material. The presence of air and water significantly affects the overall dielectric constant of the asphalt mix as the presence of low-dielectric air reduces whereas high-dielectric water increases it [4]. Therefore, velocity calibration becomes the primary source of errors if not performed appropriately and leads to unrealistic results that can have severe consequences while applied in pavement assessment and management.
The dielectric constant is a function of several parameters including testing conditions as well as material characteristics and therefore fluctuates from one location to other with variation of these dependent parameters. Most of the current GPR analysis study follows either a fixed dielectric constant for the entire pavement section or estimates it from limited number of cores extracted from the pavement. Though few proposed methods are capable to determine the varying profile of dielectric constant, their field implementation is unfavourable because either involves combination of sophisticated equipment or required cumbersome analysis approach. As an outcome, the existing GPR data analysis technique interprets results that are either accurate or reliable on large scale. The prediction of accurate dielectric constant is one of the most challenging tasks in the data interpretation of GPR analysis. In old roads, the quotient of erroneous interpretation increases exponentially because of the variability present in both i.e. structural integration (excessive voids, layer de-bonding etc.) and material condition (aging, moisture presence, anomalies etc.). Therefore, these variabilities need to be taken into account while performing pavement assessment otherwise may have serious implications on planning of maintenance activities and prediction of residual life [1].

Once the dielectric constant of material is computed the propagation velocity of the radar wave through that material can be according to equation (1) given by [5].

$$v = \frac{c}{\sqrt{\varepsilon}}$$

Where

- $v =$ velocity of EM wave in considered material
- $c =$ velocity of EM wave in air
- $\varepsilon =$ Dielectric constant of that material

The traditional method of velocity calibration in pavement structures is based on destructive approach where a core sample was collected from selected pavement site. However apart from its disadvantage of permanent damage, the obtained result is only point specific and cannot be considered as the representative of whole section. Here GPR technology outperformed the traditional approach by capturing the continuous profile of pavement structure and able to determine dielectric constant as a function of space for given attributes of GPR system.

3. GPR calibration procedures

The application of GPR is entirely based on the dielectric characteristics of pavement materials encountered with radar waves as the propagation velocity alters with change in dielectric properties. The asphalt mixture is a combination of primarily asphalt, aggregates, moisture and air etc. and hence the dielectric constant of the mix should be a value considering all the constitutive components to get the most appropriate solution. The dielectric constant of considered material provides the basic information required for road assessment including layer thickness, excess moisture and void detection, subsurface distress or other anomalies.

3.1 Dependency of calibration method on GPR system

GPR are generally available in two categories i.e. Air-coupled and Ground-coupled antenna system having their respective pros and cons, hence judicial decisions need to be taken while selecting the type of GPR system assigned to any project. Air-coupled systems have two horn antennas needs to be fixed at certain height from pavement surface and can collect data at traffic speed without hindering traffic movements. Whereas ground-coupled antenna system are in contact with ground and therefore bound to move at relatively lower speed. In the early 1990’s, the utilization of GPR is limited to pavement thickness measurements particularly in Northern America. Initially air-coupled antennas were preferred for pavement assessment however due to its obvious limitation, researchers also appreciated ground-coupled GPR systems were in order to explore more depth of penetration along with more reliable and accurate results. Many researches have given their critical views about comparison between both kinds of systems according to features considered. The elevated antennas of air-coupled systems benefitted by
reducing surface coupling effect that enables to clearly distinguish air-surface interface from other interfaces [6]. The benefit of higher penetration depth with ground-coupled antenna at a given frequency compared to air-coupled antenna however also acknowledged its speed limitation [7]. On the basis of type of GPR equipment employed, the procedure for dielectric characterization will also vary.

The most basic approach to determine the dielectric constant of asphalt pavements is to deduce its dielectric characteristics through core calibration. Although it seems to be an easy method, the collected information will be point specific apart from its common drawbacks like any conventional destructive testing method. In order to avoid damages incurred during destructive testing, [8] and [9] had established an approach predominantly know as surface reflection method to determine the dielectric constant of asphalt layers using only GPR data collected through air-coupled system by means of equation (2) to equation (4) given as

\[ \varepsilon_A = \left[ \frac{1 + \left( \frac{A_{surface}}{A_{plate}} \right)}{1 - \left( \frac{A_{surface}}{A_{plate}} \right)} \right] \]  
\[ \varepsilon_B = \left[ \frac{F - R}{F + R} \right]^2 \]  
\[ F = \frac{4\sqrt{\varepsilon_A}}{1 - \varepsilon_A} \]

Where \( \varepsilon_A \) is dielectric constant of asphalt layer, \( A_{surface} \) is maximum amplitude of the reflected signal from asphalt layer surface, \( A_{plate} \) is the maximum amplitude of the reflected signal from a perfect reflector (metal plate) placed underneath the antennae and \( R \) is the ratio of the maximum reflected amplitude from the base layer to the maximum amplitude of pulse reflected from pavement surface. These studies are only valid in air-coupled antenna system as it is difficult to distinguish between surface reflected signals and direct signals (transmitter to receiver) while using ground-coupled system. The abovementioned relation will be more effective when a homogeneous layer is present (same \( \varepsilon_A \) throughout its thickness) and the surface is free from any kind of distress. However, in practical the homogeneous condition is impossible in asphalt layer therefore the application of the described approach leads to erroneous results [10]. The unrealistic assumption of pavement layers along with presence of localized distresses and other anomalies makes analysis more inaccurate. Further in case of older pavements consisting of several overlays laid for strengthening purpose enhances the complication due to presence of materials with varying properties. Another model was provided to estimate dielectric constant based on amplitudes of reflected waves from pavement top surface and its interfaces for air-coupled antennas. But for ground-coupled GPR systems, the reflected amplitude based estimation method is not feasible due to lack of accuracy in measurement. In the latter case, the only option remains are core calibration to obtain dielectric constant by providing measured thickness and time parameters in the equation (5) given by [11].

\[ \Delta d = \frac{c \Delta t}{2\sqrt{\varepsilon_t}} \]

Where \( \Delta d \) is two way travel time, \( c \) is speed of light in free space and \( \varepsilon_t \) is dielectric constant of subjected material.

4. Methods for determining dielectric constant

4.1 Current Methodologies
There are many methods developed by several researchers to estimate dielectric constant for pavement structure by considering various computation techniques either in time domain or frequency domain analysis. Certain apparatus was also designed exclusively for measurement of dielectric properties of heterogeneous materials. Few studies have demonstrated the dependency of testing frequency on estimation.

A frequency domain model was developed in which reflected signal from layered medium are combined [12]. The layer thickness and corresponding dielectric properties were the model parameters involved. After initial assumption of layer thickness and dielectric properties, the theoretical time domain reflected signal was computed and then compared with measured reflected signals to compute mean square error. Subsequently an iterative change in the values of thickness and dielectric constant initiated until minimum square error was achieved. However, the calculation of inverse Fourier transform for each set of parameter and convergence of search algorithm to local minimum of mean square error leads to make it computationally intensive and inaccurate respectively. To account for the presence of thin bituminous overlays, a pavement model considering multiple layers was developed to estimate dielectric properties [13]. The data analysis computed the dielectric constant by iteratively detecting all the reflected pulses from the time domain signal. Nevertheless, the major drawback of this technique, due to assumption of zero conductivity, was underestimation of dielectric constant of subsurface layers.

An electromagnetic inversion technique in time domain was developed to determine dielectric constant for multilayered dielectric medium like pavement structure [14]. In this technique, the whole pavement was divided into N number of thin homogeneous layers having thickness lesser than resolution of GPR. Then it tries to accumulate the received signals on the basis of theoretical time domain model. Subsequently the Newton-Gauss iterative method was applied to estimate the best-fit dielectric constant profile that minimizes the mean square error between and measured and synthesized signals. The computationally intensive inversion method adopted in the study produced good results provided there is adequate input of material loss values. An automatic system was suggested to detect layers in a multilayered pavement system using likelihood test [15]. A probability density function (PDF) was determined for determining a reflected pulse using Markov model. The PDF for a given scan was computed from PDF of previous scan while the PDF for current scan was then computed based on Bayes theorem. The described approach was prolonged for multiple layers by iterating through layers and removing echo of individual layers detected form the total reflected signals. The iterative process was repeated until either the extraction of all known layers or the residual reflected signal drops below a fixed threshold value.

The design and calibration of an apparatus was presented for measurement of complex permittivity for heterogeneous materials [16]. It consists of a sample holder connected with coaxial cable to automatic network analyzer and data processing software. The proposed sample holder was capable to accommodate either field obtained asphalt core samples or laboratory prepared specimens lengths up to 400 mm while having maximum aggregate size of 40 mm. The dielectric constants were measured for laboratory prepared samples over the frequency range of 0.1 MHz to 1.5 GHz. The measurements of dielectric constant also suggested that the influence of variation of moisture content was more compared to mix properties on measured values of dielectric constant. It was also claimed in another study that there is increase in dielectric constant with increase in moisture content [17]. A methodology was proposed to define dielectric constant as a function of frequency range considered in GPR system [2]. The dielectric properties are frequency dependent as proved by the study and showed the variation of dielectric constant with variation in frequency. The study of Virginia Smart Road Facility was incorporated in the study to validate the results obtained. [18] have also focused on the frequency dependency by showing a correlation between frequency bandwidth and sampling interval in time domain as given by equation (6).

\[
dt = \frac{1}{f} \quad (6)
\]
Where \( dt \) is time domain sampling interval and \( f \) is upper limit of frequency bandwidth. From the equation, it can be concluded that to detect thin layers in pavement structure a broad frequency bandwidth of GPR signals is required. The SVR (Support Vector regression) method was appreciated to estimate relative permittivity and time delay in order to determine pavement thickness [19]. The study results showed that SVR predictor gives a good performance with less time consumption. The proposed method was appreciated to accurately estimate pavement thicknesses along with capability to distinguish overlapping reflected signals.

### 4.2 CMP Methodologies

The Common Mid-point (CMP) method is the most conventional method used for calibration or dielectric constant estimation in GPR study. The separation distance between the transmission and receiver antenna increases in every step while keeping common mid-point in order to obtain several combinations of transmitted waves. The CMP dataset have couple of set of direct waves transmitted through air and ground along with radar waves reflected from pavement interface subjective to change in dielectric constant. However, the CMP method requires two separate units for transmission and receiver antenna, which is not quite common in GPR systems. There are several customized CMP methods proposed by several researchers incorporating various combinations of sophisticated equipment and discussed subsequently.

A modified CMP methodology was adapted, generally used for seismic wave’s analysis, to establish the dielectric constant of asphalt layers by integrating a 900 MHz ground-coupled system with a 1 GHz air-coupled system [7]. The methodology estimates the reflection times from the bottom of asphalt layer by both ground-coupled and air-coupled systems to determine dielectric constant. The core thickness data was also collected for validation purpose by comparing with computed layer thickness based on determined dielectric constant according to developed methodology. The thickness prediction error was around 6.8 % whereas ranges from 1% to 15 % and mainly attributed due to inaccurate detection of surface reflection from ground-coupled system as well as small separation distance between bi-static antennas of air-coupled system. An improved modified CMP method by substituting the ground-coupled system with the air-coupled system was established and named it as extended CMP (XCMP) method [6]. The method has undertaken a pair of 2 GHz air-coupled system which not only enhanced the survey speed but also upgraded the result’s reliability as shown by the validation study performed on tailor-made pavement sections consisting of steel plates as perfect reflector. Their algorithm resulted in a set of equations to determine dielectric constant and conclusively thicknesses by collecting time difference between surface reflections and bottom reflections i.e. \( \Delta t_1 \) and \( \Delta t_2 \) for both the GPR systems individually. The study had also shown the inability to determine thin layer thickness due to the small difference between \( \Delta t_1 \) and \( \Delta t_2 \). In further advancement, the XCMP method was integrated with a 3-D stepped frequency GPR system to develop a 2-D thickness profile at higher speeds accounting dielectric constant calibration without coring [18]. The proposed method has incorporated a multi array radar system comprised of 11 bow-tie antennas having an effective scan width of 1.57 m and enabled to transmit a broad frequency spectrum ranges between 200 MHz to 3 GHz. The proposed method produces an error of 3% to 8% while validating with core thickness data however absolute error was less than construction tolerance limits of 5 mm.

Since all the above mentioned methodologies considering CMP technique comprises of different amalgamations of GPR systems, to estimate dielectric constant with considerable accuracy in spite of employing complex system, which further makes analysis procedure more cumbersome.

### 5. Discussion and Conclusion

Few methods discussed above have a common problem that, only a few values are obtained along the interested length of pavement, where dielectric constants are used to analyze GPR data for pavement assessment. Often, a single GPR data profile is gathered for a length of pavement, and this data is calibrated to just one dielectric constant value which considered as ‘best fit’ value for the entire data file and also referred as “representative value”. Nevertheless, there will be variations in the dielectric
properties along the length of the pavement, caused by deviations in material and environmental condition, therefore leads to uncertainties and errors in results reported for locations that are not beneath the calibration points.

Another set of improvised methods, capable to estimate dielectric constant profile as a function of space and ascertained to be very beneficial in terms of obtaining more reliable results as exploited the whole section for calibration purpose. These methods are either performed with the aid of combination of GPR equipment or involved cumbersome computation techniques leads to economically and computationally expensive solutions. Certain factors affecting the precision and consistency are related to technological and engineering limitation of GPR equipment, however, it is important to noteworthy that the inculcation of erroneous results can be evolved substantially from both the way in which the technology exploited as well as the way data analysis performed.

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