BACHELOR THESIS

GPR AS ALTERNATIVE METHOD FOR MEASURING ASPHALT PAVEMENT DENSITY

Author: Nadhim Ghanim

Student number: S2011298

BSc Civil Engineering

FACULY OF ENGINEERING TECHNOLOGY

Supervisor UT: Dr. S.R. Miller (Seirgei)

Supervisor UT: Q. Shen (Qinshuo)

Supervisor Roelofs: ing. H.C. Siedenburg (Hans)

ASPARi Paving the way forward

Roelofs

UNIVERSITY OF TWENTE.

Preface

In front of you is my bachelor thesis “ GPR as alternative method for measuring asphalt pavement density" as part of my bachelor's study at the University of Twente. This project, which was carried out in collaboration with the Roelofs and ASPARi, showed me what it is like to work for a construction company, even though, because of Covid-19, I had to work from home most of the time.

This project would not have been possible without the support and participation of some people. In this regard, I would especially like to thank my supervisors, Dr. Seirgei Miller and Mr. Qinshuo Shen, who helped me to create this project and provided their advice and suggestions at various stages of the project. I want to thank all the family and friends who have supported me and given me advice during this difficult time of the pandemic. Additionally, I would like to thank my supervisor at Roelofs, Ing. Hans Seidenberg, who guides me through collecting the data required for the analysis. I also would like to thank all the people who work at Roelofs for their kindness and support in the lab tests.

Summary

This thesis describes the development of a system based on ground-penetrating radar (GPR) that determines asphalt pavements' density using the principle of the reflection of electromagnetic waves. Density is the main factor that plays an essential role in the durability of the pavement. Different methods have been used over the years to measure the density of pavements. However, these methods showed significant limitations in data accuracy, safety, and time. That is why the researchers were trying to find alternative methods over the years. The method that has recently been applied to pavement structure measurements is GPR. Although GPR radar technology has been developed and applied for a long time, it has only recently been used for subsurface research. Analysing GPR data can provide useful information about the layer thickness, material condition, humidity and air voids of the structure. One of the most important characteristics of road pavements that can be predicted by analysing GPR signals is its density. However, for the density measurements using GPR, much less have been known about how to convert the raw signals collected from GPR to density after analysis. In this regard, with the collaboration between Roelofs and ASPARi from the University of Twente, the main objective of this thesis was to develop and validate a GPR-based asphalt density measurement framework as an alternative method to the traditional methods. This goal was achieved by assessing and evaluating the use of GPR through literature review, on-site testing, and evaluation and comparison of GPR results with nuclear measurement density and core extraction method. For this, a ground radar with a frequency range of 500-100 MH was used to collect GPR data from a road section at Roelofs. Next, the raw GPR data were analysed using the REFLEXW software. For calibration and validation, 12 cores were extracted from the site where GPR was performed. Subsequently, three EM models, the CRIM, Bottcher and Al-Qadi, Lahouar, and Leng (ALL) model, were used to determine the density from the dielectric constant obtained from GPR using the thickness of the asphalt layer. This study showed that the (ALL) model is the most accurate function compared to other models such as CRIM and Bottcher. The mean error between the prediction and the experimental result in ALL is quite small, at 3.14%. the result of this model was also compared with the result of the nuclear density gauge. The average error of the ALL model was also significantly less than the NDG, because the average error for the latter was 3.38%. Furthermore, this study has also shown that the time required to conduct GPR research is less than the time required for the nuclear measurement and core extraction method. As a result, it can be said that the proposed method is simple, fast and non-destructive and within the acceptable error range of measuring pavement density when compared with the traditional methods.

Samenvatting

Deze scriptie beschrijft de ontwikkeling van een grondradarsysteem (GPR) waarmee de dichtheid van asfalt kan worden bepaald met behulp van het principe van de reflectie van elektromagnetische golven. Dichtheid is de belangrijkste factor die een essentiële rol speelt in de duurzaamheid van de bestrating. In de loop der jaren zijn er verschillende methoden gebruikt om de dichtheid van bestrating te meten. Deze methoden vertoonden echter aanzienlijke beperkingen op het gebied van gegevensnauwkeurigheid, veiligheid en tijd. De methode die recentelijk wordt toegepast is GPR. Hoewel GPR-radartechnologie al heel lang bestaat, wordt het pas sinds kort gebruikt voor ondergronds onderzoek. De analyse van GPR-gegevens kan informatie verschaffen over laagdikte, materiaaltoestand, vochtigheid, en gaten. Een van de belangrijkste kenmerken van het wegdek die kunnen worden voorspeld met GPR analyse, is de dichtheid. De dichtheid kan echter niet rechtstreeks uit GPR-applicaties worden gehaald: de GPR-gegevens moeten eerst worden geanalyseerd. Roelofs heeft hiervoor, in samenwerking met University of Twente, een oplossing gezocht waarmee de dichtheid van de bestrating met GPR kan worden voorspeld.

Het hoofddoel van deze scriptie was het ontwikkelen en valideren van een GPR-gebaseerd raamwerk voor het meten van asfaltdichtheid als alternatief voor de traditionele methoden. Dit doel werd bereikt door het gebruik van GPR te beoordelen en te evalueren door middel van literatuuronderzoek, on-site testen, en de evaluatie en vergelijking van de GPR-resultaten met de nucleaire dichtheidsmeter (NDG) en de kernextractie-methode. Hiervoor is een grondradar met een frequentiebereik van 500-100 MH gebruikt om GPR-gegevens te verzamelen van een wegvak bij Roelofs. De ruwe GPR-gegevens werden daarna geanalyseerd met behulp van de REFLEXW-software. Voor kalibratie en validatie werden 12 kernen geëxtraheerd van de locatie waar de GPR was uitgevoerd. Vervolgens werden drie EM-modellen, het CRIM, het Bottcher en het Al-Qadi, Lahouar en Leng (ALL)-model, gebruikt om de dichtheid te bepalen uit de diëlektrische constante verkregen met GPR op basis van de dikte van de asfaltlaag. Uit dit onderzoek blijkt dat het (ALL) model het meest nauwkeurig is in vergelijking met andere modellen zoals CRIM en Bottcher. Dit komt omdat de gemiddelde afwijking tussen de voorspelling en het experimentele resultaat bij ALL vrij klein is, namelijk 3,14% is. Het resultaat van dit model werd ook vergeleken met het resultaat van de nucleaire dichtheidsmeter. De afwijking van het ALL-model was ook behoorlijk kleiner dan van de 3,38% van NDG. Verder blijkt uit dit onderzoek dat de tijd die nodig is om GPR-onderzoek uit te voeren korter is dan de tijd die nodig is voor de nucleaire meting en de kernextractiemethode. Daarom kan gesteld worden dat de voorgestelde methode eenvoudig, snel en niet-destructief is en binnen de acceptabele foutmarge van wegdekdichtheid-meting ligt.

KEY WORDS

Ground-penetrating radar (GPR), Nuclear density gauge (NDG), Cores, Pavement, Density, Dielectric constant

GLOSSARY

GPR	Ground-penetrating radar
NDG	Nuclear density gauge
AC	Asphalt concrete
%PR	percentage of asphalt granulate in the mixture
SSD	Saturated surface dry
ASTM	American Society for Testing and Materials
HMA	Hot mix asphalt
PQI	Paving Quality Indicator
NMAS	Nominate maximum aggregate size
IC	Intelligent compaction
ICMV	Intelligent compaction measurement value
AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration
EM	Electromagnetic theory
ε_r	Dielectric constant
σ	Electrical conductivity
μ	Magnetic permeability
ns	Nanosecond

List of Figures

List of Tables

Table of Contents

1 Introduction

1.1 Context

The increasing awareness of the road construction industry to improve the quality of the products, as a result of the transition to the quality-driven management pattern and the changing tendering mode, has put pressure on the infrastructure industry to focus on quality assurance to ensure and improve the quality of the products. The factor that plays a vital role in road quality assurance is density. The proper density in the pavement, foundation, and subsoil is an essential factor for a sustainable road that meets performance expectations. It is, therefore, essential for road construction companies to have reliable equipment and methods for efficiently determining density on-site.

Despite all the work done during the construction process, compaction ensures that the asphalt can reach the desired density. Achieving the target density of asphalt pavements during construction and after compaction is the most critical factor affecting life cycle performance. Robert et al. (1991) illustrated the importance of density for the life cycle of asphalt pavements by evaluating the different types of hot mixed asphalt during construction. In this study, it was proved that an over-compacted asphalt mix with high density can cause rutting, shearing, and bleeding while the low density of asphalt allows water and air to enter the pavement structure, which will lead to a greater risk of water damage, chipping, oxidation and cracking over the years. Rutting can also occur when the asphalt is not sufficiently compacted due to delayed compaction under the traffic load. Therefore, the asphalt mix's density, is routinely specified and measured.

Traditionally, density was measured by laboratory measurements of the core swatch. However, cores only deliver data to a limited number of haphazard locations, damaging the pavement layer and interrupting traffic. Another methods that have been used as an alternative method to the destructive method is the nuclear density gauge (NDG) and the non-nuclear density gauge. Still, these showed significant limitations, such as the limited amount of data provided, safety, and additional cost. To overcome the limitations of the above-mentioned conventional road density measurement methods, researchers have explored new technologies such as intelligent compaction, thermal imaging and ground-penetrating radar (GPR). Among these new technologies, GPR has shown tremendous potential because GPR surveys are non-destructive, fast and continuous. In addition, it can provide several types of information about the structure of the pavement e.g. layer thickness and substructure distress.

1.2 Knowledge gap

Ground Penetrating Radar technology has existed for a long time, but it has only recently been used in subsurface evaluation. This is due to the complex physical principle on which GPR applications are based. These applications use analysis of the signal reflection from surface and sub-surfaces. Analysing GPR data can provide desired information about depth, material condition, humidity, voids and reinforcement. Assessing road conditions and planning for follow-up maintenance are radical to the effective long-term operation of the structure. Although GPR applications have been introduced in paving research, this technology has not been widely accepted in the asphalt construction industry. This is due to the lack of knowledge about how and in what format the information can be provided. Recently, GPR is used for predicting pavement density. However, the use of GPR to predict the density of a local asphalt mix is still in the development phase, while, to the best of author's knowledge, there is little known about how to make GPR-based method compatible with the context of pavement density measurement. It is also unclear to which extent it can be regarded as the alternative to other traditionally applied density measuring methods, given the initial application of this method is to the domain of subsurface detection. Therefore, its performance must be verified and validated before it is used for practical purposes.

1.3 Objective

On these premises, the overall aim of this research is to contribute to the quality assurance of the infrastructure sector by developing a method that can be used quickly and efficiently to determine density, as density is one of the most critical aspects of road quality. This goal will be achieved by developing and validating a GPR-based asphalt density measurement framework as an alternative method to the traditional methods for measuring asphalt density. This will be done by assessing and evaluating the use of GPR through literature review and on-site testing and assessing and comparing the results of GPR with NDG and core extraction method. Thus, the objective of this research can be formulated as follows:

To develop a systematic density measurement framework using GPR as an alternative method considering the accuracy, continuity, speed, and distress.

1.4 Research questions

The above research objective will be achieved by answering the general question that is derived from the problem context and the main goal of this research:

How and to which extent is the use of Ground Penetrating Radar feasible for measuring asphalt density and replacing the traditional methods?

This central question is answered based on some sub-questions. These sub-questions are divided into three phases:

Phase (a): Theoretical analysis

- ❖ What are the main challenges in measuring asphalt pavement density and why?
- ❖ What different methods have been used to measure pavement density?
  - What are the commonly applied density measuring methods, and what are the theories behind them?
  - How efficient are these methods for measuring pavement density?
  - What are the parameters/factors/criteria involved in those currently available density measurement methods?
- ❖ What are the theories behind the application of GPR for measuring different asphalt volume characteristics, and how can it be converted in asphalt density measurement?
  - What are the fundamental theories of GPR methods?
  - How can the GPR method be compatible with the context of asphalt pavement density measurement, and what are the parameters to be measured?
  - What is the limitation of measuring density by GPR?

Phase (b): Strategies for data collection and analysis.

- ❖ What is the on-site density measuring scheme using GPR?
- ❖ How are the raw data analysed and programmed? What software is used?

Phase (c): Calibration and validation through laboratory testing

- ❖ How to calibrate the GPR-based density measurement method and nuclear method to conduct the on-site measurement and the comparison?
- ❖ To which extent can the GPR-based method be regarded as the alternative method considering the accuracy, speed, road distress and continuity?

2 Methodology and research design

This chapter describes the methodology applied for this research and the way the research was designed

2.1 Methodology

This study is conducted to assess the feasibility of GPR for measuring asphalt pavement density. The focus of the assessment is to develop a method to predict density using the GPR and compare this density with the density of the core measured in the laboratory and the density measured with the nuclear density gauge. The comparison is based on four key factors. Namely accuracy, speed, continuity and distress in terms of damage or hindrance to traffic. To collect the necessary data, the descriptive method was used using a quantitative approach. To illustrate this, the methodology flow chart is made as shown in Figure 1.

The following steps were followed in this methodology :

Gathering data

In general, there are two types of data: quantitative data and qualitative data. Quantitative data is the information collected by measuring and counting. The qualitative data is data collected through interviews and observation. Because the data required to carry out this thesis are numeric in values and properties, these data are quantitative. Two types of these data were discussed in this study:

- Primary data

Are the data gathered by the researcher. This is the GPR data collected by conducting GPR surveys. This data is gathered from the on-site test at Roelofs.

- Secondary data

Are the data collected by the Roelofs company. This data can be classified into two types of data;

1- Nuclear density gauge data was collected by conducting nuclear tests. This data can be directly read out from nuclear device after conducting nuclear tests.
2- Cores data can be collected by extracting the cores from the road surface. However, this data cannot be extracted directly after the cores and require laboratory experiment. By conducting a laboratory experiment, various core parameters necessary for analysis can be collected, including the density of the cores, such as the binder content (%), the specific gravity of the aggregate, etc.

Analysing of the data

Because the GPR data cannot be directly interpreted, they must first be visualized and analysed using GPR software, which will be chosen based on the accuracy, simplicity, and scalability. The purpose of analysing GPR data is to estimate the dielectric constant of the asphalt. Once the dielectric constant is known the density of the cores can be estimated by EM models using this dielectric constant and other parameters gathered from lab experiments.

Results and interpretation

There are three final results in this research;

1- Density read directly by the nuclear test

2- Density extracted from the cores
3- Density estimated from GPR

To investigate the ability of GPR to measure the density of asphalt pavements, a comparison between these densities will be made. The comparison will be based on four factors, the average error for each of these densities, the speed at which each density was calculated, whether the density can be measured continuously and whether the road distress was caused by measuring these densities. This distress can be in terms of damage to the surface or the traffic hindrance.

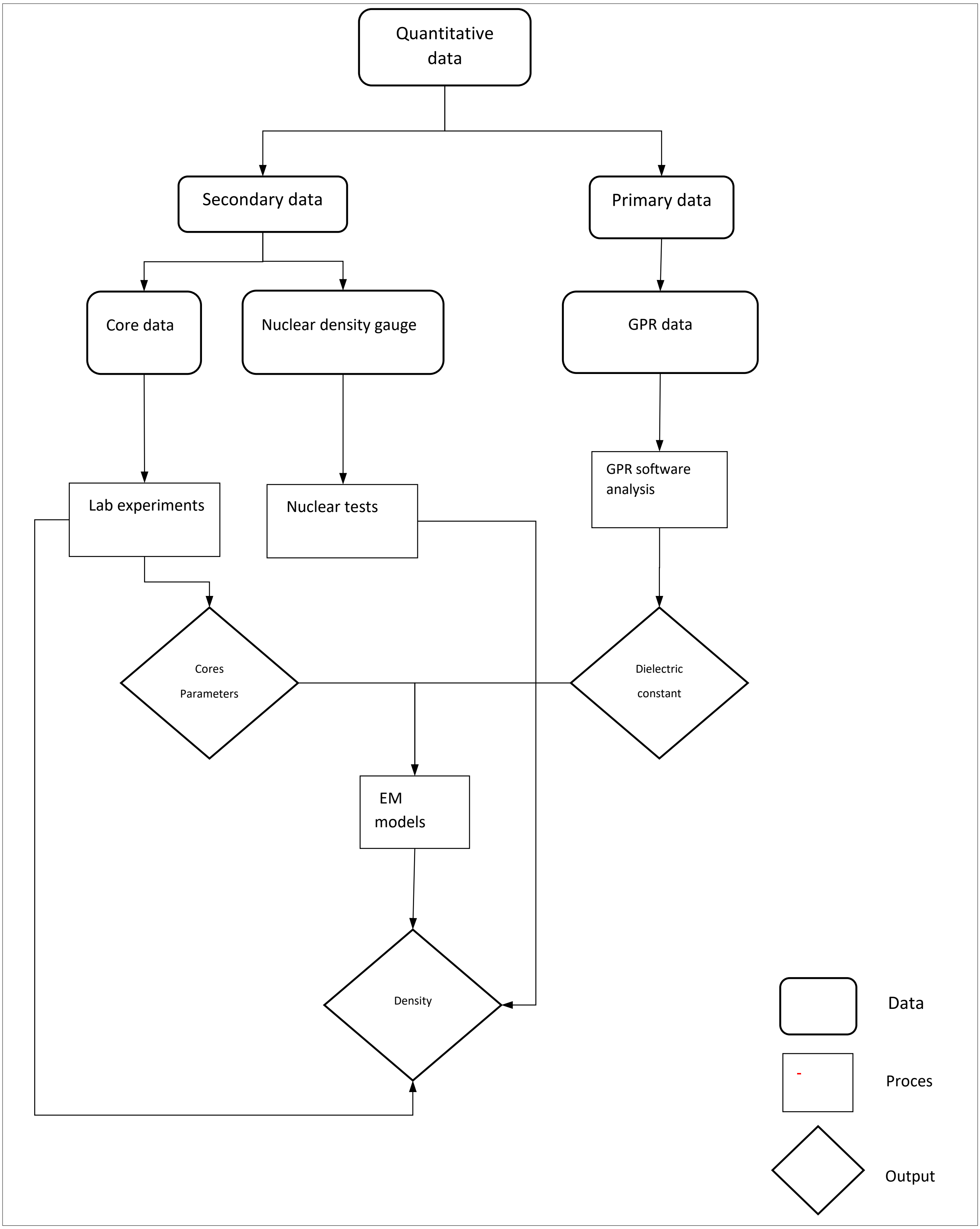


Figure 1 Flow chart of the methodology

2.2 Research design

In this section, the research design is outlined to answer the general research question. The research design is divided into three phases, each phase deals with an associated sub-research question. Figure 2 demonstrates the design framework of this study.

The first phase deals with the theoretical analysis of the research as a whole. In this phase, the pavement is first defined and its function illustrated in order to gain more insight into what pavement is and what layers it is consisted of. Different types of pavement will be listed as each of these types has different density requirements and thus different design requirements for each. Subsequently, the main challenges of measuring the density of the asphalt pavement will be identified to illustrate the problem of measuring the density of the pavement. Different methods for determining the density of asphalt pavements are discussed based on previous researches. Consequently, its efficiency is addressed through how simple and accurate their results can be obtained. This phase also illustrates the methodology by which GPR applications can predict the volumetric properties of asphalt pavement. Because the GPR has only been used in recent decades to determine the volumetric characteristic of the pavement, the theory behind this application must be identified. The theory behind the use of GPR for predicting the density of asphalt pavements is investigated through literature researches. For this, previously researches on the use of GPR as an instrument for prediction the asphalt density is used as a reference. Particularly, because the density cannot be derived directly from the GPR device, these researches can provide insights into identifying various models and parameters involved in the density measurement process. In general, there are different methods available to measure the density of asphalt pavements directly or indirectly. Each of these methods has its advantage and disadvantage. These methods will be identified based on a literature study. Additionally, the method and process of each of these methods for determining or predicting density are addressed in this phase.

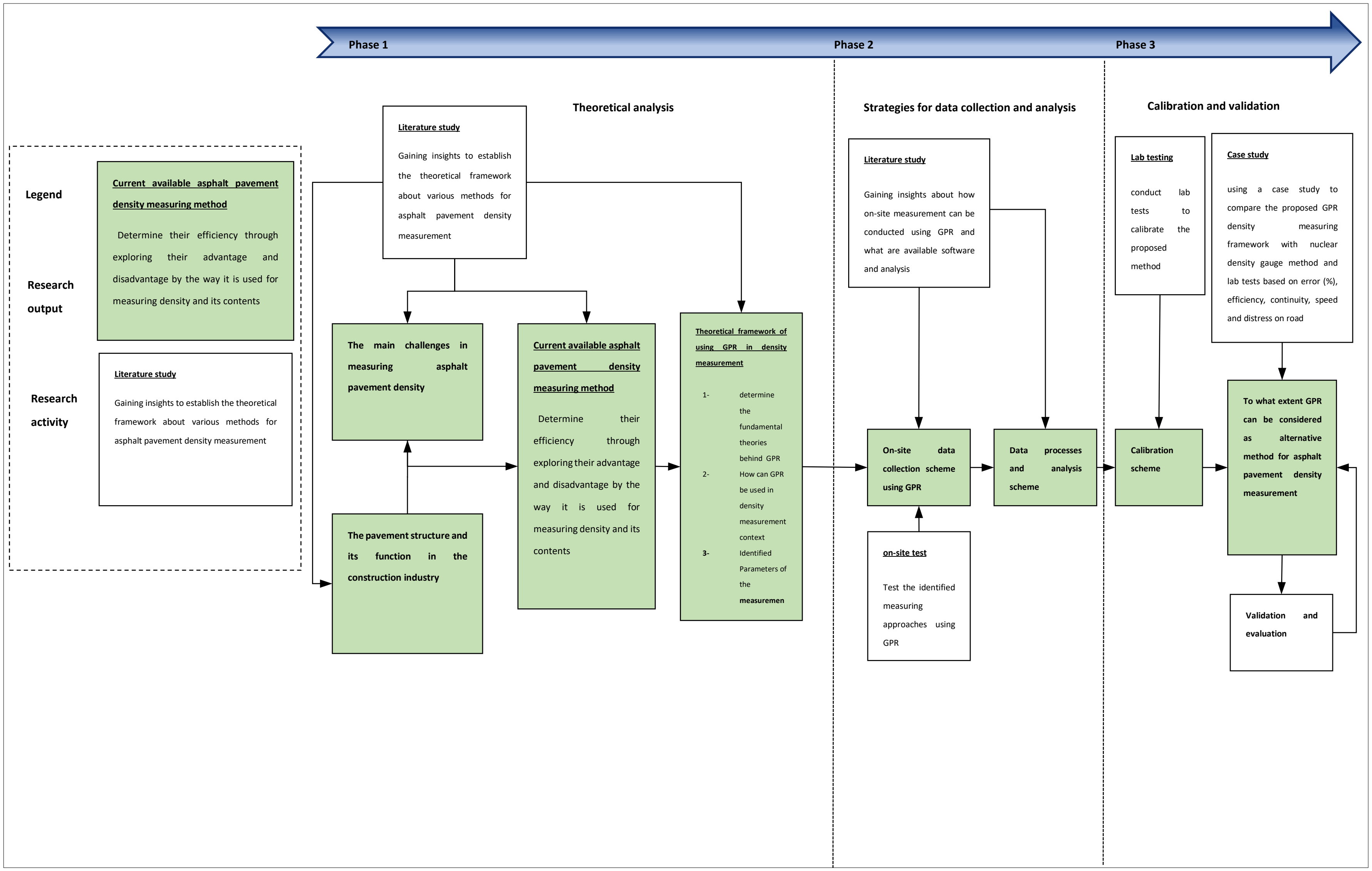


Figure 2 Design strategy framework

The second phase deals with the collection and analysing of data necessary for calibration and validation. In this phase, a plan is made to collect different types of data required for this research. This section covers the process of collecting data from the GPR surveys, NDG tests and core extraction. Furthermore, the software for analysing GPR data is covered in this phase. To perform the GPR survey, the GPR equipment is used to collect the data from a road section at Roelofs. A survey is conducted to collect one or more scans along each line of interest. All GPR data is stored on a digital storage device for later interpretation. The GPR data collected on-site is imported into the GPR processing software, which allows visualization of GPR scans. The ability to analyse and map GPR data helps to easily visualize the result and edit the data for further advanced processes. Since the invention of the GPR application, various software has been developed to analyse the GPR data. The most appropriate software for this research is determined based on how easy it can be used, its ability to simplify complex GPR analysis, the ease of editing and manipulating the acquired data, and whether the GPR data can be easily marketed and reported. This is because in the context of the on-site measurement, the operators may not be able to interpret and process the raw GPR signal to obtain the density. Therefore, it is essential and necessary to consider the simplicity of the software's analysis process. In addition, because this software is expensive to access, the cost of the software is also taken into account when choosing the most suitable software. Considering the cost of the training, the software should offer quite a "black-box" functionality.

The last stage is about the calibration and validation of the result. In this stage, the feasibility of the GPR for measuring density will be illustrated. For calibration, comparison, and validation of the result obtained from the GPR survey and nuclear density gauge, on-site cores measurement is used. The one-site measurement is the data from the exact location where the GPR survey and nuclear gauge measures will be performed. The specific gravity and volume characteristics are measured from these cores in the laboratory. In the lab, various methods can be used to estimate the bulk-specific gravity from the cores extracted from the field. e.g., the saturated surface dry method (SSD), the Corelok method, and the physical method. The method is chosen based on its ease of use and accuracy for providing results. To perform GPR measurements and NDG tests, one section with a width of *w* m and length of *l* m is selected at Roelofs. From this section the number of lanes (*N*) from which laboratory data will be extracted was selected. For the most accurate result, these lanes should be flat and clean. Subsequently, the density for *M* points along these lanes is estimated using the NDG measurement method and the core extraction method. The number of lanes and points will be chosen based on the actual length and width of the road, because more lanes and points are costly and time consuming, while less leads to less accurate density results. To determine the accuracy of the GPR and NDG methods, mean error and root square mean error is used. The calibration is based on the percentage error results of both GPR and NDG concerning the laboratory results. Finally, for validation of the GPR as an alternative method, a comparison will be made between the results of NDG, GPR and cores. The comparison is based on several factors that will be assessed in this study. The first factor is accuracy, by comparing the result of GPR to the result of NDG using lab results for the exact location and exploring whether the GPR provide the same or even better result than NDG using mean average error and the root mean square error. The second factor is the ability to measure density continuously, which can reflect the coverage of the measuring mechanism. The third factor is the time from which the data is collected from the test area using the different density measurements. The last factor is whether the method causes some distress on the road. This can take the form of traffic delays on the road or damage to it.

3 Literature review

The literature review was carried out to learn more about different aspects needed for this research and to answer the question from the first phase concerning theoretical analysis. First, an overview is given of what pavement is and how is designed to illustrate the importance of pavement in the construction of the roads as well as to gain knowledge of how the density be measured of the pavement. Subsequently, the main challenges in asphalt density measurement were defined. After that, the current density measurement methods are addressed to clarify their advantages and disadvantages. Their factors and way of measuring density should be illustrated in more detail to identify the drawbacks of these methods. The last and most important issue is to gain knowledge about how GPR satisfies the principle of density measurement.

3.1 An overview of road pavement

Before going deeper into the problems and methods related to the density measurement of pavement, it is a must to first establish what the pavement is and how it is designed. This section provides an overview of paving and its importance to the construction industry. Different types of pavements are also shown as each of these pavements has its target density and different design requirements for each. This is because each of these pavements consists of different types of material and thus different density requirements for each.

A pavement is defined as a structure designed to carry the load of vehicles. Over the years, the importance of carefully constructed and maintained paving structures has been recognized. The most famous application of road paving technology in history was done by Roman Empire, which built a network of approximately 78,000 kilometres of roads that are paved within its empire (Ali et al., 2016). Those paved roads were important to maintain and expand the empire. This is because those paved roads connect different parts of the empire. Consequently, the movement of the vehicle and the military was smooth across the empire.

Watson defines the main function of pavement as a tool to distribute the vehicle load on the road surface over several layers (Watson, 1993). Over the years, the density of the layers will continuously change due to the loading of the vehicles and the weather conditions. The most important layer of the pavement is the surface layer. This is because this layer is in direct contact with the vehicles. Therefore, the density of this layer must be measured continuously. The road surface must also offer sufficient slip resistance, sufficient ride quality, proper light reflection properties and a low noise level. Therefore, the main function of pavement is to provide a durable structure that is safe and stable under the influence of both the vehicle load and weather.

In general, the pavement consists of several layers of material laid on a natural surface (Evans, 2009; Civilworld, 2021). A schematic of these layers is shown in Figure 3. At the bottom, there is a sub-grade layer. This layer usually consists of unbound compacted aggregate. This compacted subsoil forms the basis of all the layers above. Each layer above this layer carries the load to this layer. Therefore, it is necessary to ensure that the subgrade is not overloaded. For this reason, this layer must be sufficiently compacted to the required density close to the optimum moisture content. The sub-base is the layer of material between the subgrade and the granular base layer. It plays an important role in providing structural support, improving drainage and reducing the penetration of fine particles into the pavement structure from the sub-grade layer. The overlying sub-layer is the main structural layer of the paving. This granular base layer provides additional load distribution for the material layer just below the surface of the binder layer to support subsurface drainage. This layer is composed of various materials such as crushed stone or other untreated or stabilized material. This layer is designed to resist and disperse the load on the vehicle's road surface without damaging the base material. The surface of the paving is placed on top of the base layer. This surface comprises two layers, a binding layer and a coarse layer. The main function of the binder layer is to distribute the load over the base granular layer. This layer mainly consists of aggregate mixed with binder. The top layer is the surface layer, which supports direct traffic loads and generally contains high-quality materials.

In general, there are four types of pavements (Rajput, 2019), each having its specific use and a different design in which different target density is required because each of these pavements has a different composition:

1. **Flexible pavement** is the type of pavement that has no reinforcement or low flexural reinforcement. Thus, it is quite flexible in its structural action under the influence of loads. For example, water-bound stabilized soil roads with or without asphaltic layer and macadam roads can be classified as flexible pavement. The design of flexible pavement is based on that for any load, the load force decreases as it is transferred downwards from the surface and spreads to an area where the layer of granular material increases (Mishra, 2021).
2. **Rigid pavements** are those pavements with significant bending strength or stiffness. This pavement consists exclusively of cement-bound material. The pressure is not transferred from the grain to the substrate because the flexible road layer is convenient. The design of this type of pavement is based on providing structural slabs with sufficient strength to withstand heavy traffic. The rigid pavement has stiffness and high elasticity modulus, distributing the load over a relatively large ground space.
3. **Semi-rigid pavement** is a type of pavement in which the underlayer or underlayment consists of concrete, lean cement concrete, or ground cement. This type of paving layer generally has a much higher flexural strength than a flexible layer.
4. **Composite pavement** This payment is composed of multiple major structural layers with several heterogeneous compositions. An example of such pavement is a concrete pavement of the sandwich type.

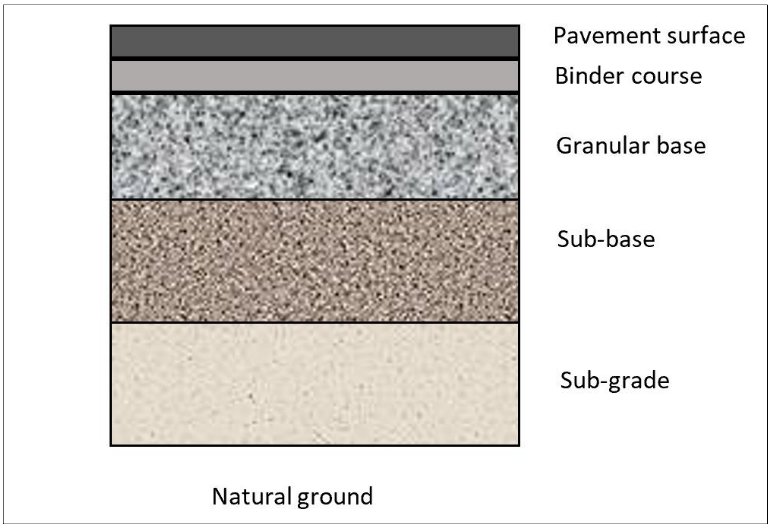


Figure 3 The structure of the pavement

3.2 The main challenges of measuring the density of asphalt pavements.

As demonstrated in the previous section, the pavement is defined as a structure designed to carry the load of vehicles. Over the years, the importance of carefully constructed and maintained pavement structures has been recognized. Road surface quality is the most important factor that researchers have been trying to improve over the years. The conventional quality pavement can withstand the different weather conditions and the heavy load of the vehicles. In this way, unnecessary costs for accommodation and repairs can be avoided. There are several quality indicators used to assess the result of the paving construction e.g., air voids, layer thickness, etc. Among all the quality indicators, density plays a crucial role in pavement longevity. On a hot mix asphalt pavement, increasing pavement density from 92 to 93 % of theoretical maximum density (The maximum density of asphalt assuming there are no air voids) or a decrease to 7 or 8% of air voids can improve pavement life by 10 % (Blankenship, 2015). For the Dutch standard, the required density is 98-102 % of the theoretical maximum density for asphalt concrete base, asphalt concrete bin and asphalt concrete surf while for very open asphalt concrete and stone mastic asphalt layer the required density is 97-103%. If a pavement is of low density, the air voids are interconnected and can lead to premature pavement problems. These can be in the form of premature oxidation aging, increased cracking, rutting, weakening of the structure, fraying, and stripping (Roberts et al., 1996). The pavement must have sufficient air voids to allow some plastic deformation. At the same time, the voids ratio should not exceed acceptable limits to prevent water ingress and moisture damage, which can be well reflected by measuring the density of asphalt pavement. Additionally, too high or too low density may cause premature road surface distress and failure, resulting in excessive accommodation and repair costs.

Consequently, the capability of mapping the asphalt density is the critical factor that helps to control the installation of asphalt and lead to a long road surface life. The density of high-density mixtures should be controlled over their lifetime with an air void domain of 3% to 8% (Roberts et al., 1996). When the air voids in over-compacted asphalt mix are less than 3%, rutting, shearing, and bleeding can occur on the asphalt surface. On the other hand, when it exceeds 8%, it allows water and air to pass through the pavement, leading to water damage, oxidation, fraying and cracking. Table 1 demonstrates the target density of several different mixtures in the Netherlands (Van Horssen et al., 2020). The target density is chosen based on the thickness of the mixture layer.

Table 1 layer thickness and target densities for the industry-representative asphalt mixtures (Van Horssen et al., 2020).

Asphalt mixture	Layer thickness (m)	Target Density (kg/m^3)
AC	0.05	2350
AC, 30% PR	0.05	2350
AC, modified asphalt	0.05	2350
AC intermediate layer or underlayer 50 % PR	0.07	2370
Very open asphalt concrete	0.05	2000
Durable very open asphalt concrete 30% PR	0.05	2000
Two-layer very open asphalt concrete top layer modified asphalt	0.025	2000
Two-layer very open asphalt concrete underlayment	0.045	2100
Sound-absorbing stone mastic asphalt layer	0.03	2300
Hydraulic engineering asphalt concrete	0.15	2350
Open stone asphalt	0.20	2000
Mastic asphalt, hydraulic engineering	0.30	2100

For the above reasons, achieving target density is important to improve the quality of the road. To obtain this goal the pavement should be built in such a way that it can be resistant to bad weather conditions and loads of vehicles. Over the years, the researchers have focused on improving road quality by developing new technologies and approaches, i.e., new compaction technology, and different approaches in which pavements can be laid and measured.

Given the importance of density in the asphalt pavement quality, the accuracy and efficiency of the density measuring methods become a necessity. Density is generally defined as the total mass of substances divided by the total volume of those substances. However, the total mass and volume of asphalt are difficult to determine because asphalt consists of several components, e.g. aggregate, binder and air. Therefore, there are many challenges in limiting the effectiveness of density measurements for paved roads (Al-Qadi et al., 2010). The biggest challenge is the accurate measurement of density. Researchers were always looking for new methods that could accurately measure because knowing the exact density of the roads helps whether the road needs more or less compaction to achieve the target density of a specific road. Consequently, improving the quality of that road. However, there are not many methods that meet this requirement. The second challenge is the time it takes to measure it. Measuring density is a complex approach and in many cases, it takes days to fully measure. The third challenge is the safety in which it can be measured because the density is not easy to measure and several approaches are needed, some of which can be dangerous. The fourth challenge is causing damage to the road surface and hindrance to traffic. During and after measuring the density of the road surface, damage to the road surface can occur and the flow of the traffic is limited by the measurement. For this purposes, various methods have been developed over the years to measure the density of the road. The first method that was used for this purpose was the 'core extraction method' which removes the core from the pavement and measure its characteristic in the laboratory. The disadvantage of this method is the high costs associated with this method. The time and ability to accurately measure the density of the pavement with a relatively large size is another drawback of this method. Therefore, the researcher explored another alternative method to measure density. In this regard, the researcher developed nuclear and non-nuclear density gauge instruments, intelligent compaction, etc. However, these methods reveals high limitations in the accuracy or safety of both.

3.3 Road pavement density measurement

As briefly mentioned in the previous section, several types of methods can be used to determine the density of pavement. These methods will be further explained in this section. Their parameters and procedure will also be discussed to clarify the disadvantage of these methods.

3.3.1 Coring Sample Method

Core extraction is the traditional way of measuring the density and other characteristics of the pavement. Although the core extraction method is the most expensive method to determine the characteristic of the layer to be tested, it is the most widely used method so far. For asphalt and concrete, it is the process of taking cylindrical samples or cores from existing sidewalks, pavement layers, slabs, or other structures for laboratory analysis. This method makes it possible to extract a complete core sample that retains more fluid and formation properties than cutting a piece of core from the site test. Core extraction can be performed for an accurate evaluation of formation and structure. In general, the core extraction process is usually carried out after the compaction is completed but is sometimes also carried out during the laying of the pavement. Coring is performed by a pick-and-place syringe with a diamond tip mounted on the electric drill. Typically, the diameter of the extracted core is in the range of 10 to 15 cm (Earth engineering, 2021). During the sampling process, water is sprinkled on the extraction site to keep the diamond blade cool when the sample is taken. After the process is complete, the core site is restored with the appropriate materials such as asphalt. This method is an expensive operation but provides useful and accurate information for determining the characteristic of core samples.

To examine the advantages and disadvantages of this method, the components involved in this method and its procedure must be identified.

3.3.1.1 Equipment and materials

The materials and equipment that is used during the coring process consist of the following:

- **Portable drilling equipment** - Installed on trailers or another similar equipment that is used for transportation purposes. The drill is equipped with a suitable power source to drive the core cylinder. The drilling unit is equipped with an air or water source to cool the drill rod while drilling.
- **Core Barrels** – to extract the core from the test site. The most efficient core barrel used for this purpose is a wall-mounted barrel with a diamond cutting edge inlaid on the surface.
- **Core Retrieval Tool** – is a tool designed to take the cores from the hole once the drilling process is complete, without damaging the cores.
- **Marshall Portable Compaction Hammer** – to compact the hot asphalt mix in the hole after the core is extracted.
- **A container** – for the preservation of the cores.
- **Towels –** to dry out the extracted core

The section above demonstrates that this method can be costly and dangerous. For example, portable drilling equipment incurs additional costs associated with this method including the transport of this component by the vehicle. Besides, the cost of fuel and causing pollution should be also taken into account. On the other hand, involving the core barrel and core retrieval tool in this method means that this method can be dangerous and must be performed carefully, thus increasing the cost for training.

3.3.1.2 Procedure

Before starting the procedure, the location where the core of the asphalt layer is to be removed must be marked and cleaned of dust (MSMT, 2012). The procedure then involves placing the core drill in a designated sample position where the central cylinder is perpendicular to the asphalt concrete surface, as shown in Figure 4. Then the central cylinder cooling device is turned on and the rotating cylinder is continuously lowered to drill. The barrel rotation is stopped as soon as the barrel passes through the asphalt concrete. At the same time, the cooling equipment is turned off. The cores are then removed from the hole using the core retrieval tool. Because the water is used for drilling, the core should be dried with a towel to minimize water moisture in the cores. Each core is then identified with a number for later analysis. After cores have been removed from the road and sample numbers marked, they are placed in an insulated container equipped to maintain the core temperature at an appropriate level until delivered to the lab for analysis. After the drilling process is complete, the core hole is filled with a hot asphalt mixture and compacted with a portable Marshall portable compaction hammer. It can be concluded that the procedure of core extraction is expensive because of the costs associated with special instruments for the extraction process, the costs of maintenance of the equipment, the costs of transport and storage of the sample, and the costs associated with the training. Furthermore, this procedure can be dangerous if not done carefully as it involves both electricity and drilling. Although the core site will be filled with asphalt after the process is completed, this procedure will damage the road surface as it affects the homogeneity, harmony and aesthetics of the road where it is drilled. Moreover, the process of the coring may hinder the traffic flow if it is performed on dense traffic roads. Since this procedure only extracts one core at a time, it will take long time to complete this method if the road section is long and many cores need to be extracted.

Figure 4 Core extraction method (Ctmrecruitment, 2019)

3.3.1.3 Density by the conventional method

The density of the core cannot be measured directly on-site and must be measured in the laboratory as mentioned earlier. Therefore, once the cores are extracted, they are preserved in an insulated container and taken to the lab. In the laboratory, there are several methods by which the specific gravity of the core sample can be determined (Galacgac, 2003). The bulk specific gravity test is a method of determining the density of a dense asphalt mixture by measuring the weight ratio of the compacted sample to the weight of an equivalent volume of water. Although the most common method that has been used for determining bulk specific gravity is the Saturated Surface Dry method (SSD), many others can be used for determining bulk specific gravity, including the following:

Parafilm

This method is provided in the American Society for Testing and Materials (ASTM D118) procedure to determine the bulk specific gravity of compacted bituminous mixture using parafilm. The process of this method is as follows:

First, the HMA core is dried in the oven and weighed in the air. Then he core is wrapped in parafilm, and its weight is taken in the air. Subsequently, the wrapped cores are submerged and weighed in the water. Finally, the bulk specific gravity is calculated using the following equation:

$$Bulk\ specific\ gravity = \frac{C}{P - M - \left(\frac{P - C}{W}\right)}$$

Where A is the weight of the core in the air, P is the dry core's weight plus parafilm in air, M is the dry core 's weight plus parafilm in water and W is the specific gravity of parafilm.

Water displacement method

This method is the most commonly used method for determining the bulk specific gravity of HMA. This method is also called the Saturated Surface Dry (SSD) method. It is used widely because of the low cost associated with it, as it only requires a water tank and scale. This method was first provided by the American Association of State Highway and Transportation Officials (AASHTO) or the American Society for Testing and Materials (ASTM D2726). The principle of measuring density using this method is based on Archimedes' principle. The volume of the sample can be calculated by subtracting the mass of the sample in the water from the mass of the SSD sample. The SSD state represents a situation when the air void of the sample is filled with water while the surface is dry. The process is as follows. First, the weight of the cores is calculated in the air. Subsequently, the cores are submerged in the water and weighed. Finally, the cores are weighed in a saturated surface dry state. The following equation can be used to determine the bulk specific gravity of the core:

$$Bulk\ specific\ gravity = \frac{mass_{dry}}{mass_{SSD} - mass_{sub}}$$

Where $mass_{dry}$ is the mass of core in the air, $mass_{sub}$ is the mass of the core in water and $mass_{SSD}$ is the saturated surface dry core mass.

Paraffin method

This method is the same as the water replacement method which determines the volume, but unlike water displacement, it uses paraffin instead of water. The paraffin is first melted and filled in the internal hole of the core. Therefore, there is no possibility of the wax flowing after the wax has hardened. However, it is difficult to apply this method correctly. Consequently, the volume measured is overestimated.

Corelok

The method uses an automatic vacuum chamber to determine the bulk specific gravity. This automatic chamber is used with flexible bags specially designed to completely seal asphalt mixture cores. The process is as follows: first, the HMA sample is carefully placed in custom designed plastic polymer bag, placed in the chamber of the vacuum sealer, and the door of the chamber is then closed. The pressure in the vacuum sealer causes the bag to tighten around the cores. The bag is then removed, and the sample is taken to measure it in the air and water. The calculation of specific gravity is then the same as the parafilm method.

Dimensional

This method is used by calculating the volume of a core or other sample shape obtained from a field. The specific gravity of cores can be calculated by dividing the dry mass of the core by its volume. However, this method can often lead to errors because the sample volume is overestimated including irregularities and voids as a fraction of the total sample size.

Gamma-ray

This method uses the principle of the scattering and absorption properties of gamma rays which depend on the type of material to determine the density. In this method, the primary energy source in the Compton band is placed close to the material and the gamma rays are counted with an energy selective gamma-ray detector. The scattered and non-dispersive gamma rays with the energy of the Compton band are calculated separately. With the right corrections, the amount of gamma radiation can be directly converted into the density or density of the material.

Using any of the above methods for measuring density can provide an accurate result for density measurements but can also be costly and take long time to be performed.

Thus, it can be concluded that the core extraction method can provide relatively accurate result of density measurement using any density method in the laboratory. However, performing this method is quite expensive and time consuming . Furthermore, this methos can be used for a specific location and thus cannot cover a density of a large area. The other disadvantage is that this method is destructive because it causes damage to the surface.

3.3.2 Nuclear density gauge (NDG).

3.3.2.1 NDG history

In the past, there was an urgent need for researchers to find an alternative method to the core extraction method for measuring density. This is due to the high costs and time-consuming relationship with the latter method. One of the methods discovered at that time was the nuclear density gauge (NDG). NDG is the method in which the density is measured by emitting a gamma-ray through the surface. Since the discovery of this method, many studies have been conducted to examine the performance of this method. The performance was assessed by comparing the result of this method with the core extraction method. The first document about measuring asphalt density using NDG method was announced at a conference in Chicago (Stephens, 1964). Subsequently, in 1971 (ASTM) developed a test method for measuring the density of hot mixed asphalt (HMA) using these gauges. Since then, several studies have been conducted to examine the accuracy of this method and compare it with the core method. For example, in 1987, a study examined whether there is a correlation between the result of the NDG and core densities obtained in the field (Burati and Elzoghbi, 1987). In this study, three different NDG devices were used. Namely - Troxler 3411-B, Seaman C-75BP and CPN M-2. The results reveal a significant difference between the NDG measurements and the core measurements as shown in Table 2. To a large extent, the results of NDG were relatively lower than those of the cores. Additionally, the NDG measurements turned out to be more scattered than the core values. In another study, the aim was to investigate the correlation between the NDG measurements and density of the cores using the data of seven projects (Padlo et al., 2005). In all projects, the compaction thickness was 31.6 mm. The results of NDG were found to be neither consistent between the three gauges used nor consistent with the core density results. The inconsistency between the result measurement of NDG and the core densities ranged from 0.3 to 1.2% of the maximum theoretical density. As a result of these studies, it can be concluded that the density results of NDG are not entirely accurate compared to the density of the cores.

Table 2 Comparison between Core and nuclear gauges mat density result for Rochester project (Burati and Elzoghbi, 1987).

	Core	CPN M-2	Troxler 3411-B	Seaman C-75BP
Mean density (kg/m^3)	2414	2344	2366	2214

3.3.2.2 Nuclear gauge components

The main components of NDG are:

- **Gamma source** – Source that emits gamma rays. An isotope of cesium (Cs-137) is used usually as a source for gamma radiation. The quantity of radioactive used in this source is often 0.296 or 0.37 GBq (Department of Transport and Main Roads, 2021).
- **Detector of gamma radiation**
- **Source of neutron radiation for moisture content measurement**- An isotope of americium (Am-241) in combination with beryllium is usually used as a source. The quantity of radioactivity used is often 1.48 or 185 GBq.
- **Slow neutron detector**

The nuclear gauge components indicate that this device used complex technology, as will be illustrated in more detail in the next section, and that it could be hazardous to health because it contains both a gamma source and a beryllium source. For example, beryllium is highly toxic to lung tissue. also, inhalation of beryllium dust and fumes can cause a granulomatous long illness similar to sarcoidosis (Group, 2013). On the other hand, gamma rays can be dangerous for the whole body. They can easily penetrate barriers such as skin and clothing. Gama rays have high penetrating power and can easily pass through the human body. When they pass, they can cause ionization, leading to tissue and DNA damage. Therefore, whoever works with this device must have a license, which in turn results in additional costs.

3.3.2.3 Principle

NDG is a non-destructive technique that to some extent provides an accurate result of the characteristic measurement of the asphalt mixture layer, as previous research showed. The device can measure the moisture content and density of different materials by computing the specific gravity of the tested material through direct transmission and backscatter and air-gaps modes (Tidwell et al., 1993). Using advanced microprocessor technology, the NDG offers relative density and moisture. Figure 5 illustrates the mechanisms of an NDG (gamma-ray gauge), including the gamma-ray source, detector and shield. Since the principle of this method is based on gamma radiation, it poses security risks and therefore the person who would perform this method must be professional with these applications.

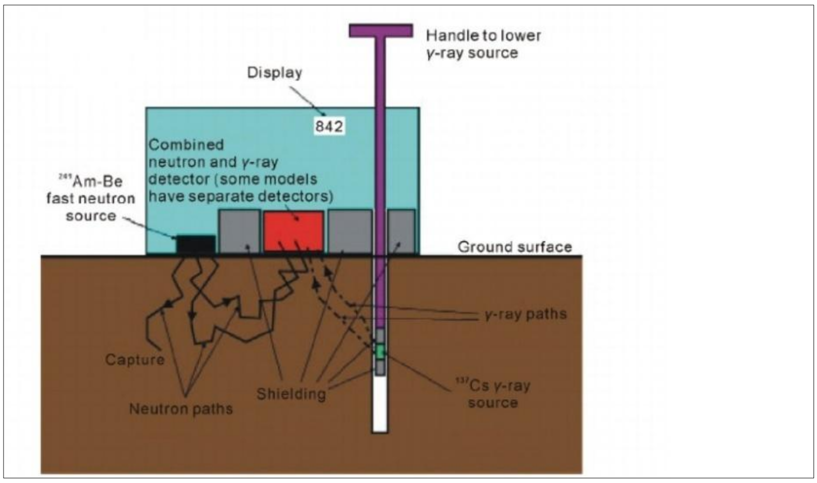


Figure 5 Schematic diagram of the basic component of nuclear gauge (Cooper, 2016).

NDG measures density by gamma-ray emission in the material under test. The sensor then measures the radiation reflected from the material. The density can then be calculated from the percentage of radiation returning to the sensor.

3.3.2.4 Density measure by NDG

The nuclear gauge uses gamma radiation and detection to measure material density. Gamma radiation is a type of high-energy radiation that easily penetrates most materials. Due to the transmission of gamma rays between the source and the detector, some of these rays are absorbed and scattered, depending on the density of the material between the detector and source. Increasing the density of the material will lead to an increase in the number of gammas that will be absorbed and scattered. As a result, the number of gamma rays reaching the detector decreases. Then there is exist a relationship between the detected gamma rays and material density (Yin et el., 2009). This relationship is formed as follows

$$DCR = Ae^{B\mathrm{d}} - C$$

where:

DCR = Density

d= density of the material read by the gauge ($\mathrm{kg/m^3}$)

A, B, C are constants for the nuclear gauge used for calibration

A and C are constants that can be obtained with a recalibration method that relies on the geometry of the gauge. B is a constant obtained by a recalibration method that depends on the mass attenuation coefficient.

3.3.2.4.1 Density measure modes

Using NDG, the density of the pavement, or any other type of soil, is measured using three different modes. These modes are direct transmission, backscatter and air gap mode. Each of these modes has advantages and disadvantages when measuring density (Tidwell et al., 1993).

- <u>Direct transmission</u>: In this mode, a hole is first made in the material to be tested. Next, a core source rod is inserted into the material under test to the desired depth, as shown in Figure 6a. A depth of 15 cm is the most recommended depth to simultaneously test both moisture content and density of the soil that is used in backfill and subsoil. This method can generally be used for any type of material in which a hole can be made. However, this method is not truly non-destructive, as holes must be made for the rod to be inserted in the material to be tested. The other disadvantage of this method is that it is used mainly for cohesive and non-cohesive substances in substrate and subsoil layers, but not for asphalt concrete layers.

- Backscatter mode: In this mode, the measurement source and detector are close to the test surface, as shown in Figure 6b. Measurement depths typically range from 1.30 to 15 cm below the test surface. This method can be applied to substances for which a certain calibration curve is made. The main advantage of the backscattering method is that it is easy to be used and can be classified as a non-destructive method. However, the disadvantage of this method is that one calibration curve is not sufficient to be used for all materials. Also, the measurement depth cannot be accurately verified. The material closest to the test surface also has the greatest impact on the test.
- Air gap density measurement: The main reason for developing this method was to overcome the errors in the chemical composition of the backscatter method. In this method, backscatter measurements are compared to air gap measurements measured at a fixed height on the test surface. The air gap method generally produces results similar to the backscatter mode and uses only one correction curve for different materials types. The measurement depth however cannot be accurately adjusted and the substance closest to the surface has the most effect on the test result.

In conclusion, using any of the modes of NDG to measure density can provide an accurate result for density to some extent as compared to the core extraction method. However, as with the core extraction method, all modes return the result only for a specific location. Therefore, all modes limit the measurement of a high coverage density. Furthermore, performing this method is dangerous because of the radiation emitted by this method for both measuring density and moisture content.

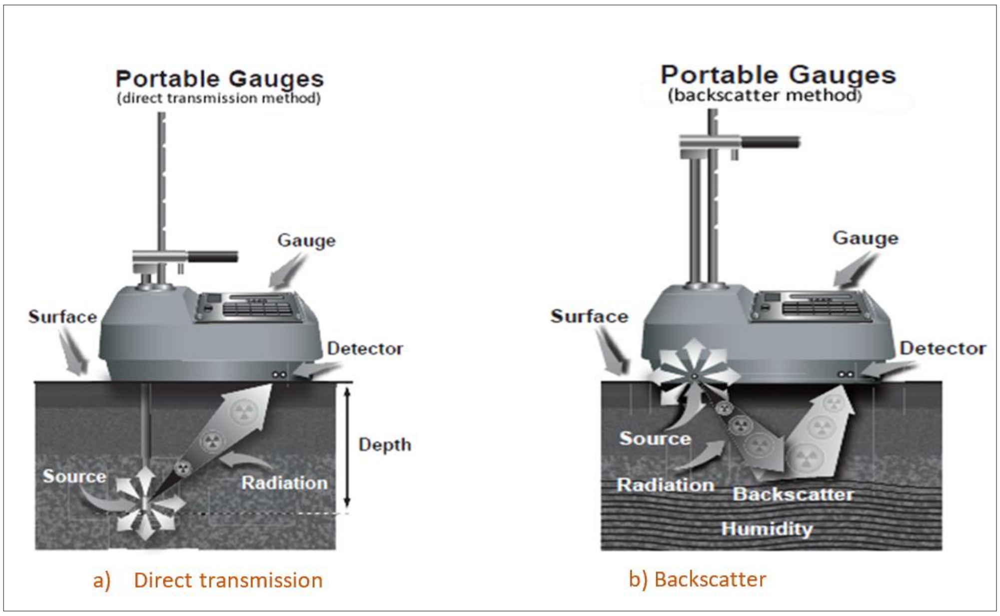


Figure 6 NDG direct transmission and backscatter modes (Cooper, 2016)

3.3.3 Non-nuclear density gauge

Because of the increased costs and destructive properties associated with the traditional base methods used to determine the density of asphalt mixes, researchers are investigating many other methods for measuring asphalt characteristics that are safe, cost-effective to use, and are non-destructive. For this, a nuclear density gauge was previously introduced. However, since this device uses gamma radiation and beryllium source, there are health and safety concerns. Therefore, the researchers developed a new device called a non-nuclear density gauge, which is not dangerous to use. The development of non-nuclear density gauges in recent decades has revolutionized asphalt density measurement because it is not destructive and safe to use. Nowadays, there are two electromagnetic gauges have been manufactured. The first gauge is the Paving Quality Indicator (PQI) which is manufactured by TransTech and the other is the PaveTracker manufactured by Troxler. The two gauges are equipped with similar technology to improve the measurement of the dielectric characteristics of the mixed asphalt. Consequently, the change in density is correlated with an increase or decrease in the dielectric properties. The density of asphalt pavement is measured by these devices by emitting electromagnetic rays to the surface. When the rays are hit by the road surface, which is a non-conductive material, these rays lose their power. The density is then measured by measuring the change in the electromagnetic field. Figure 7 demonstrates a schematic of the (PQI) sensing plate. A transmitter is displayed, from which the ray is sent to the surface and is received by a receiver that collects the scattered rays. Since HMA contains many components and the dielectric constants of each component differ greatly, the density of HMA measured with a non-nuclear gauge is greatly affected by the type of material used in the asphalt mixture.

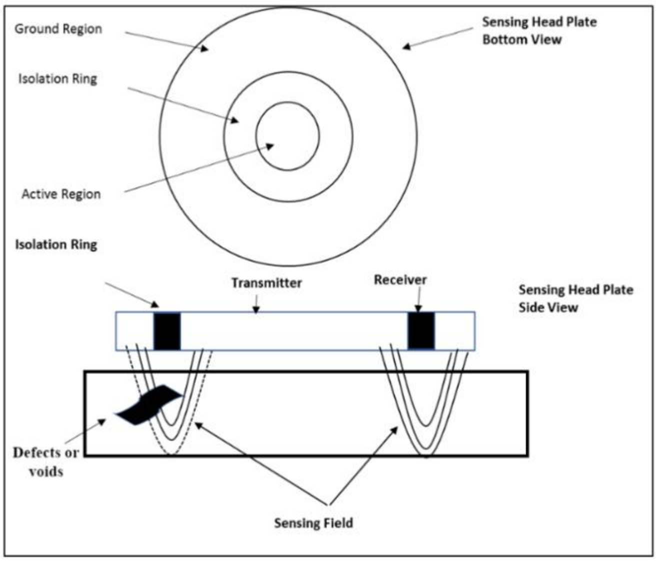


Figure 7 Schematic of PQI sensing plate (NCHRP-IDEA, 1999)

3.3.3.1 History

The first time the non-nuclear density gauge was used to measure HMA density was made by TransTech Systems in 1998 (AECOM, 2016). Since then, many studies have been done to evaluate and compare the result of this method to the one of NDG and the core method. For example, in 2002 a study was conducted to assess whether the commercially available non-nuclear density gauge can be used to determine the density of HMA (Romero, 2002). In this study, both the Pavement Quality Indicator (PQI) and the PaveTracker were used. It was established over two construction seasons to assess the impact of different conditions, such as using a different aggregate size, nominated maximum aggregate size (NMAS), aggregate source, temperature and humidity, on the accuracy results obtained by the device. It has been assumed that changes in NMAS were altered by offsets during the correction process. Aggregate assessment, aggregate source and temperature changes were found to generate another correlation between PQI and asphalt density. Another study was conducted to assess the performance of the PQI Model 300 and Pave Tracker as an alternative method to the nuclear gauge and conventional method (Sargand et al., 2005). The effect of different conditions on PaveTracker was also assessed in this study in the laboratory by changing the temperature, humidity, sample area, aggregate size and mat thickness. It turned out that the gauge results had decreased by an average of 16 kg/m^3 for coarse mixtures and 24 kg/m^3 for fine mixtures when the temperature has decreased by 50 °C (90 °F). The most recent study found out that the non-nuclear density gauge method can obtain accurate results of the pavement density (Kara et al., 2017). However, the disadvantage of this method is that training is required for effective use of the non-nuclear gauge, the measured density values are temperature dependent and the value for offset has to be adapted to the local situation.

3.3.4 Ultrasonic pulse velocity (UPV) method

Ultrasonic technology was used to assess the fundamental properties of solids for decades. The principle of using this technology for the evaluation of the characteristic of solids is based on the fact that this technology uses the emission of high-frequency acoustic energy by the materials in the waveform. For many decades, it has been used to assess the dynamic coefficients of asphalt mixtures with acceptable accuracy (Leng, 2011). Furthermore, Dunning's study tested the practicality of using non-contact ultrasound techniques for determining the specific gravity of hot asphalt mixture (Dunning, 2006). In his study, the aim was to determine whether a non-contact ultrasonic transducer could penetrate asphalt concrete and produce a measurement of the specific gravity of the material. It was reported that the proportion of asphalt mixture is closely related to the energy rate of decay during the passage through the material. This study laid the basis for ultrasonic technology as an instrument for measuring density in the future. Though, the correlation is undefined and requires many work to be considered for application in the industry.

3.3.5 Intelligent compaction

Intelligent Compaction (IC) is a device-based technology that uses modern vibratory rollers equipped with an integrated measuring system to compact road materials, such as the layers of soils, aggregate bases, or asphalt pavement materials (Xu et al., 2012). The integrated measuring system consist of accelerometers, GPS, infrared temperature sensors, and computers that can display IC measurements as color-coded maps. IC measurements include roller passes, asphalt surface temperatures, and roller settings including roller vibration frequencies, amplitudes, and speeds. The color-coded plots can be viewed to see the precise location of the roller, the number of passes the roller makes, and in some cases the stiffness of the material.

The IC System has been further enhanced to convert compression energy into material density. In 2015, Volvo published their new intelligent compaction system model "Density direct system " which can convert vibrations into density measurements using its artificial neural network, as shown in Figure 8. The Density Direct system has a screen where the user installs the system on a calibration test strip. When calibration is initiated, the system automatically plots the area covered by the operator in four paths. These passes are used to train the system's artificial neural network. When the calibration is complete, the calibration is saved, and the Co-pilot displays the predicted density as a percentage. The results of this study reported that the density calculation was accurate to 1.5 percent of the core sample (Volvo 2015).

It can be concluded that this method can be considered as a non-destructive method, although this method is still in the development stages and a many work is required for this method to consider it as a density measurement.

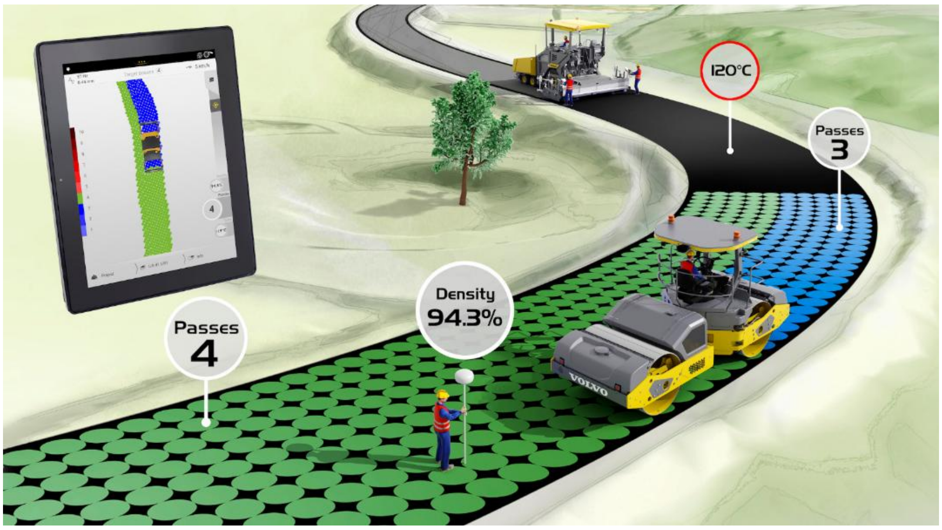


Figure 8 Intelligent compaction system (Volvo, 2015)

3.3.6 Ground penetrating radar GPR

3.3.6.1 History

Due to the limitations that other methods have in terms of safety or result accuracy, there was a need for an alternative method that is non-destructive, time and cost-efficient and can provide accurate results. In this regard, GPR came in. GPR is a device using radar pulse to image the subsurface. It has been used for the evaluation of pavement in the last decades. Historically, GPR was mainly used for mining processes for detecting the material underground. The materials underground were detected by the electromagnetic wave that the GPR was sending towards the sub surfaces and reflected to the antenna. In the mid-1970s, the Federal Highway Administration (FHWA) initiated the use of GPR in pavement research to explore the feasibility of using GPR in tunnel applications. (Black & Kopac, 1992). It was found that GPR can provide useful information that was not available before. The first attempt that were made to predict the properties of asphalt mixtures using GPR was by Al-Qadi (1992). In this study, a regression model were developed for estimating the volumetric moisture content of asphalt mixtures according to their permittivity. In particular, the focus was on predicting the water content of asphalt mixes from the dielectric constant, but the same principles can be applied to predicting the void content. Three types of asphalt cement (Conoco AR4000, Shamrock AC-20 and Witco AR1000) were tested to measure their dielectric properties. The results revealed that the three types of cement had the same dielectric constant magnitude with a different loss factor. Moreover, different types of aggregate and mixture were tested. The results were different for each type and mixture. For example, the limestone aggregate had a higher dielectric constant than piedmont gravel and the open graded limestone had a higher dielectric constant than the dense-graded limestone mixture. Since then, the application of GPR for structure characteristic evaluation has expanded to many areas. Furthermore, the GPR application has shown significant potential advantages for measuring pavement density. According to Al-Qadi et al., GPR can predict pavement density if a proper model is used (Al-Qadi et al., 2010). In this study, the ability of GPR to estimate accurate density results under controlled laboratory conditions was examined. The density and air voids of different types of asphalt mixtures are estimated from the dielectric constant. The result has shown that the dielectric constant can predict density and air void accurately if a proper model is used. In another study, prediction models and advanced digital signal processing methods have been developed to improve the asphalt concrete (AC) layer thickness prediction (Leng et al., 2014). Today, the GPR application is used for various applications, such as concrete imaging, environmental inspection and road inspection. However, although the GPR has many advantages in terms of time saving and efficiency, it has some limitations. These limitations will be discussed in more detail later in this thesis.

3.3.6.2 The fundamental theory

As mentioned before, the result of the road surface characteristics cannot be extracted directly using GPR. This is due to the complex physique theory on which this method is based. The fundamental theory of GPR for the investigation of the underground layers and evaluation of pavement characteristics measuring lies in the Electromagnetic theory (EM). The theory is based on the fact that there exists a relationship between the dielectric constant that can be measured with this method and the road surface characteristics. This theory is illustrated in more detail in the next section.

3.3.6.2.1 Electromagnetic wave.

When a radar signal passes through a material, the laws of physics for EM waves apply. Electromagnetic waves are alternating electric and magnetic fields propagated by oscillating electric charges, and there are various types of electromagnetic waves that make up the whole electromagnetic spectrum. Different types of electromagnetic waves are distinguished by their frequencies, which are measured in electric and magnetic fields in cycles per second (Hz). GPR non-invasively assesses the underground environment using these waves. The GPR system emits electromagnetic waves that propagate through materials and are partially reflected by surface objects with relatively dielectric properties. After the antenna receives the reflection, the system creates a radar signal that depends on several factors, e.g., amplitude, polarity and propagation time of the signal. The trajectory is the measured value of a single GPR position within a specific time window. The frequency of the wave and the velocity of the wave depends on the type of material. The spectrum of electromagnetic waves includes various types from the highest frequency gamma wave with a wavelength of 0.01 nanometres to the lowest frequency propagation with a wavelength of 1 kilometre (Evans et al., 2007). The abbreviation "radar" refers to waves of radio frequency, but GPR that has a modern system operates in the lower frequency range of microwaves, which have a wavelength of about a few centimetres. Dielectric refers to a material that cannot conduct electricity well but produces an electric field. A material's response to electromagnetic waves is a function of the material's dielectric properties, primarily permittivity, conductivity, and permeability.

3.3.6.2.1.1 Electrical permittivity

The permittivity is defined as the proportional constant between the electric field strength and its displacement. This constant corresponds to approximately $8.85 * 10^{-12}$ farads per meter (F/m) in space (TechTarget, n.d.). For other materials, it can vary widely and is often much greater than the value of free space, denoted by ε_0.

For technical applications, permittivity is expressed in relative rather than absolute terms. Since ε_0 represent the permittivity of the free space (about $8.85 * 10^{-12}$F/m) and the permittivity of the material is also farads per meter, it can be concluded that relative permittivity is also called the dielectric constant mentioned by:

$$\varepsilon_r = \frac{\varepsilon_s}{\varepsilon_0}$$

where ε_r is the dielectric constant, ε_s is the dielectric constant of the substance under investigation and ε_0 is the dielectric constant of space. The permittivity value is important to analyse because it is related to multiple parameters needed to interpret the GPR data. To determine the depths of GPR data, the signal velocity through the substance is needed so that the two-way travel time of the GPR signal (time needed for GPR signal to travel from the antenna to the asphalt structure and reflected antenna) is recorded by the GPR system can be converted to depths:

$$d = \frac{t}{2} * v$$

Where d is the depth of the feature and t is the two-way travel time of the GPR signal that is reflected from the substance. GPR frequency EM wave reflection occurs when the wave corresponds to the boundary between two other substances that have different permittivity. Some energy of the GPR that is passing from one substance to another is reflected by the antenna at the substance boundaries. In the adjacent substances which have similar permittivity, the EM reflected wave may be small, and in such a situation, it is difficult to distinguish the boundary between the materials. The amount of reflected radar energy is expressed as a reflection factor. This energy depends on the material's dielectric constant and is specified as follows:

$$R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

where R is the reflectance coefficient and ε_1 and ε_2 are the dielectric constants of the substances. Figure 9 provides a schematic of the emission and reflected rays of the EM wave towards the pavement layer. A typical GPR system consists of four essential components: a transmitter and receiver connected to the antenna, data display, unit, controller and storage. The antenna device can be a single antenna that sends and receives radar signals or two separate antennas (a transmitting antenna and a receiving antenna). In both cases, the antenna must be light enough to be easily placed above the area to be measured. The transmitter/receiver device consists of a transmitter for signal generation, a receiver for signal detection, and a timing electronic device for synchronizing the transmitter and receiver. The controller is an operator interface that controls the overall operation of the GPR system and transfers the received data to the data storage and display device. The transmitting antenna emits a high-frequency EM pulse to the ground which is then deflected and reflected at the ground to the received antenna and occurs mainly in the face of changes in permittivity and electrical conductivity (Basson, 2000).

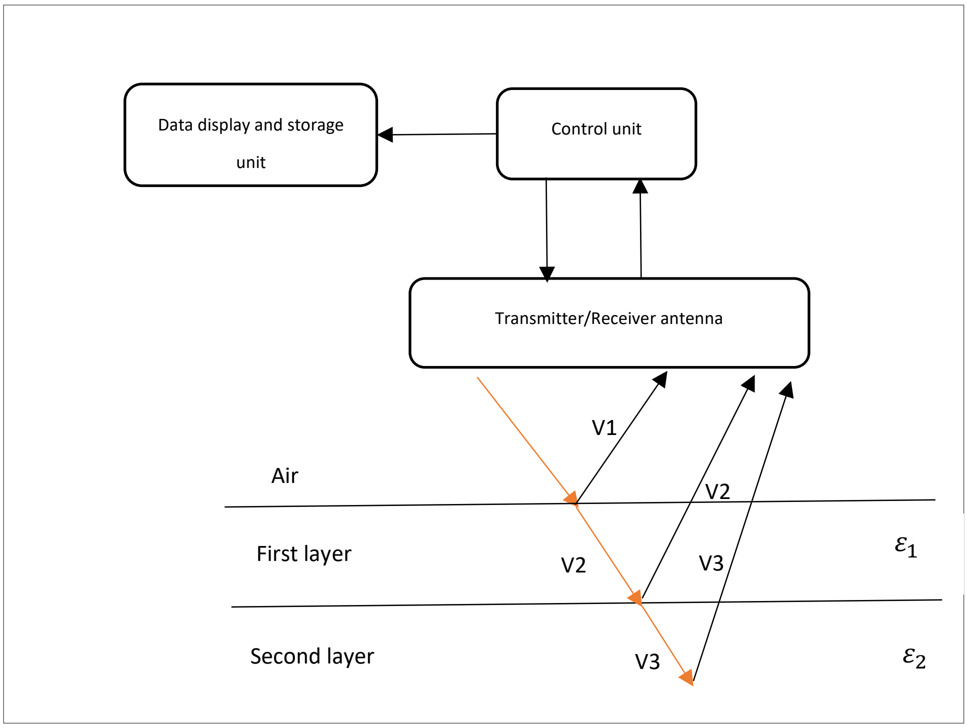


Figure 9 Transmitted of a wave to the pavement layers

3.3.6.2.1.2 The electrical conductivity

The material's electrical conductivity (σ) is a measure of how an electrical current moves within the material. The higher the electrical conductivity of the material, the higher the current density of the given potential difference. In other words, electrical conductivity is the ability of a substance to conduct electricity. This electrical conductivity can have a significant impact on the energy loss or attenuation of electromagnetic signals. Conductivity and signal frequency are the main factors affecting signal attenuation and determining the penetration depth of the signal. The high conductivity substances quickly attenuate the GPR signal (Evans, 2009).

3.3.6.2.1.3 The magnetic permeability

Magnetic permeability (μ) is the ability of a magnetic material to withstand the generation of a magnetic field. In other words, permeability is a proportional constant between the magnetic field strength and magnetic induction. The higher the permeability of the material, the higher the conductivity of the magnetic field and vice versa. The permeability of material indicates that an external magnetic field easily causes a large magnetic attraction to the material (Evans, 2009). Permeability (μ) and permittivity affect how the energy of EM is collected and emitted while the EM wave passes through. Depending on how the EM wave acts on the magnetic minerals of the material studied and the magnetic dipole moment of the atom, this can be an important element of GPR research and can affect both the EM wave velocity and the attenuation. However, the relative magnetic permeability value for magnetic materials is 1. Highly corroded steel mills and materials with a high magnetic mineral content can affect both the attenuation and velocity of GPR signals. In practice, however, most paving materials have a value of 1, which does not affect the signal rate and GPR pulse attenuation.

3.3.6.2.2 Determine the dielectric constant of pavement

As mentioned earlier, the GPR principle is based on sending a pulse from the antenna to the ground and recording the reflection characteristics of this pulse (the time GPR signal takes to go back to the antenna, the phase, and amplitude of the GPR signal, etc.). Whether the radar pulse penetrates the material depends on the several properties of the material, e.g., condition, water content and stomatal content of the material. These material properties influence the dielectric constant of the material. Permittivity determines the velocity at which an electromagnetic signal travels through a substance. The permittivity information of the material must be analysed to convert raw data from GPR into data that can be useful for measuring asphalt characteristics. The permittivity value can be obtained in several ways. For example, from various studies that have been conducted for different types of soil. An example is shown in Table 3, in which public values of various data from various materials are shown. The use of these common values is a factor in the different properties of paving materials and a factor that influences the obtaining of many exposure values prepared in the laboratory or artificially sample. This is the most inaccurate method because it does not take into account the condition of the material on the site.

Table 3 Velocity and permittivity through different materials (Cao et al., 2007)

Material	Dielectric constant	Propagation velocity(m/ns)
Air	1	0.30
Frozen soil	4	0.15
Granite	9	0.1
Limestone	6	0.12
Sandstone	4	0.15
Dry sand	4-6	0.12-0.15
Wet clay	33	0.052
Asphalt	3-6	0.12-0.17
Concrete	9-12	0.087-0.1
Water	81	0.033

There is another way to determine the dielectric constant from GPR raw data which can offer a more accurate result.

The signal velocity (Time interval)
The permittivity can be estimated using the velocity of the GPR signal passing through the material. The GPR signal velocity through the substances is related to its permittivity by the relation:

$$v = \frac{c}{\sqrt{\mu_r \mathcal{E}_r}}$$

where v is the GPR signal velocity that passes through the substances, c is the light velocity in free space approximately 300,000 km/s and µr is the relative magnetic value.

From Amplitude
The dielectric constant can be calculated from the amplitude of the signal and is based on comparing reflection amplitudes of the surface of an asphalt layer and the surface of a metal slab, the metal slab took as 100% reflectance, e.g., a steel or copper slab. The dielectric constant of the asphalt slab can be calculated by the equation:

$$\varepsilon_a = \left(\frac{1 + \frac{A_1}{A_m}}{1 - \frac{A_1}{A_m}} \right)^2$$

Where ε_a is the dielectric constant of the asphalt layer, $A_1$is the amplitude of the reflection from the asphalt layer, A_m is the amplitude of the reflection from the metal plate surface which is considered to be perfectly reflective. This can present an accurate dielectric constant result. However, only the top layers of the road surface are investigated and when there are different layers of different ages or compositions, this can lead to errors. Furthermore, this method is only applicable to air-penetrating radar, because with ground-penetrating antennas it is difficult to distinguish between reflected surface waves and direct waves. This is because, during operation, the ground penetrating antenna is touching the ground or a short distance from the ground, while the air penetrating radar has its antenna half a meter above the ground as shown in Figure 10.

a) Air-penetrating radar (Allied-associates.com)

b) Ground-penetrating radar (Severnpartnership.com)

Figure 10 Pictures of air-penetrating and ground penetrating radar

Thickness of the layer

To determine thickness by GPR, the signal velocity through the substances is required to convert the two-way times recorded by the GPR system into depth values by the following equation (Zhang et al., 2016):

$$h = \frac{ct}{2\sqrt{\varepsilon_r}}$$

where c is the velocity of the EM wave through the vacuum (3×10^8 m/s), t is the travel time of the transmitted pulse within a pavement layer and ε_r the medium's dielectric constant. To determine the dielectric constant from the layer thickness, this equation can be rewritten:

$$\varepsilon_r = \left(\frac{ct}{2h}\right)^2$$

When travel times and depths at interfaces are estimated from the raw GPR data, the signal velocity and subsequently the dielectric constant of substance can be determined. This method can provide an extremely accurate result of the dielectric constant at core sites where the thickness of those cores is measured in the lab. However, errors can occur when the GPR data is taken from a location that is not accurately associated with the corresponding core data.

CMP method

The Common Midpoint (CMP) is a method commonly used for dielectric constant estimation in GPR research. The distance between the transmitting and receiving antennas increases with each step and maintains a common midpoint to obtain different combinations of transmitting waves. The CMP data set includes radar waves reflected from the interface in the surface that can change permittivity, and a series of direct waves emitted both in the air and on the ground. However, this method requires two separate devices for the transmit and receive antennas, which is not commonly used in GPR applications.

3.3.6.3 Density model

From the dielectric constant measured by one method in the previous section. The density model can be developed. The model of density estimation is based on the theory of EM theory. According to this theory, the dielectric constant of the asphalt mixture is a function of the dielectric properties and volume of the components which are air, binder, and aggregate. This function provides a direct physical relationship between the dielectric constant of the asphalt mixture and its density. Al Qadi et al. (2010) developed two density models from two EM mixing models. Namely, the complex refractive index model (CRIM) and the Bottcher model, respectively.

$$G_{MB} = \frac{\sqrt{\varepsilon_M} - 1}{\left(\frac{p_b}{G_b}\right)\sqrt{\varepsilon_b} + \left(\frac{1 - P_b}{G_{se}}\right)\sqrt{\varepsilon_s} - \left(\frac{1}{Gmm}\right)}$$

$$G_{mb} = \frac{\left(\frac{\varepsilon_M - \varepsilon_b}{3 * \varepsilon_M}\right) - \left(\frac{1 - \varepsilon_b}{1 + 2\varepsilon_M}\right)}{\left(\frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s + 2\varepsilon_M}\right)\left(\frac{1 - P_b}{G_{se}}\right) - \left(\frac{1 - \varepsilon_b}{1 + 2\varepsilon_M}\right)\left(\frac{1}{G_{mm}}\right)}$$

Where:

G_{mb} : is the Bulk specific gravity

G_{mm} : is the maximum specific gravity

G_{se} : is the effective specific gravity of the aggregate

P_b : is the binder content %

G_b : is the specific gravity of binder

ε_s : is dielectric constant of aggregate

ε_b : is dielectric constant of binder

ε_M : is dielectric constant of asphalt mixture

Note that in these equations, the specific gravity of a material is equal to the density of the material divided by the density of water at 4 °C (1 g/cm^3), So it is numerically equal to the density of the substance in g/cm^3. In the same study, the Al-Qadi Lahouar Leng (ALL) model is developed to estimate the bulk specific gravity of the asphalt mixture based on its dielectric constant.

$$G_{mb} = \frac{\left(\frac{\varepsilon_M - \varepsilon_b}{3\varepsilon_M - 2.3\varepsilon_b} - \frac{1 - \varepsilon_b}{1 - 2.3\varepsilon_b + 2\varepsilon_M}\right)}{\left(\frac{\varepsilon_s - \varepsilon_b}{\varepsilon_s - 2.3\varepsilon_b + 2\varepsilon_M}\right)\left(\frac{1 - P_b}{G_{se}}\right) - \left(\frac{1 - \varepsilon_b}{1 - 2.3\varepsilon_b + 2\varepsilon_M}\right)\left(\frac{1}{G_{mm}}\right)}$$

All the parameters in those two models and the ALL model can be obtained directly during or after asphalt construction, except for the dielectric constant of aggregate (ε_s) which can be obtained from back-calculation of core data. The values for the parameters P_b, G_{se} and G_{mm}, can be obtained in the mixture designs and the values for parameters G_b,and ε_b are generally constant around 1.015 and 3, respectively. The values of ε_s depends on the type and source of the aggregation.

In the previous sections, the fundamental theory of GPR and the density model were illustrated. The next section discusses the limitation of GPR.

3.3.6.4 GPR Limitation

The transmission of GPR signal pulses is ruled by the physical laws of electromagnetic waves through the surfaces. The use of GPR data is the basis for recording the reflections of electromagnetic waves emitted from road structures. Different types of electromagnetic waves have different frequency characteristics. Both the velocity and frequency of the wave determine the wavelength, and the wavelength of the material has a significant influence on both the resolution (or precision), which can determine the depth and depth of penetration of an electromagnetic wave signal (Evans et al., 2007). While this phenomenon improves the resolution of high-frequency signals, the penetration is lower than that of low-frequency signals, which are considered a physical limitation of GPR technology and must be considered when planning GPR acquisition methods. Certain paving and flooring conditions can affect the quality of the retrieved GPR data, such as high moisture materials, high conductivity materials, and pavement reinforcement to obscure deep features. Therefore, the presence of such features on the road surface may limit the information that can be obtained. The existence of these situations is to be expected, and even when recognized from survey results, GPR helps to collect data from road surface surveys. The nature of the road surface is another factor that can influence the effectiveness of GPR. For example, signal reflections at collapsed material boundaries are sometimes difficult to determine accurately with pseudo-GPR segments, leading to uncertainty in defining clear boundaries between substances. However, this problem is not limited to the core data of the GPR data, and other intrusion data is also affected by uncertainty in determining the depth of the collapsed material. In general, since materials have a range of permittivity values, it is not necessarily limited that the permittivity between different materials is always obvious, and the result of low reflection coefficient sometimes means that material boundaries are difficult to resolve.

3.4 Conclusion on the literature review

The literature review aimed to define the gaps and problems for measuring the density of the asphalt pavement and to answer the questions for the first research phase.

- ❖ What are the main challenges of measuring the density of asphalt pavements and why?
- ❖ What different methods have been used to measure pavement density?
    - What are the commonly applied density measuring methods, and what are the theories behind them?
    - How efficient are these methods for measuring pavement density?
    - What are the parameters/factors/criteria involved in those currently available density measurement methods?

The literature review verified that density is the most important characteristic for the life cycle of the road. Moreover, the challenges researchers faced when measuring asphalt density were identified. These challenges can be in terms of cost, safety and accuracy. Furthermore, various methods of measuring density were determined with the aim of defining the problem and gaps associated with each method. For this purpose, their principle of density measurement, their advantages and disadvantages have been demonstrated. To illustrate this, a comparison is made between the methods shown in Table 4. The methods are compared based on their usability, their ability to obtain accurate results, safety to use, time efficiency and ability to provide high coverage measurement. As the table illustrates, the only method that is considered to be not safe is the nuclear gauge method. In addition, the table illustrates that the only method that is time-saving, provides accurate results and can provide a high coverage measurement of the tested area is GPR.

Table 4 Available methods for measuring density and its advantage and disadvantage

Method name	Practical	Accurate result	Safe	Time efficient	High-coverage measurement?
Cor method	√	√	√	Low	Not feasible
Nuclear density gauge	√	√		Low	Not feasible
Non-nuclear density gauge	√	√	√	Middle	Not feasible
Ground penetrating radar		√	√	High	Yes
Ultrasonic method			√	middle	Not feasible
Intelligent compaction			√	High	Yes

The other aim of the literature review was to gain knowledge about how the GPR predicted the volumetric characteristics of pavement. Thus, the following questions had to be answered.

- ❖ What are the theories behind the application of GPR for measuring different asphalt volume characteristics, and how can it be converted in asphalt density measurement?
    - What are the fundamental theories of GPR methods?

- How can the GPR method be compatible with the context of asphalt pavement density measurement, and what are the parameters to be measured?
- What is the limitation of measuring density by GPR?

The basic principle of using GPR for subsurface research, including density, is based on the dielectric constant the material has. Each material has a different dielectric constant. There are several ways in which the dielectric constant can be estimated. One way is to take the dielectric constant from the research done earlier. However, this method produces the most inaccurate results because it does not take into account the conditions of the test on which this method is based. Other methods have been used which could offer a more accurate result. However, these methods do not apply to all types of GPR. Because the ground-penetrating antenna is used in this study, the only method that can be used is to determine the dielectric constant from the thickness of the layer, because other methods for measuring dielectric constant are only applicable for air-penetrating radar. Although GPR has a potential advantage for measuring density, it has some limitations when measuring it. For example, the quality of the retrieved GPR data can be affected by pavement and floor conditions, such as high humidity, high conductivity materials, and pavement reinforcement to obscure deep features. Additionally, the GPR signal can be affected by the nature of the pavement surface. For example, signal reflections at collapsed material boundaries are difficult to determine accurately, which leads to uncertainty in defining clear boundaries between substances.

4 Strategies for data acquisition and analysis

Based on the knowledge of the literature review the second phase can be performed. In this phase, the data from the GPR surveys are first collected. Consequently, the nuclear density gauge tests are performed to estimate the density from the same location of the GPR survey. The cores tests are then performed to extract cores for calibration and validation of GPR results. After the GPR data is collected, the GPR data is analysed for compatible GPR data with density measurements.

4.1 Data acquisition

To achieve the objectives of this research, three types of data need to be collected. The first GPR data is collected on the site test. This is done by performing a GPR survey. Subsequently, the nuclear density gauge data is collected by conducting nuclear tests at the same location of the GPR study. Finally, the data from the cores are collected by extracting the core from the same location from which the GPR survey and nuclear test were conducted.

4.1.1 GPR data

GPR data is collected by the InfraRadar 141 provided by the University of Twente, which can be seen in Figure 11 a. The GPR tests were performed on a site section at Roelofs, as shown in Figure 11 b. This section is mainly used by Roelofs to perform various types of asphalt tests. This section is considered a suitable test site as this section is only built for performing asphalt tests. Therefore, during the test measurement, traffic will not be hindered, which will be the case if the measurements are performed on roads with traffic. In this road section, a section with a length of 15 m and a width of 5 m was taken to carry out the GPR investigation. This section was chosen because this section is quite flat, which grant for more accurate result for the GPR survey. Also opting for a short section will provide a more accurate calibration result with not many cores and nuclear testing. Long sections require more cores to be extracted and more nuclear testing to be performed, which is time-consuming and costly. In this section, two straight lines were marked with chalk to ensure a smooth measurement along the route. The lines were chosen to be close to the edge of the section because the middle of the road is damaged, which can affect the accuracy of the GPR signal. The GPR surveys are conducted at both lanes so that it is half a meter from the road edge and extends to 15 meters. For each line, three GPR surveys were performed for each GPR mode in both directions for sensitive analysis. In the GPR device, various modifications can be used for data collection, clay, dry soil, limestone, etc. Three modes were used for this study. Mainly concrete, granite and limestone. These modes were chosen based on the similar nature of these materials to the asphalt, the different permittivity they have and the fact that the asphalt mode does not exist in this GPR device. All GPR testing is performed on a dry surface to obtain the accurate data needed for analysis and to reduce the influence of moisture on the GPR signals. The test section consists of only one asphalt layer which consists of coarse aggregate with the binder. The density is therefore only measured for one layer of asphalt. This is different from the multi-layer highways in the Netherlands. With an uniform walking speed, the GPR investigations were carried out on both lanes.

a) InfraRadar 141 b) Site test

Figure 11 Pictures of GPR device and site section

4.1.2 Core extraction and nuclear gauge measurement

Before the core is removed from the road surface, the NDG measurements must be performed. A total of twelve cores will be extracted from the path on which the GPR was performed. Thus, a total of twelve points must be marked for cores extraction and nuclear gauge measurements. To illustrate this, a schematic has been made as shown in Figure 12. The nuclear test and core measurement will be performed on both parts of the road section, each with six locations. The distance between two on the same path is 3 m. This distance is considered to be appropriate because within this distance only 6 cores need to be extracted from each path and along the entire path. The nuclear measurements are performed to estimate the density of each measurement point. This density will be used to calibrate the density obtained from GPR and cores. After the nuclear measurements are completed, the core on both sides of the section is extracted to measure the thickness and other asphalt characteristics in the laboratory. This is necessary for the calibration and validation of the GPR results.

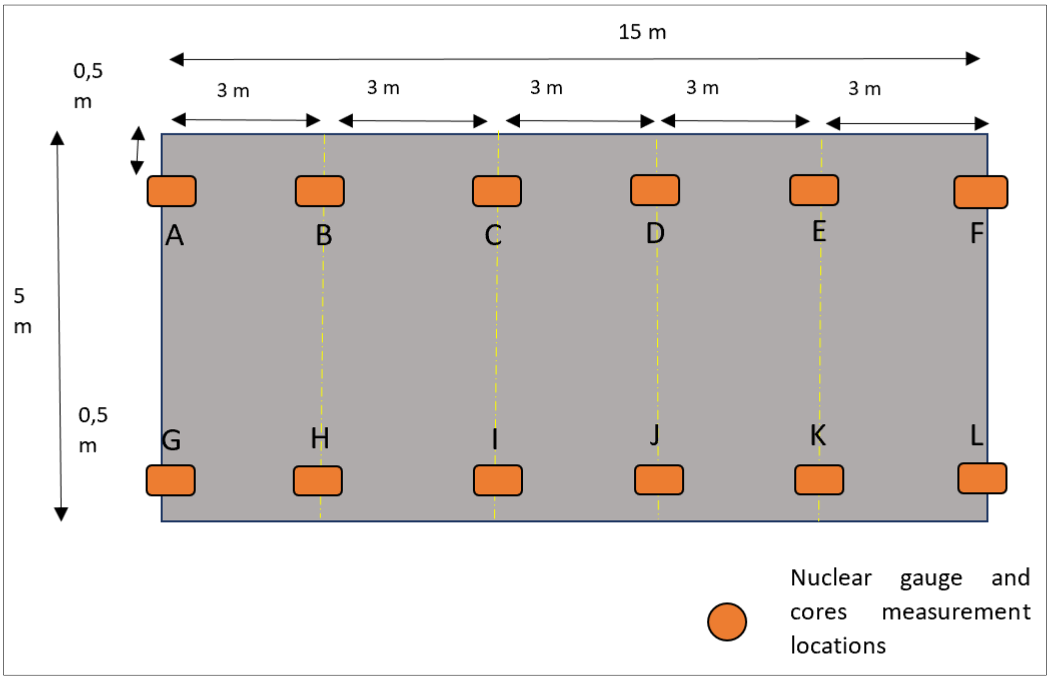


Figure 12 Schematic representation of cross-section for asphalt layer

4.2 Analysing the raw data

As mentioned before, density cannot be taken directly from the raw GPR data and this data must go through several processes to derive its density. The raw GPR data contains various original information and the desired information that can be extracted by analysing. Analysis of the GPR data can be done through GPR software's. In this study, the special software REFLEXW 2D was used. REFLEXW 2D is a software that enables easy import, display process and interprets 2D ground-penetrating radar zero offset and seismic single-shot data. The GPR raw data can be seen as radargram's image in this software and its quality can be enhanced by applying specific filters to exclude noise, signal resonances and highlight relevant interfaces. This software was used to process and analyse data according to the following filter order.

1. Time-zero correction – cutting off the direct waves by removing the layer of air between the antenna and asphalt surface. For this, filter static correction with move time has been used to remove all data in front of the time zero.
2. Bandpass frequency filter - Composite low-pass and high-pass filters with a lower limit of 500 MHz and an upper limit of 1000 MHz is used to remove low- and high-frequency components from signals outside the effective operating frequency range of the antenna. Figure 13 demonstrates GPR raw data, a) without applying any filters and b) with applying those filters.

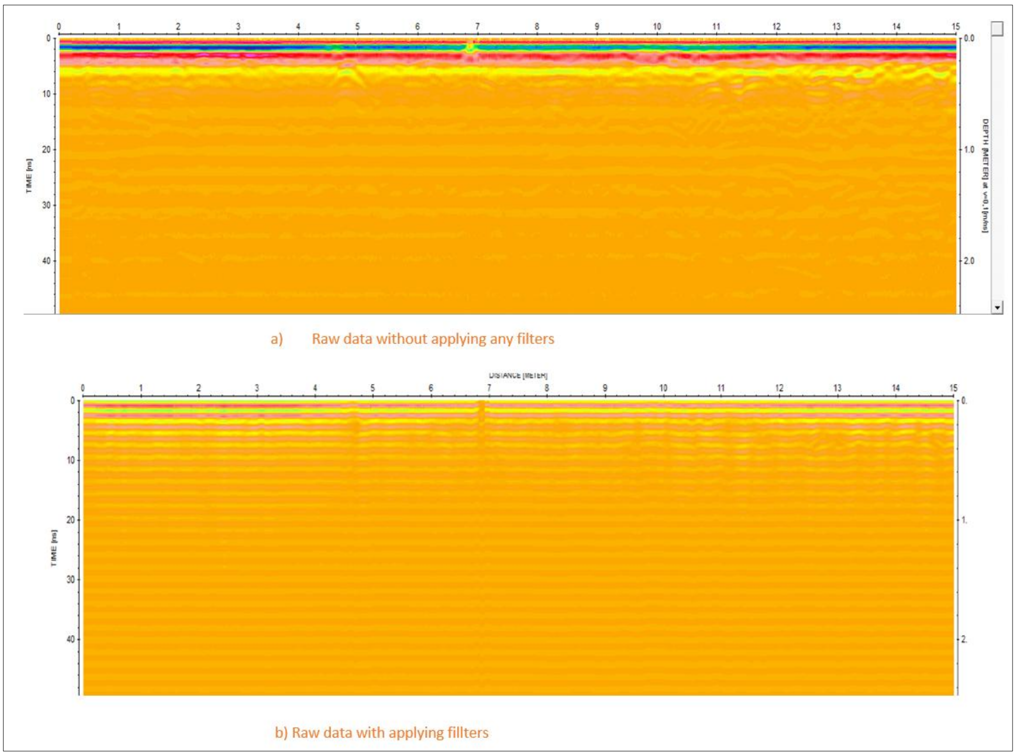
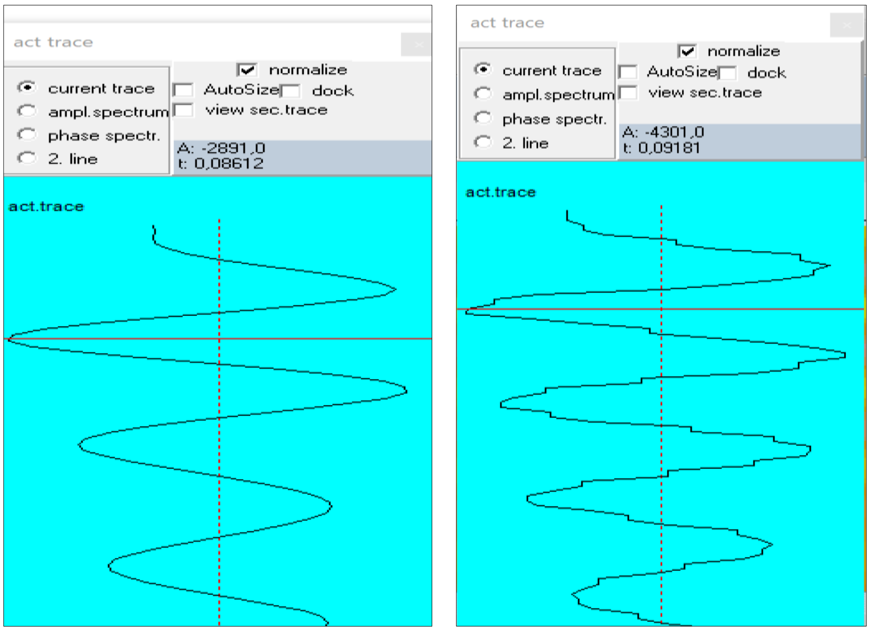


Figure 13 Influence of applying a filter on GPR data

3. Time depth conversion – to convert the time data into depth. To use this, the signal propagation velocity in the medium has to be known. The velocity analysis of asphalt mixtures is complex because the velocity of the signal is influenced by many factors such as moisture, damping, etc. The velocity through the layer, therefore, differs per location and layer. It is assumed that the asphalt layer is homogeneous so that the velocity is constant over the entire route. This assumption is made based on the complexity of analysing the velocity through inhomogeneous substances. Also because constant velocity is easily handled in the REFLEXW program. Assuming the constant velocity can lead to inaccurate results of layer density because the velocity is involved in layer thickness measurement, which in turn is involved in density analysis. In order to estimate this influence, a sensitivity analysis was made in which different signal speeds were chosen each time, see Appendix B. This is done by increasing the speed by 0.03% each time. The results indicate that for some speeds the signal trace is not smooth, which means that estimating the dielectric constant at this signal speed will lead to inaccurate result. To mitigate this influence, the speed that present the smoothest signal track is chosen.

   Because three modes are used for the collection of GPR data, the velocity through each of these modes will be used with the corresponding raw data. The velocity is chosen from Table 3. In that table, the velocity through some mediums is not constant. For example, for concrete, the propagation velocity ranged from 0.087-0.1 (m/ns). To select the correct velocity from this range, a sensitivity analysis is made as mentioned earlier. Then velocity has chosen which presents a smooth signal track. This is because, with non-smooth signal traces, the reflection at the top and bottom of the layer is difficult to follow. Simple tracking of signal reflection at the top and bottom of the layer will help determine the layer thickness. The wiggle window function is used for this purpose. The result indicates that once the velocity reaches 0.09 m/ns, the trace of the signal is no longer smooth, as shown in Figure 14. Consequently, the velocity should be selected within the range of 0,087-0,089 m/ns. Any velocity within this range will fulfil the need for further analysis. Therefore, a velocity of 0.089 is chosen for the time-depth conversion process for concrete mode. For the granite and limestone modes, propagation signal velocity is constant through these modes and thus this velocity can be used in the time-depth conversion process. The results and the processes of time-depth conversion are illustrated in more detail in Appendix A and B.



a) Signal traces using velocity of 0,087 m/ns   b) Signal traces using velocity of 0,09

Figure 14 Act traces

GPR data analysis was performed to determine the permittivity and thickness of the asphalt layer. Because the asphalt in the site test consists of one layer, the analysis is only performed for one layer. The thickness of asphalt layers was determined using the time-depth conversion filters as shown in Figure 15.

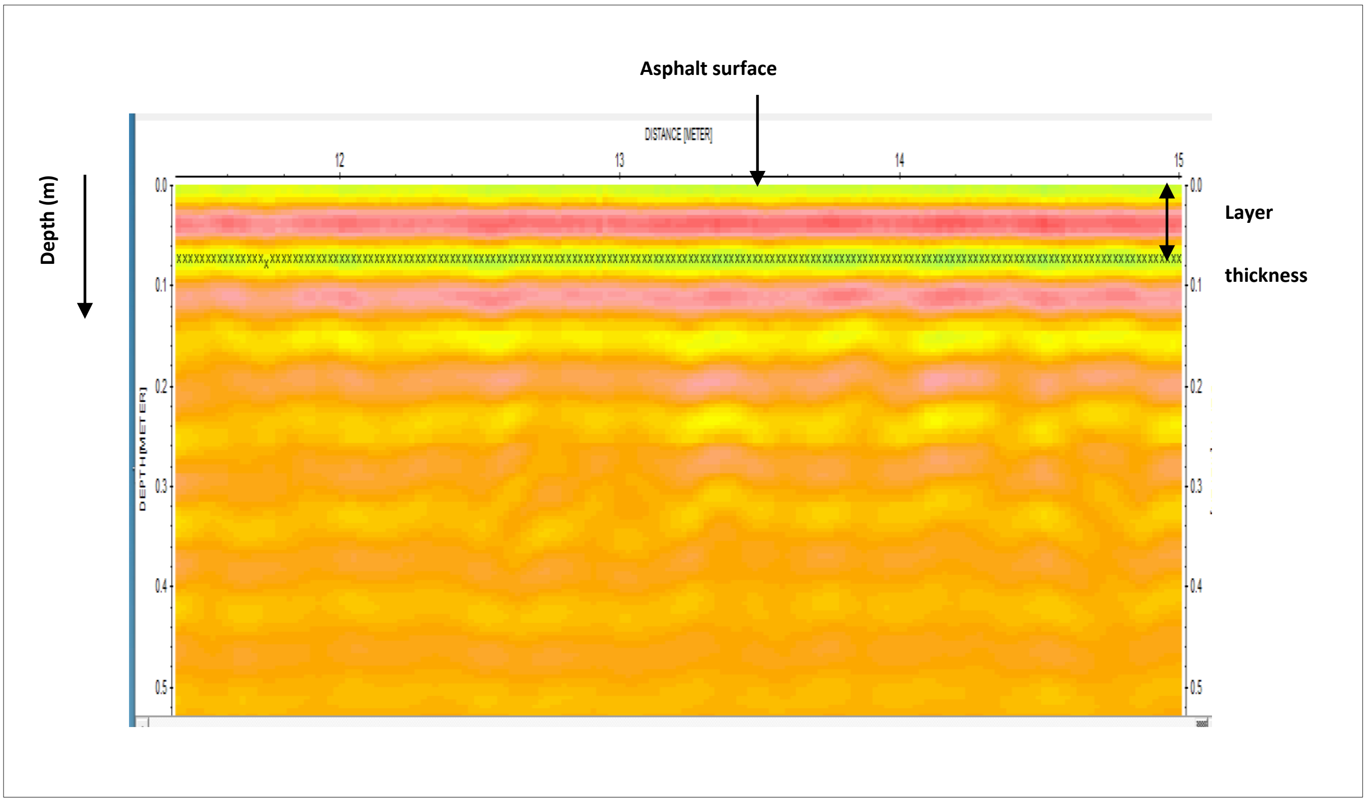


Figure 15 Layer Thickness

The thickness of the layer at different points was estimated with aid of amplitude using the function wiggle window as shown in Figure 16 where the red line indicates the signal reflected from the bottom of the asphalt layer.

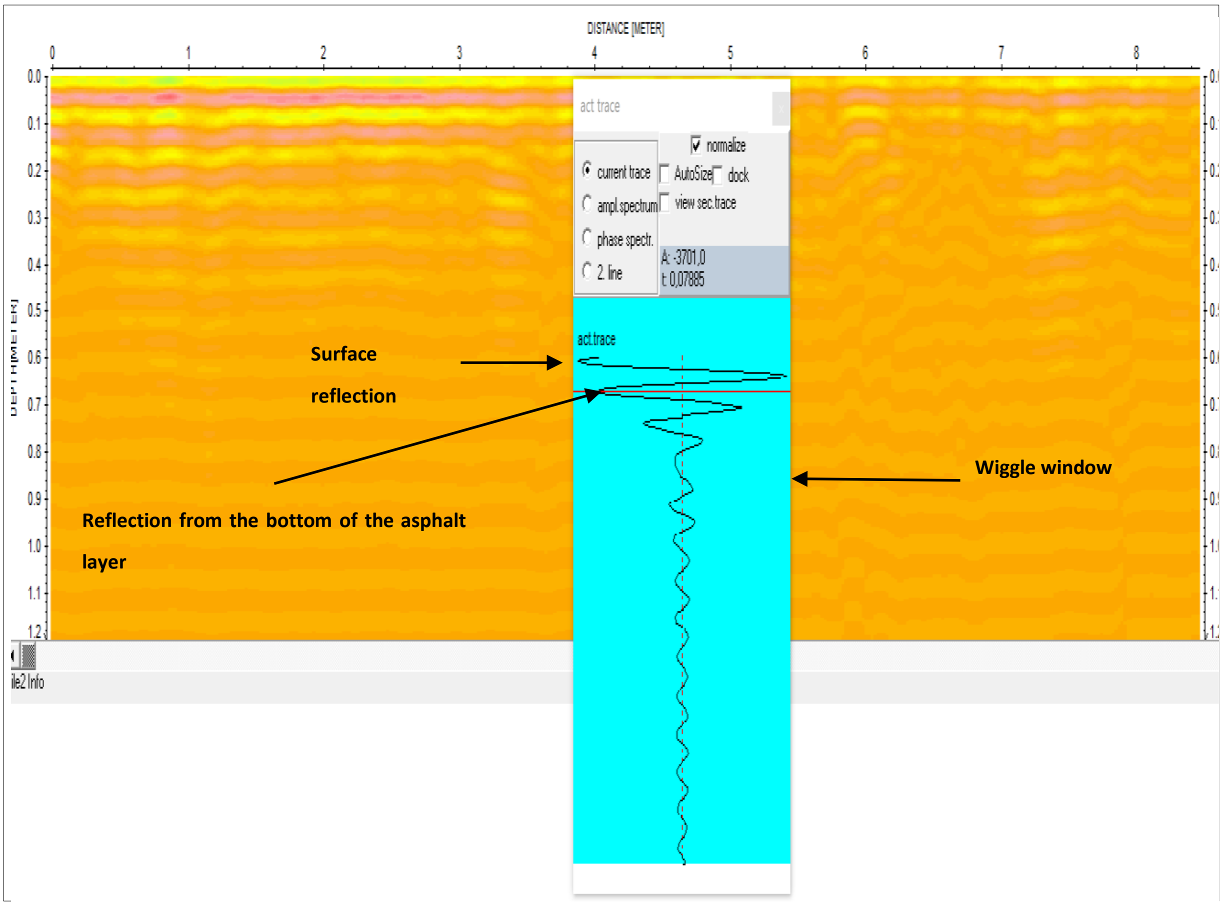


Figure 16 Wiggle window

4.3 Conclusion on Strategies for data collection and analysis

The second phase of this research was dealing of the collection and analysing of the GPR data. In this phase, two main questions needed to be answered:

- What is the on-site density measuring scheme using GPR?
- How are the raw data analysed and programmed? What software is used?

The first question was about collecting the GPR data for density measurement. This question was answered by selecting a road section with length 15m and width 5m at Roelofs. The GPR data was then collected from this section using ground radar. The required cores were obtained at the same location, as was the nuclear measurements. The second question is about choosing the GPR software for analysing the GPR data. This question was answered by some criteria, e.g. the ability to simplify the GPR data, the cost and whether it can be licensed by the University of Twente.

5 Calibration and validation through laboratory testing

This section discusses the third and last phase of this research. In this phase, the results of GPR, nuclear gauge and core are used for calibration and validation of the GPR. First, the lab experiments are performed to measure the thickness and other pavement characteristics required for density analysis. Furthermore, the calibration of the thickness obtained from GPR is done to estimate the accuracy as it is used to measure the density. Finally, the calibration and validation of the density of GPR are done using the density result of the results of nuclear gauges and cores.

5.1 Lab experiment

Various experiments were performed in the lab for calibration and validation. As mentioned earlier, the thickness of the cores is required for the measurement of the dielectric constant, which is essential for the measurement of the density of cores using GPR. Therefore, the actual thickness of the cores was measured to compare it with the thickness obtained from raw GPR data for accuracy. Since the extracted core is not stable in shape, the cores are measured from four sides. The average is then taken as the actual thickness for each core. Moreover, the density of the cores is measured in the lab using the saturated surface dry method (SSD) for further calibration and validation. This method was chosen because it is easy to implement and offers a relatively accurate result for density. The results are shown in Table 5.

Table 5 Extracted core data

Core position	Thickness(cm)	Density of cores($\mathrm{kg/cm^3}$)
A	7,9	2430
B	7	2431
C	6,9	2468
D	7,1	2427
E	6,9	2437
F	6,9	2366
G	7	2394
H	6,3	2374
I	7,9	2417
J	8,7	2415
K	7,8	2422
L	8,5	2416

In addition, some parameters have to be extracted from the cores while the others are constant to measure the density of the EM models. The specific gravity of the aggregate and binder content has been estimated using two cores. The content of the binder is the same over the entire road section. The average of the specific gravity of aggregate is taken from the two cores tested to be the true value for density analysis. The maximum specific gravity is estimated using two more cores. The average is taken as the maximum specific gravity for the whole section. The dielectric constant of aggregate was estimated from the back-calculation in EM models using the density of the core. This parameter depends on the type of mixture and is constant over the entire section. The results are shown in Table 6.

.

Table 6 Density model's parameters

Core	Maximum specific gravity(kg/m^3)	Specific gravity of aggregate (kg/m^3)	Dielectric constant of aggregate	Binder content (%)
A	2482		12,45	
L	2466		12,45	
B		2648	12,45	4,3
K		2653	12,45	4,3

5.2 Accuracy assessment of the measured thickness

Since the dielectric constant is calculated from the measured thickness, it is important to evaluate the accuracy of the thickness. The estimation of the thickness accuracy is performed based on the comparison of the thickness result obtained from the data analysis with the actual thickness obtained from the core. Thickness analysis was done for the three modes and in both directions. The direction that provides the most accurate result with respect to the mode was chosen for comparison between the modes and further analysis. This direction is chosen because then the impact of the building and other surrounding objects on the GPR signal is minimum. It was found that GPR surveys performed from left to right according to Figure 12 provides more accurate result than when the GPR is performed from right to left for all modes see Appendix C. This difference in result may be due to the impact of attenuation of the GPR signal. In Figure 17, the asphalt layer thickness is determined by the GPR data analysis method using the three modes and compared with the actual thickness obtained from the core. The difference in the estimated results of the analysis of the asphalt layer thickness from the actual thickness is quite small, as the average error varies from 11% and 19 % for concrete and granite modes respectively, while this value is larger for limestone 40%.

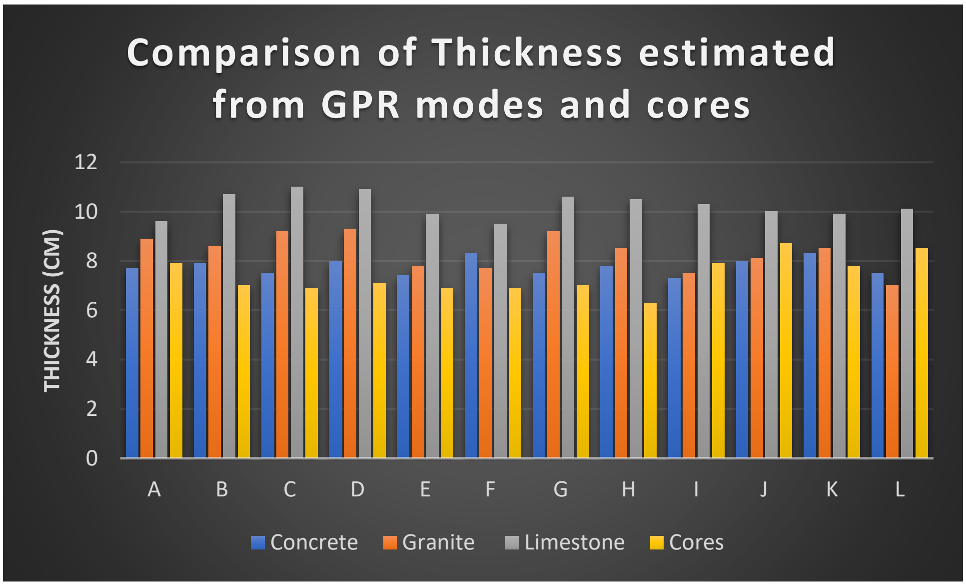


Figure 17 Comparison of thickness between different GPR modes and cores

Furthermore, accuracy assessment is performed from the results of twelve points using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - E_i)^2}{n}}$$

where RMSE is the root mean square error of the estimation result, n is the number of points, O_i is the actual value of the thickness measured from the cores and E_i is the estimation thickness. RMSE is a metric that indicates the average distance between the estimated values of the model and the actual values. The lower the RMSE, the better a given model can fit into a data set. For this model, this value varies by each mode used in GPR. The RMSE for concrete, granite and limestone are 0.85, 1.52, 3 respectively. Thus, RMSE for concrete has the smallest value which means that concrete data can best fit into the actual data as the error is smallest compared to actual thickness.

5.3 Accuracy assessment of estimated density

Because the concrete mode provided the most accurate result for determining the thickness of the cores and because the thickness plays an essential role in measuring the dielectric constant of the asphalt mixture, this mode is assumed to provide the most accurate results for density. To test this, the density results of this model are compared to the other two modes, granite and limestone. The comparison is done based on the actual density from the cores. As expected, of the three modes, the concrete mode performed the best with the smallest error as shown in Figure 18.

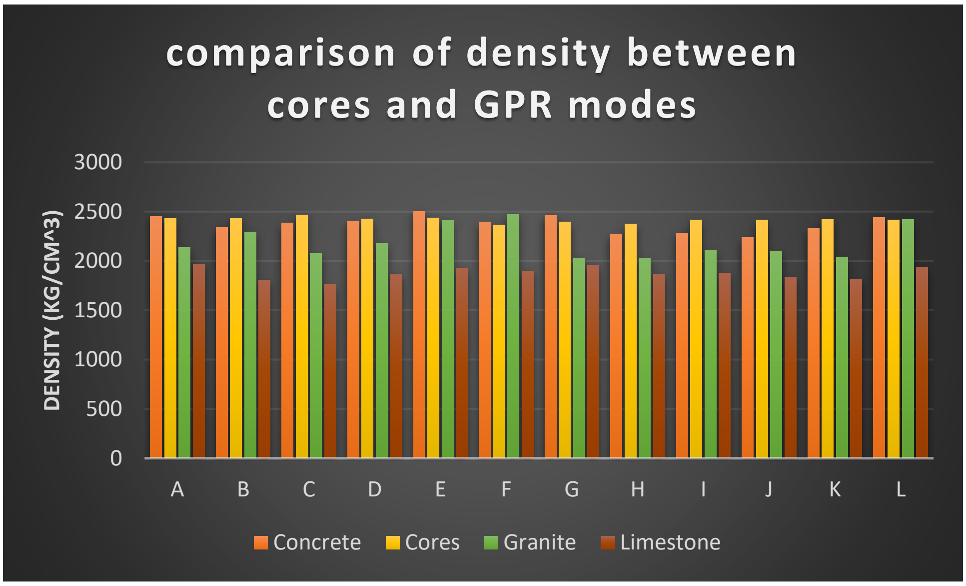


Figure 18 Comparison of density estimated from ALL model using different GPR modes with the core density

Furthermore, the accuracy of the three EM models was assessed using the results of these models and comparing it with the actual density of the core. Among all models, the ALL model was the most accurate model with a mean error of 3.14 %, as shown in Figure 19.

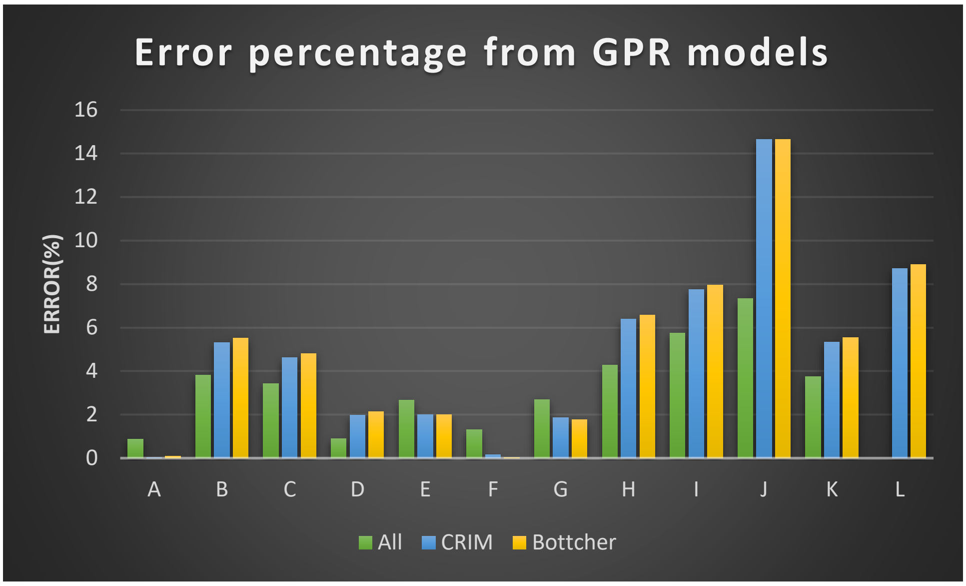


Figure 19 Error resulting from different models based on the density of the cores

The results of the ALL model were compared with those of nuclear and cores, as the aim of this thesis is to investigate the feasibility of GPR as an alternative method to traditional methods for measuring density. Feasibility was assessed based on four factors. Namely the accuracy of the result, the speed with which each method can be performed, continuity and causing distress on the road. Continuity is a situation where density can be measured over the entire section by performing a test only once. Distress on the road can be in the form of disruptive traffic on the road or damage to the road surface. These factors are considered to be the most important factors for the validation of GPR as these factors are the limitation of traditional methods. To illustrate the accuracy, a comparison is made of the result of different methods as shown in Table 7.

Table 7 Comparison of the results

Density of cores	**Density of NDG**	**Error of NDG (%)**	**ALL model**	**Error of All model (%)**
2430	2363	2.75	2451,18	0.87
2431	2361	2.87	2338,429	3.8
2468	2305	6.6	2383,306	3.43
2427	2363	2.63	2405,384	0.89
2437	2330	4.39	2501,797	2.65
2366	2265	4.26	2397,165	1.31
2394	2332	2.58	2458,636	2.69
2374	2241	5.6	2272,215	4.28
2417	2385	1.3	2277,947	5.75
2415	2366	2.02	2237,915	7.33
2422	2334	3.63	2331,008	3.75
2416	2370	1.9	2439,549	0.97
Average error (%)		3.38		3.14

Furthermore, Figure 20 demonstrates the error of both the ALL model and the nuclear gauge relative to the actual density of the core. From this figure, the average error result from the ALL model is quite lower compared to nuclear density as the average error for ALL model and nuclear are 3.3 % and 3.1% respectively. In addition, the accuracy of these two methods is also performed using the root mean square error RMSE. The result reveals smaller RMSE for ALL model than a nuclear test. The RMSE for ALL model and the nuclear gauge are 0.08939 and 0.08968 respectively. This means that the result of the All model is more accurate than the result of the nuclear gauge.

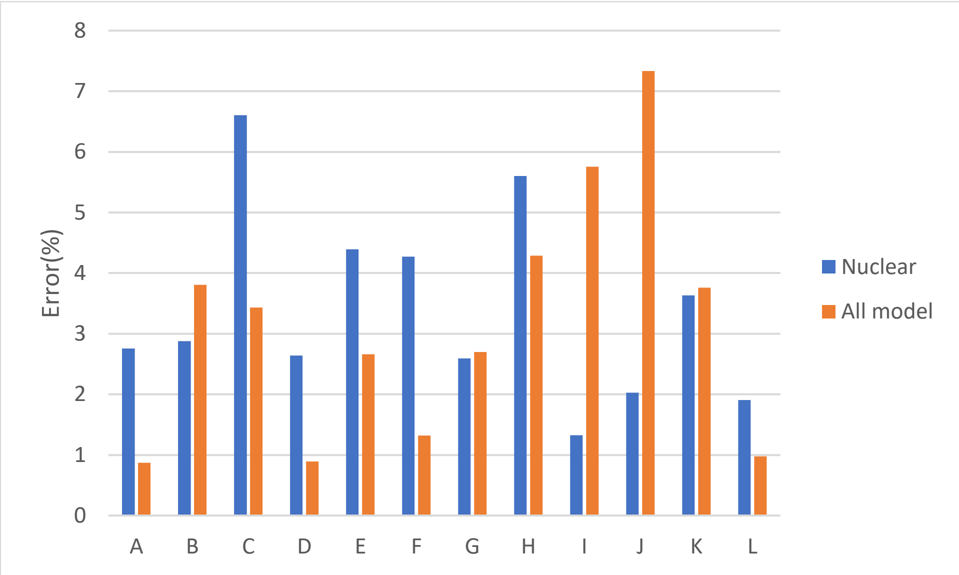


Figure 20 ALL model vs nuclear gauge error

Moreover, the speed of the three methods was evaluated by comparing the time required for each method to test, as shown in Table 8.

Table 8 Time comparison of the methods

Method	Average time required (s)
GPR survey	30
Core extraction (for each core)	300
Nuclear density gauge (for each test)	135

The average time required for each GPR survey was 30 s, while the average time for each nuclear test was 1.5 minutes. However, the density result for nuclear gauge can be obtained directly, while the result of GPR needs to be analysed. The analysis of the GPR data also required some results of the extracted cores, such as density, aggregate specific gravity, etc. as previously explained. These results cannot be obtained directly and the cores must first be analysed in the laboratory. The time it took to analysed the cores varied. In this study, the time was approximately one day to obtain the various parameters required for the GPR analysis. However, the advantage of GPR is that the density at any point along the entire road section can be estimated without having to do GPR surveys over and over. This is not the case for nuclear density gauges, as the tests must be done for each point along the way.

This is especially time-consuming if the section is long, and many points had to be collected. The time it took to extract each core was 5 minutes each. However, the site consists of only one layer of asphalt. More time may therefore be required for the multi-layer asphalt. Furthermore, the density has to be calculated in the laboratory as mentioned in the literature review section, which takes long time to attain the final density result. To investigate whether the three methods cause distress on the road. This is difficult to estimate because the tests were performed in a traffic-free location. In general, however, it can be said that both GPR and nuclear measurement methods will cause little or no distress on the road, while the extraction core method may cause distress on the road in terms of damage and traffic disruption.

5.4 Conclusion on calibration and validation through laboratory testing

The third phase of this research was about the calibration and validation of the GPR data. In this phase, two main questions needed to be answered:

- ❖ How to calibrate the GPR-based density measurement method and nuclear method to conduct the on-site measurement and the comparison?
- ❖ To which extent can the GPR-based method be regarded as the alternative method considering the accuracy, speed, and continuity?

The first question was about how the GPR results were compared with the nuclear measurement results. For this, the mean error and the square root mean error was used to compare the result of these two methods with the result of the cores extracted from the field test. It was observed that the average density error from GPR using the ALL model is quite lower than the density estimated by nuclear density. The average error for GPR and nuclear are 3.1 and 3.4 respectively. The second question concerns the feasibility of the GPR as an alternative method for measuring pavement density. This is the main question for this research. To answer this question, the GPR results were compared with the results of the nuclear density gauge and cores. The comparison was made based on the accuracy of the data, the time it takes to perform each method, and the area in which the density can be calculated non-stop. The comparison verifies that GPR can provide a more accurate result than nuclear gauge readings as shown in Table 7. The time required for GPR was shorter than that required for core extraction tests and nuclear measurements as can be seen from Table 8. Moreover, the GPR could continuously calculate density at all points along the way if the proper GPR software and models are used while this is not possible for the core extraction method and nuclear density method. The latter methods require a test to be performed for each point along the road.

The conclusion of the third phase was discussed in the previous section. The following sections address the conclusion of the report as a whole, reflect on the research questions, discuss the key issue related to this research, and finally provide appropriate recommendations for future research.

6 Conclusion, reflection on the research questions, discussion and recommendation

6.1 Conclusion

The study aimed to evaluate the practical use of GPR-based devices as an alternative method for structural density measurements. The data was collected using a blue GPR system with three modes: concrete, granite and limestone. When evaluating the blue GPR system and assessing its capabilities and limitations, optimal operational parameters were defined for the determination of asphalt density. As part of this task, two techniques were also identified that would improve the quality of the collected data. These include using the thickness of the layer to determine the dielectric constant of the layer that can be used for density measurement. The other uses a software application for the automated processing of the GPR data.

However, the main aim of this study was to develop and validate a systematic density measurement framework using GPR as an alternative method. Due to a lack of time and lack of instruments, this could not be fully realized. Instead, a density model has been developed based on the thickness of the asphalt pavement. A workflow has been developed for this. This workflow has been tested at Roelofs. The scheme of this workflow is shown in Figure (21). This workflow can be summarized as follows. First, the necessary GPR data was collected on the on-site segment with a length of L m and a width of W m using a ground radar. The length and width of the segment should be chosen based on the total length of the road and the number of cores (N) that will be extracted as a wide and long segment will require more cores to be extracted for calibration and validation. Next, the GPR data were analysed with GPR software to estimate the time required for the GPR signal to penetrate the asphalt layer (t) and the layer thickness (h). From the estimated thickness and time, the dielectric constant of the asphalt layer (ε_M) was estimated. The necessary cores (N) were also obtained from this segment. Various parameters necessary for EM models have been extracted from these cores using laboratory tests. These parameters are; the maximum specific gravity (G_{MM}), the effective specific gravity (G_{se}), the binder content (P_b), the bulk specific gravity (G_{mb}) and the dielectric constant of aggregate (ε_s). However, this last parameter cannot be extracted directly from the cores and is calculated back from the EM models.

Based on the estimated dielectric constant and other parameters, the density was predicted using three EM models. Namely CRIM, Bottcher and ALL model. To investigate the performance of this model and three GPR modes, the estimated density was compared with the density of the extracted cores and the density of NDG previously collected from the on-site segment. The results show that all three models were effective in predicting asphalt mix density, although the ALL model performed better. The concrete mode also seems to outperform the other two modes. It has been found that when using the ALL model, the GPR can give a comparable or better result than using a nuclear density meter. For the asphalt mixes, the mean density prediction error of GPR was 3.14% while that of the NDG was 3.38%.

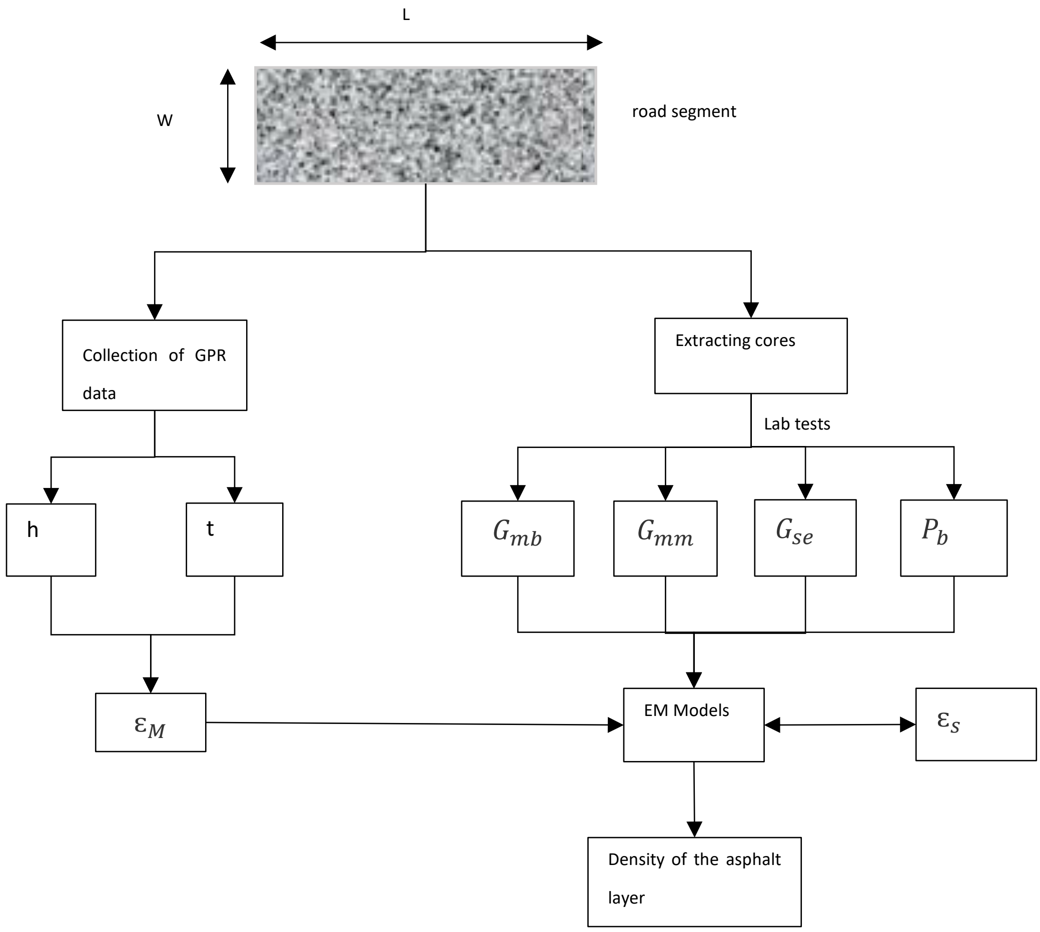


Figure 21 Workflow of the study

6.2 Reflection on the research questions

This research aimed to answer the general question "how and to what extent GPR can replace the traditional method". To this end, the research has been divided into three phases, each phase dealing with sub-questions. The questions in the first phase were answered with the aid of a literature search. In this phase, several methods have been identified with which the density can be measured. However, some of these methods were not fully illustrated due to the lack of knowledge about how this method contributes to the measurement of asphalt volumetric characteristics. For example, it could not be illustrated which parameters or models contribute to density measurement using the ultrasonic pulse velocity (UPV) method due to the lack of studies conducted for this method. Additionally, the fundamental theory of GPR for measuring asphalt volume characteristics, which included EM theory was illustrated in this phase. However, this theory is a broad context and needs more illustration. For example, the effect of resolution and attenuation on the signal could have been illustrated in more detail. This could have been done by using more literature on this theory. The second phase was about collecting and analysing data. In this phase, different approaches and methods for data collection were identified. However, the quality of the results could have been improved if a different approach had been used. For example, GPR with all its modes could have been used to collect GPR data to verify which one performs best. For GPR data analysis, other GPR software could have been used to compare with the chosen one. The last phase was about calibration and validation of the result. At this stage, the question of the feasibility of the GPR has been answered by using the result of this application and comparing it with one of the cores and nuclear measuring equipment.

In general it can be said that the research question has been answered to a certain extent. This is because the research is divided into three phases as above. Each phase has its sub-question in which a different approach is used to answer each. So the questions of the first phase were answered with the help of literature review. The questions of the second phase were answered by selecting a road section of length L and width W at Roelofs. From this section, the required GPR data, nuclear measurements and the required number of cores were obtained. For the analysis of the data, some criteria were used to choose the appropriate GPR software. The final stage is to calibrate and validate the results. Two main questions were answered by using some criteria to compare the GPR results with the nuclear density measurements and core results. However, these results are not sufficient due to many issues, as will be illustrated in the discussion section.

6.3 Discussion

The analyses of the results reveals some shortcomings. For example, the way the thickness is expressed is not very transparent, although it is explained to a certain extent. This is because the analysis of GPR data to derive thicknesses is complex using REFLEXW. The analysis of this software is based more on the visualization of raw data from different layers. The thickness estimation of the pavement layer is done by determining the top and the bottom layer of the radargram's image in REFLEXW. This visualization illustrates large errors at both the top and bottom of the layer. To determine the top of the layer, the GPR signal was analysed where the signal penetrated the road surface. It is virtually impossible to determine exactly where the signal penetrates because the signal first travels through the air before reaching the pavement layer. The bottom of the layer was determined using the signal reflectance from the bottom using the wiggle window function. This feature in the REFLEXW software is sensitive to signal reflection from the surface and bottom of the layer. This causes errors in determining the exact position of the bottom layer. Furthermore, the density was analysed using the dielectric constant of the layer calculated from the thickness of the layer and the travel time of the GPR signal through the layer. Since the thickness estimate has some uncertainty, the density will have some uncertainty as well.

The location of the points in REFLEXW software is believed to correspond to the exact location of the cores according to Figure 12, which may not be the case compared to reality, as there will always be an error on the GPR scale in the horizontal direction. This results in a misjudgement of the location of the cores in the REFLEX radargram image. Different propagation velocity range with the associated material was used in REFLEXW for estimating thickness and time through the asphalt mixture layer. To choose the proper velocity, a sensitivity analysis was used. The sensitivity analysis is accomplished by increasing the signal velocity by 3% each time within REFLEXW to test the influence of different signal velocity on the signal pad. However, if the rate of change had been smaller, such as 1 %, it might have yielded better results. Because more speed is tested within that range. Moreover, only three modes of GPR data collection have been explored using the GPR. Namely, concrete, granite and limestone mode. These modes were assumed to provide a relatively accurate result because the nature of these modes is similar to the asphalt mode and because the GPR used in this study does not have the asphalt mode. Of the three modes chosen, the concrete mode performs best. However, there are several modes in the blue GPR that have not been tested. Thus, it is not known which GPR mode will provide the most accurate result when measuring thickness and density. According to Table 3, the average dielectric constant of asphalt is between 3-6, but in this study, the average dielectric constant of asphalt was 10.3. This large difference may be due to the different types of mixtures in this study compared to the study on which the table is based, which will have a different permittivity.

At Roelofs, a section 15 m long and 5 m wide was selected to conduct GPR research and other tests. This section of route consists of the same type of mixture along the route and consists of only one asphalt layer. For example, the GPR data may differ for a different type of multi-layer asphalt mix and a different type of analysis may be required. Furthermore, in total, only 12 points have been chosen for calibration and validation of the result. This may not be enough, as more points provide more accurate result. The GPR that has been used is the ground penetrating radar and can only be used with the walking speed. This may not be efficient for long stretches of road. In that case, the air-couple radar can be used, as it can be attached to the vehicle and surveyed at quite a high speed, which will cover a large area in a short time.

According to the limitation of GPR in literature search, the quality of the retrieved GPR data can be influenced by pavement and floor conditions, such as high humidity, high conductivity materials and pavement reinforcement to obscure deep features. However, it is difficult to validate this limitation in this study because the GPR was measured on only one layer of the asphalt mix. This layer was dry, so the effect of the moisture was neglected. Furthermore, the penetration depth was not of interest in this study because only the thickness of one layer has to be determined, therefore not much attention was paid to the influence of changing frequency on resolution and penetration of the radar signal. The only issue which is important to reflect on is the difference in the result obtained from GPR when performed in both directions. The effect of the attenuation of the signal could be the reason for this difference as a result of horizontal resolution. In the end, the result of using GPR for density measurement was quite accurate because the accuracy of the result was comparable or better than using the nuclear density measurement method with a mean error of 3.14%. This is acceptable compared to other studies. For example, GPR's mean density prediction errors were between 0.5% and 1.1% (Al-Qadi et al., 2010). However, for the latter study, the air coupler radar was used using the amplitude method by placing a steel plate under the road surface to estimate the dielectric constant of the asphalt instead of using the layer's thickness. According to Table 8, it has been proved that the time required for conducting GPR is less than the time needed for cores and nuclear gauge tests. Additionally, GPR method is believed to cause no distress on the roads.

It should also be noted that density measurement in the context of this research is primarily concerned with on-site measurement. Since the density is measured immediately after paving and compaction is completed, machines may still be on-site and paving projects are being carried out nearby while the density measurement is being performed. Therefore, ground radars are best used due to their portability, size, ease of use and operation as they can be easily pulled over the surface by just one person. In this way the measurement can be carried out without limiting the other activities on-site. This is not the case with air-coupled radars, as they must be attached to a vehicle during density measurement. This causes some distress in the form of restrictions and noise in the work area. In addition, using the thickness layer technique in air-coupled radar can cause large errors in the dielectric constant estimation, as the antenna is about half a meter from the ground and thus the thickness estimation will not be accurate in REFLIXW software. Therefore, ground radar for on-site measurement will be more feasible than air-coupled radar.

Another issue that is important to consider is the current situation of the COVID-19. More accurate results from this study required physical interaction at some stage, which was not possible in this pandemic. For example, the analysis of the raw data could have been improved by applying other means with the help of the members from the University of Twente or from Roelofs who may have more knowledge of the software. Furthermore, the core extraction and nuclear gauge tests were only possible at the end of this study and were performed only once. Consequently, for any uncertainty about the result, it would not have been possible to redo the tests and the sensitive analysis of these tests was not possible.

Based on the above results, this research can contribute to help the construction industry to improve road quality, as this research aimed to determine a non-destructive method with which the density of pavement can be estimated quickly, efficiently, and accurately. This research can be useful for construction companies such as Roelofs, as the use of GPR can reduce the costs of traditional methods. Another reason is that because this technology takes a shorter time than other methods to survey a large area of pavement. However, more research needs to be done on GPR to fully verify its usefulness.

6.4 Recommendation

Future work should focus on improving some of the factors of this study. The first factor is the improvement of the correlation factors between the dielectric constants and the road surface densities. In other words, an effort can be made to determine the accurate dielectric constant of the asphalt mixture from the GPR since the dielectric constant is the most important factor in determining the density of GPR. The influence of frequency or attenuation on the GPR result has not been included in this study. For future research, the effect of different frequencies on the measurement data of GPR can be evaluated. In addition, the analysis of the raw GPR data was made with REFLEXW. The analysis can be done using other GPR analysis software and the result can be compared with REFLEXW. Furthermore, test protocols, such as the number of investigations needed, different locations are chosen, error effect can be improved. In addition, ground radar was used in this study. In the future, the ability of air-coupled radar to measure density can be explored using the same technique. The test site also consists of only one layer of asphalt with only one type of aggregate. For example, the evaluation of different multi-layer asphalt mixtures can be investigated. Finally, the results of the GPR prediction were only compared with the extracted cores and nuclear density gauge. In future studies, the performance of GPR can be evaluated by comparing the result of GPR with, e.g., non-nuclear density measurements.

References

1. AECOM. (2016). *Improving Durability TSCS – Measuring.* Nottingham: AECOM. Retrieved from https://www.aecom.com/uk/wp-content/uploads/2017/09/report_highways-england_task-671.pdf
2. Ali, M. Y., Paul, A., Hossain, M. I., & Akhtar, M. R. Impact of New Road on Rural livelihood in Bangladesh
3. Al-Qadi, I. L. (1992). Using microwave measurements to detect moisture in asphaltic concrete. Journal of testing and evaluation, 20(1), 43-50.
4. Al-Qadi, I. L., Leng, Z., Lahouar, S., & Baek, J. (2010). In-place hot-mix asphalt density estimation using ground-penetrating radar. Transportation research record, 2152(1), 19-27.
5. Basson, A. (2000). *Ground penetrating radar.* Retrieved from GeoSense: https://geo-sense.com/index.php/methods/ground-penetrating-radar-gpr-surveys/ground-penetrating-radar-gpr/
6. Black, K., & Kopac, P. (1992). The application of ground-penetrating radar in highway... Public roads, 56(3), 96-103.
7. Blankenship, P. (2015). Improving Pavement Density. Asphalt, 30(3).
8. Burati Jr, J. L., & Elzoghbi, G. B. (1987). Correlation of nuclear density results with core densities. Transportation Research Record, 1126, 53-67.
9. Cao, Y., Dai, S., Labuz, J., & Pantelis, J. (2007). Implementation of ground penetrating radar.
10. Department of Transport and Main Roads (2021). *Nuclear Gauge Testing Manual.* The State of Queensland. Retrieved from https://www.tmr.qld.gov.au/business-industry/Technical-standards-publications/Nuclear-gauge-testing-manual.aspx.
11. Dong, Z., Ye, S., Gao, Y., Fang, G., Zhang, X., Xue, Z., & Zhang, T. (2016). Rapid detection methods for asphalt pavement thicknesses and defects by a vehicle-mounted ground penetrating radar (GPR) system. Sensors, 16(12), 2067.
12. Dunning, M. R. (2006). Feasibility for the use of non-contact ultrasound for application with asphalt concrete materials. University of Nevada, Las Vegas.
13. Earth engineering. (2021). *Asphalt & concrete coring.* Retrieved from Earth engineering: https://earthengineering.com/geotechnical-investigations/asphalt-concrete-coring/#:~:text=Asphalt%20and%20concrete%20coring%20is%20a%20process%20where,core%20measure%204%20or%206%20inches%20in%20diameter.
14. Evans, R. D., Frost, M., Dixon, N., & Stonecliffe-Jones, M. (2007). Variation in information obtained from interpretation of ground penetrating radar (GPR) pavement investigation data.
15. Evans, R., Frost, M., Stonecliffe-Jones, M., & Dixon, N. (2007). Assessment of in situ dielectric constant of pavement materials. Transportation research record, 2037(1), 128-135.
16. Evans, R. D. (2009). *Optimising ground penetrating radar (GPR) to assess pavements* (Doctoral dissertation, Loughborough University).
17. Galacgac, G. I. (2003). *Evaluation of methods for determining bulk specific gravity of Hma specimens*. University of Nevada, Las Vegas.
18. Group, E. (2013, May 16). The Health Dangers of Beryllium. Retrieved from Global healthing: https://explore.globalhealing.com/health-dangers-beryllium/#:~:text=Beryllium%20is%20extremely%20toxic%20to%20lung%20tissue.%20Prolonged,with%20a%20scary%20similarity%20to%20sarcoidosis.%20%5B%202%5D
19. Leng, Z. (2011). Prediction of in-situ asphalt mixture density using ground penetrating radar: theoretical development and field verification. University of Illinois at Urbana-Champaign.
20. Leng, Z., & Al-Qadi, I. L. (2014). An innovative method for measuring pavement dielectric constant using the extended CMP method with two air coupled GPR systems. NDT & e International, 66, 90-98.

21. Mishra, G. (2021). Types of pavement-Flexible pavements and rigid pavements. Retrieved from The constructor: https://theconstructor.org/transportation/types-of-pavement-flexible-and-rigid-pavement/9570/#google_vignette
22. MSMT. (2012). *Procedures for sampling asphalt mixture/density core and random sampling methods.* Retrieved from Roads: https://www.roads.maryland.gov/OMT/msmt457.pdf
23. Padlo, P. T., Mahoney, J., Aultman-Hall, L., & Zinke, S. (2005). Correlation of nuclear density readings with cores cut from compacted roadways. *Connecticut DOT Report CT-2242-F-05-5*.
24. Porubiaková, A., & Komačka, J. (2015). A comparison of dielectric constants of various asphalts calculated from time intervals and amplitudes. Procedia Engineering, 111, 660-665.
25. Rajput, K. (2019). Difference Between Flexible Pavement and Rigid Pavement | What is Pavement | Types of Pavement. Retrieved from civiljungle: https://civiljungle.com/difference-between-flexible-pavement-rigid-pavement/
26. Roberts, F. L., Kandhal, P. S., Brown, E. R., Lee, D. Y., & Kennedy, T. W. (1991). Hot mix asphalt materials, mixture design and construction.
27. Romero, P. (2002). Evaluation of non-nuclear gauges to measure density of hot-mix asphalt pavements. Pooled Fund Study Final Report, the University of Utah, Department of Civil and Environmental Engineering.
28. Sargand, S. M., Kim, S. S., & Farrington, S. P. (2005). Non-nuclear density gauge comparative study. Draft Final Report. Ohio Research Institute for Transportation and the Environment, 114, 45701-2979.
29. Stephens, J. (1964). Evaluation of nuclear and other device methods for obtaining bituminous paving densities. In 6th Annual Paving Conference.
30. Stroup-Gardiner, M., & Newcomb, D. E. (1988). Statistical evaluation of nuclear density gauges under field conditions. National Research Council, Transportation Research Board.
31. TechTarget. (n.d.). *permittivity (electric permittivity)*. Retrieved from WhatIs: https://whatis.techtarget.com/definition/permittivity-electric-permittivity#:~:text=Permittivity%2C%20also%20called%20electric%20permittivity%2C%20is%20a%20constant,per%20meter%20%28F%2Fm%29%20in%20free%20space%20%28a%20vacuum%29.
32. Tidwell, L. E., Ahlrich, R. C., & Regan, G. L. (1993). Evaluation of surface density nuclear gauges for acceptance testing of asphalt concrete overlays. ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS GEOTECHNICAL LAB.
33. van Horssen, R. A., Jonkers, E. N., Overmars, L., Leendertse, P., Stadhouders, E. P., Hofman, R. R., ... & Kneepkens, T.(2020) Product Category Rules voor bitumineuze materialen in verkeersdragers en waterwerken in Nederland (" PCR Asfalt").
34. Civilworld, V. (2021). Road Pavement Layers – Components and Functions. Retrieved from Vincivilworld: https://vincivilworld.com/2020/12/22/road-pavement-layers-components-functions/
35. Volvo Construction Equipment (2015) "Density Direct – Volvo Intelligent Compaction"
36. Vuye, C., Kara, P., Couscheir, K., Blom, J., & Van Bouwel, P. (2017, September). The use of a non-nuclear density gauge for monitoring the compaction process of asphalt pavement. In IOP Conference Series: Materials Science and Engineering (Vol. 236, No. 1, p. 012014). IOP Publishing.
37. Watson, J. P. (1989). Highway construction and maintenance.
38. Xu, Q., Chang, G. K., Gallivan, V. L., & Horan, R. D. (2012). Influences of intelligent compaction uniformity on pavement performances of hot mix asphalt. Construction and Building Materials, 30, 746-752.
39. Yin, H. M., & Luo, Z. (2009). Investigation of the NDG calibration method. *Road materials and pavement design*, *10*(3), 625-645.

Appendixes

Appendix A

Conversion of time (ns) to depth (m) in GPR data.

Before converting time to depth, the GPR data must follow two processes. The first process is to remove the signal time through the air, as the data analysis only requires time through the layer. This can be done by using filter time-zero correction. This filter in the REFLEXW is known as static correction muting. Many processes can be executed within this filter, each of which has a different function. For the analysis, only the move starttime function is needed, as it cuts the time through the air, as shown in Figure 22. For this, the parameter movement time (ns) must be entered. This parameter should be chosen so that the GPR signal penetrates the surface at zero ns**.**

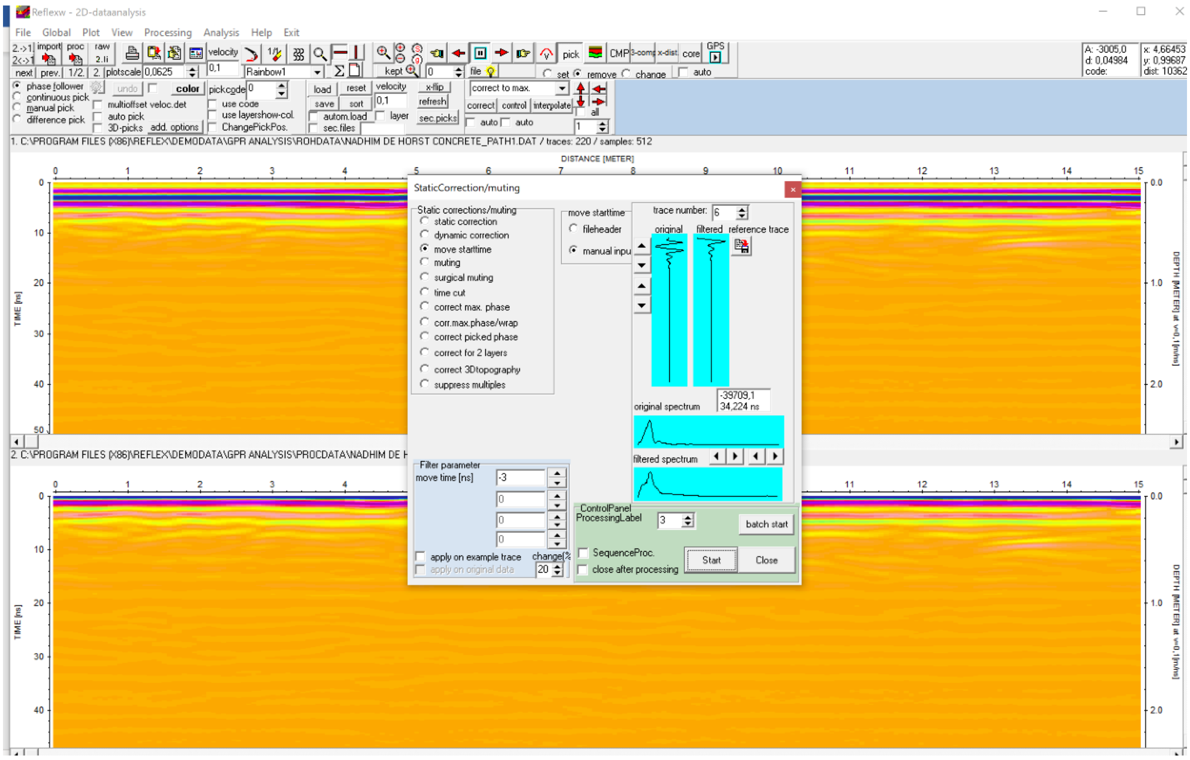


Figure 22 Process of removing GPR signal time through the air

The second process is to remove low and high frequency components from signals outside the effective operating frequency range of the antenna. This can be done using bandpassfrequency filter.

Using this filter, the software only recognizes the signal of frequency 500-1000 MHz as shown in Figure 23.

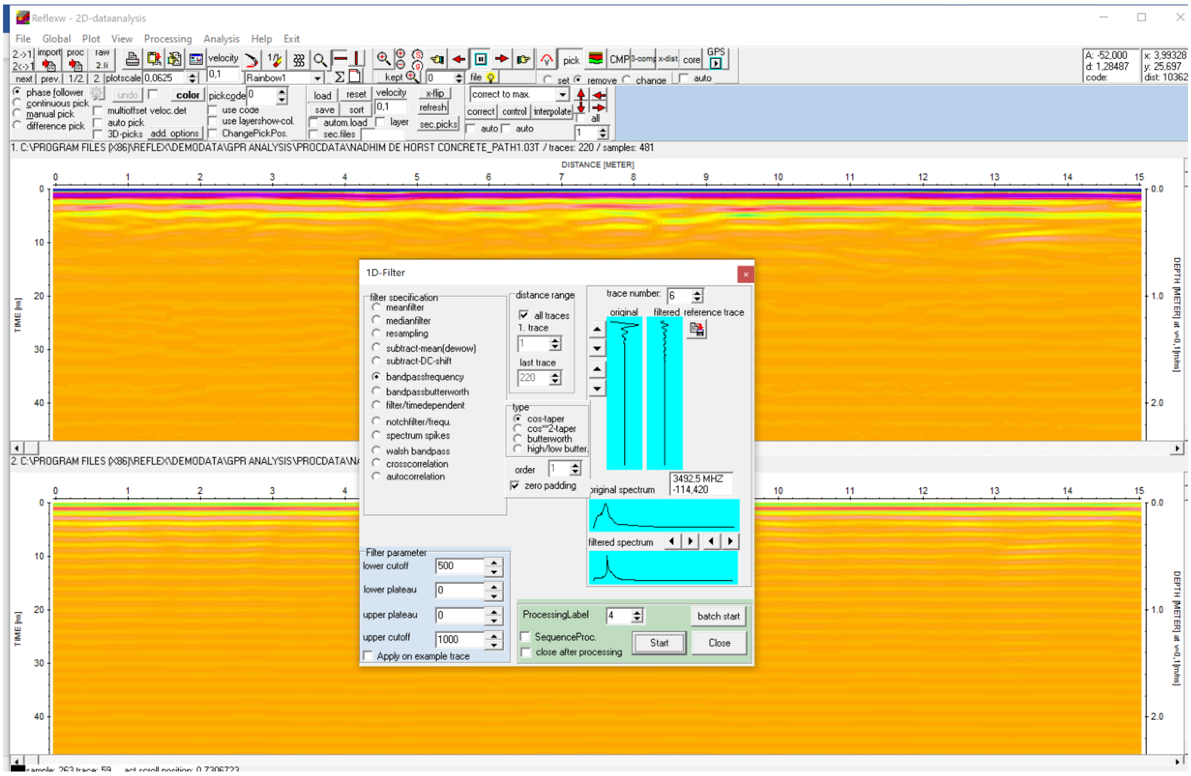


Figure 23 Process of removing noise and unnecessary signal frequency from GPR data

Once the two processes are completed, the time can be converted to depth using the time-depth conversion function as shown in Figure 24. The velocity through the medium is required to perform this function. For a medium that has a constant velocity, this can be done by simply entering this velocity in the velocity cell. However, for a medium that does not have a constant velocity, such as concrete, a sensitivity analysis is required to select the most appropriate velocity, as will be illustrated in Appendix B.

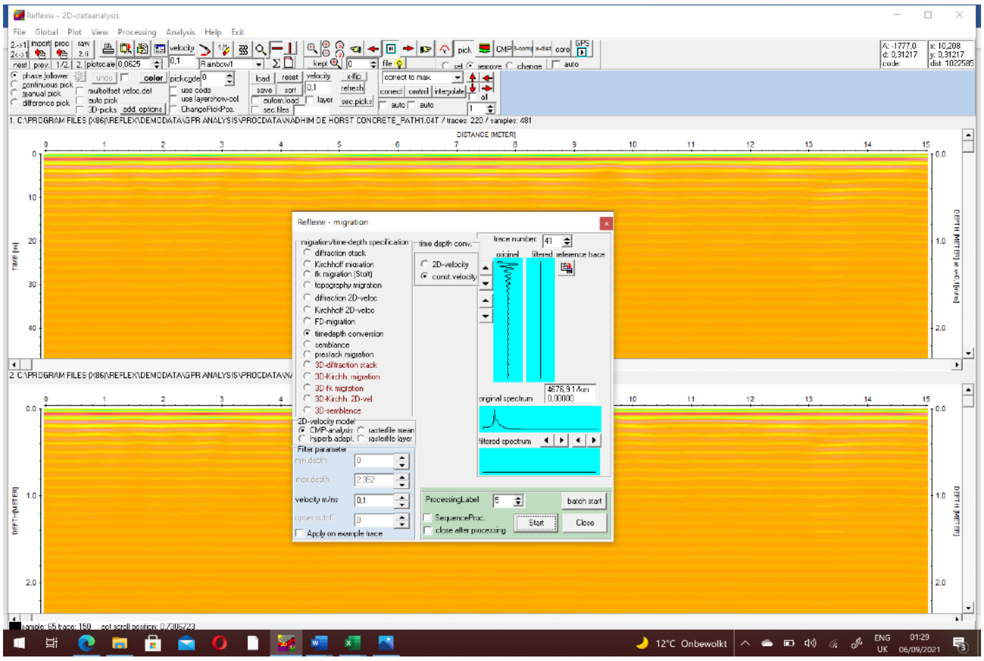
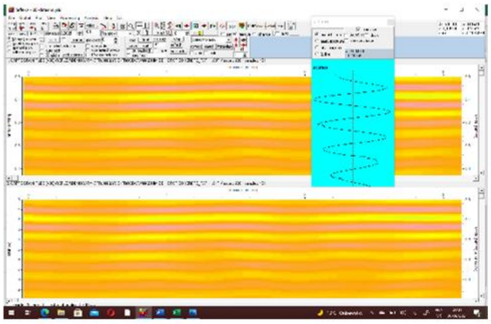


Figure 24 Conversion of time to depth

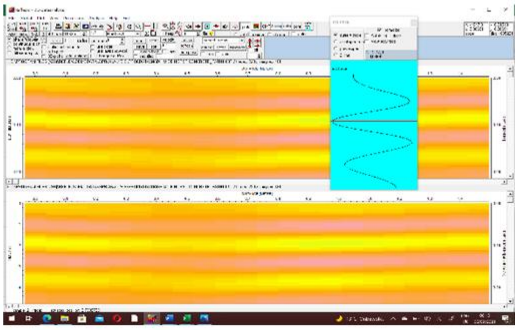
Appendix B

Sensitivity analysis

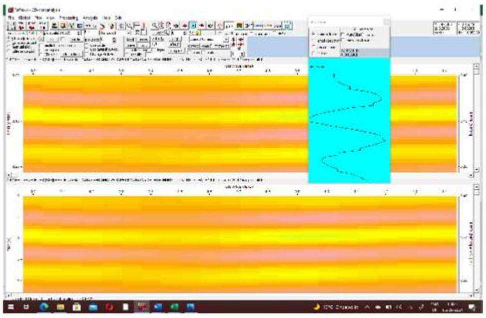
The signal velocity in some media such as concrete is not constant. Therefore, it is difficult to select the precise velocity for time-depth conversion analysis. To select the appropriate velocity in this medium for the GPR data analysis, a sensitivity analysis is performed. This analysis is done based on the effect of increasing velocity through this medium on the GPR data results. To inspect the result of the GPR data, the wiggle window function is used. This function presents the signal traces through the medium. Therefore, the velocity that provides the smoothest traces will be chosen. This is because with smooth signal traces it is easy to follow the signal reflection at the top and bottom of the layer, which is useful for determining the layer thickness. The velocity through concrete varies from 0.087-0.1 m/ns. A 3% velocity increase was chosen for our analysis because this range is small and therefore a small increase rate is needed. Thus, the velocities used for analysis are 0.087, 0.089, 0.092, 0.094, 0.097, 0.1 respectively. These velocities are used in the time-depth conversion filter as illustrated in Appendix A. The result is shown in Figure 25. The results indicate that once the velocity reaches 0.09 m/ns, the signal track is no longer smooth. Thus, the velocity should be chosen within a range of 0.087-0.089. Any velocity within this range satisfies the need for further analysis.



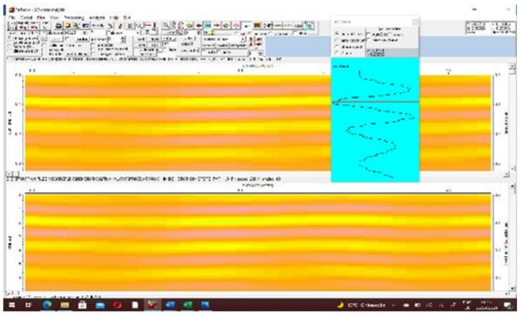
signal velocity of 0.087



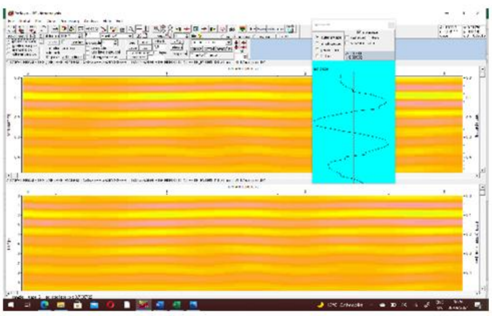
signal velocity of 0.089



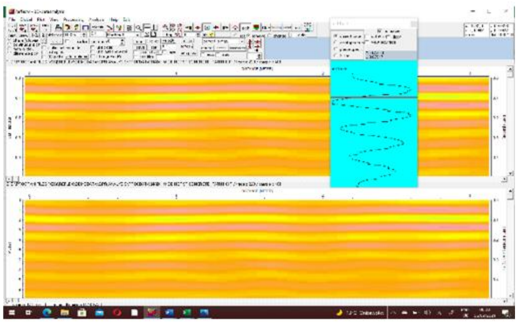
signal velocity of 0.092



signal velocity of 0.094



signal velocity of 0.097



signal velocity of 0.1

Figure 25 Time-depth conversion using different signal velocities

Appendix C

Layer thickness and dielectric constant resulting from different GPR modes and performing GPR in both directions.

The thickness of the layer is estimated from the GPR data after analysis of the GPR data through various filters, as illustrated above. Once the thickness of the layer is known, the dielectric constant can be calculated using the signal time through the asphalt layer. To investigate which mode offers the most accurate result and in which direction GPR should be performed, a comparison is made between the same mode in both directions and between the different modes. The comparison is based on the error resulting in estimating the layer thickness using the chosen mode and direction of the GPR survey compared to the actual thickness obtained from the location section. RMSE is used to make this comparison. The direction or mode with the smallest RMSE value presents the most accurate thickness result compared to the actual thickness. The result reveals that when performing GPR surveys from left to right according to Figure 12, the thickness results are more accurate than when performing from right to left for all modes. The result also reveals that the concrete mode performs the best among the different GPR modes, as shown below.

GPR survey performed on the test site from left to right

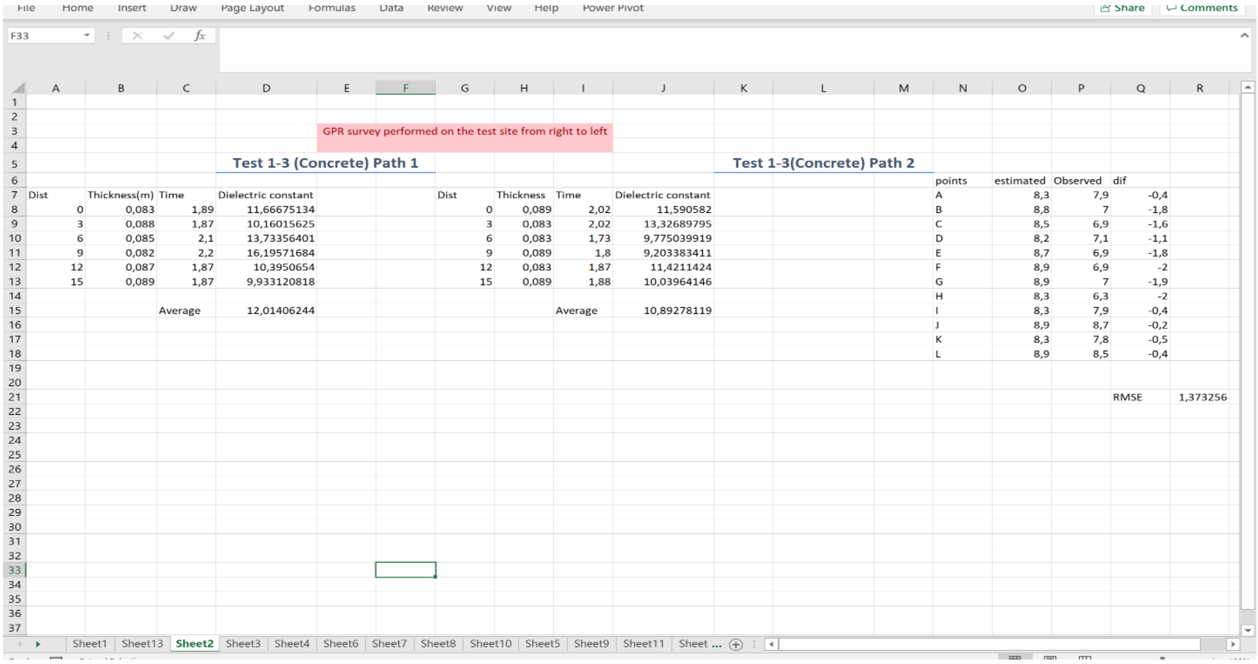
Test 1(concrete), Path 1

Dist	Thickness(m)	Time(ns)	dielectric constant
0	0,077	1,69	10,83863215
3	0,079	1,67	10,05451851
6	0,075	1,61	10,3684
9	0,08	1,73	10,52191406
12	0,074	1,65	11,186313
15	0,083	1,79	10,46483524
		1,89	
		Average	10,57244

Test 1(concrete), Path2

Dist	Thickness	Time(ns)	dielectric constant
0	0,075	1,65	10,89
3	0,078	1,61	9,586168639
6	0,073	1,51	9,626993807
9	0,08	1,63	9,340664063
12	0,083	1,75	10,00235883
15	0,075	1,64	10,7584
		Average	10,03409756

Points	time(ns)	Observed	estimated(cm)	Differnece	error %
A	1,85	7,9	7,7	0,2	2,531646
B	1,89	7	7,9	-0,9	12,85714
C	1,88	6,9	7,5	-0,6	8,695652
D	1,9	7,1	8	-0,9	12,67606
E	1,711	6,9	7,4	-0,5	7,246377
F	1,89	6,9	8,3	-1,4	20,28986
G	1,85	7	7,5	-0,5	7,142857
H	1,71	6,3	7,8	-1,5	23,80952
I	1,7	7,9	7,3	0,6	7,594937
J	1,85	8,7	8	0,7	8,045977
K	1,99	7,8	8,3	-0,5	6,410256
L	1,56	8,5	7,5	1	11,76471
			RMSE	0,857807	



GPR survey performed on the test site from right to left

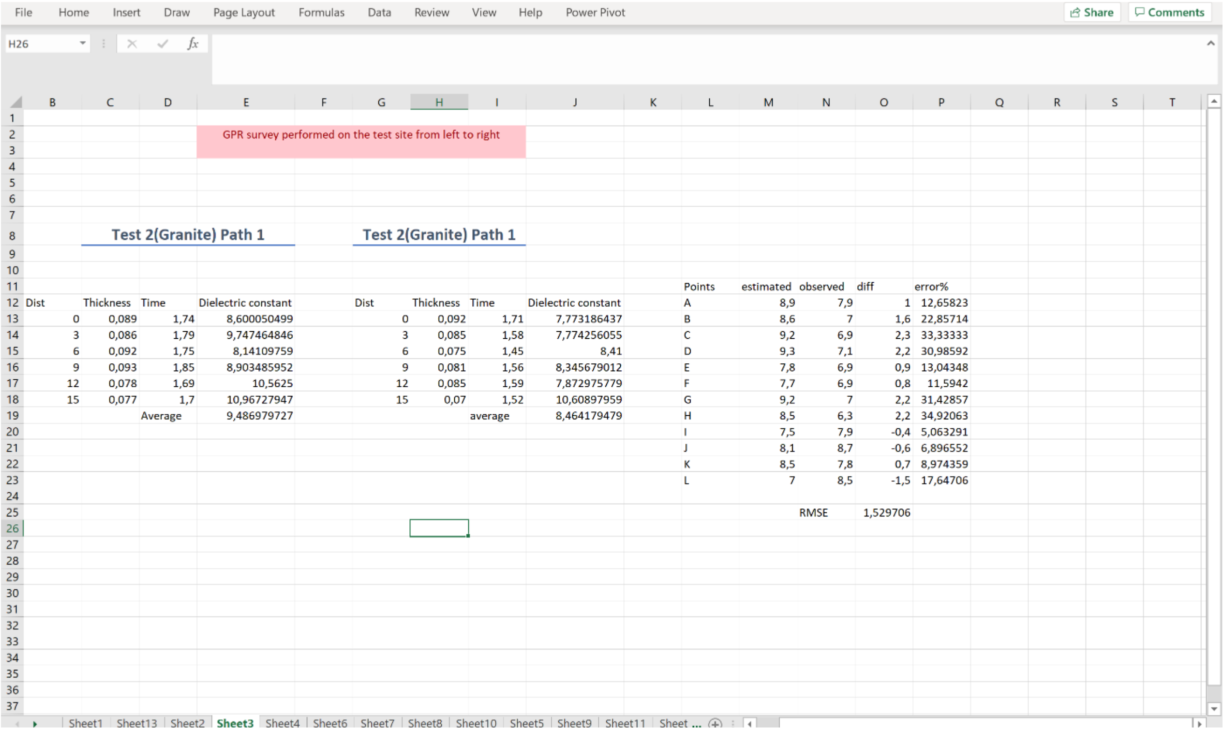
Test 1-3 (Concrete) Path 1

Dist	Thickness(m)	Time	Dielectric constant
0	0,083	1,89	11,66675134
3	0,088	1,87	10,16015625
6	0,085	2,1	13,73356401
9	0,082	2,2	16,19571684
12	0,087	1,87	10,3950654
15	0,089	1,87	9,933120818
		Average	12,01406244

Test 1-3(Concrete) Path 2

Dist	Thickness	Time	Dielectric constant
0	0,089	2,02	11,590582
3	0,083	2,02	13,32689795
6	0,083	1,73	9,775039919
9	0,089	1,8	9,203383411
12	0,083	1,87	11,4211424
15	0,089	1,88	10,03964146
		Average	10,89278119

points	estimated	Observed	dif	
A	8,3	7,9	-0,4	
B	8,8	7	-1,8	
C	8,5	6,9	-1,6	
D	8,2	7,1	-1,1	
E	8,7	6,9	-1,8	
F	8,9	6,9	-2	
G	8,9	7	-1,9	
H	8,3	6,3	-2	
I	8,3	7,9	-0,4	
J	8,9	8,7	-0,2	
K	8,3	7,8	-0,5	
L	8,9	8,5	-0,4	
			RMSE	1,373256



GPR survey performed on the test site from left to right

Test 2(Granite) Path 1

Dist	Thickness	Time	Dielectric constant
0	0,089	1,74	8,600050499
3	0,086	1,79	9,747464846
6	0,092	1,75	8,14109759
9	0,093	1,85	8,903485952
12	0,078	1,69	10,5625
15	0,077	1,7	10,96727947
		Average	9,486979727

Test 2(Granite) Path 1

Dist	Thickness	Time	Dielectric constant
0	0,092	1,71	7,773186437
3	0,085	1,58	7,774256055
6	0,075	1,45	8,41
9	0,081	1,56	8,345679012
12	0,085	1,59	7,872975779
15	0,07	1,52	10,60897959
		average	8,464179479

Points	estimated	observed	diff	error%
A	8,9	7,9	1	12,65823
B	8,6	7	1,6	22,85714
C	9,2	6,9	2,3	33,33333
D	9,3	7,1	2,2	30,98592
E	7,8	6,9	0,9	13,04348
F	7,7	6,9	0,8	11,5942
G	9,2	7	2,2	31,42857
H	8,5	6,3	2,2	34,92063
I	7,5	7,9	-0,4	5,063291
J	8,1	8,7	-0,6	6,896552
K	8,5	7,8	0,7	8,974359
L	7	8,5	-1,5	17,64706
		RMSE	1,529706	

GPR survey performed on the test site from right to left

Test 2-2(Granite) Path1

Dist	Thickness	Time	Dielectric constant
0	0,09	1,71	8,1225
3	0,09	1,72	8,217777778
6	0,087	1,711	8,7025
9	0,099	1,85	7,85697888
12	0,092	1,56	6,469281664
15	0,085	1,56	7,578685121
		Average	7,824620574

Test 2-2(Granite) Path2

Dist	Thickness	Time	Dielectric constant
0	0,085	1,71	9,106193772
3	0,08	1,42	7,08890625
6	0,078	1,42	7,457100592
9	0,084	1,71	9,324298469
12	0,085	1,7	9
15	0,078	1,42	7,457100592
		average	8,238933279

Points	estimated	observed	diff
A	9	7,9	1,1
B	8,5	7	1,5
C	8,7	6,9	1,8
D	9,9	7,1	2,8
E	9,2	6,9	2,3
F	8,5	6,9	1,6
G	8,5	7	1,5
H	8	6,3	1,7
I	8,7	7,9	0,8
J	8,4	8,7	-0,3
K	8,5	7,8	0,7
L	7,8	8,5	-0,7
		RMSE	1,560983

Sheet1 Sheet13 Sheet2 Sheet3 Sheet4 Sheet6 Sheet7 Sheet8 Sheet10 Sheet5 Sheet9 Sheet11 Sheet ...

G4 — GPR survey performed on the test site from left to right

GPR survey performed on the test site from left to right

Test 3(Limestone) Path1

Dist	Thickness	Time	Dielectric constant
0	0,096	1,73	7,306885
3	0,107	1,7	5,679535
6	0,11	1,6	4,760331
9	0,109	1,83	6,34208
12	0,099	1,74	6,950413
15	0,095	1,63	6,62385
		Average	6,277182

Test 3(Limestone) Path2

Dist	Thickness	Time	Dielectric constant
0	0,106	1,89	7,153102
3	0,105	1,77	6,393673
6	0,103	1,74	6,421058
9	0,1	1,64	6,0516
12	0,099	1,6	5,876951
15	0,101	1,78	6,988433
		average	6,480803

Points	estimated	observed	diff	Error%
A	9,6	7,9	1,7	21,51899
B	10,7	7	3,7	52,85714
C	11	6,9	4,1	59,42029
D	10,9	7,1	3,8	53,52113
E	9,9	6,9	3	43,47826
F	9,5	6,9	2,6	37,68116
G	10,6	7	3,6	51,42857
H	10,5	6,3	4,2	66,66667
I	10,3	7,9	2,4	30,37975
J	10	8,7	1,3	14,94253
K	9,9	7,8	2,1	26,92308
L	10,1	8,5	1,6	18,82353
		RMSE	3,00846	

G3 — GPR survey performed on the test site from right to left

GPR survey performed on the test site from right to left

Test 3-2(Limestone) Path1

Dist	Thickness	Time	Dielectric constant
0	0,099	1,56	5,586777
3	0,11	1,74	5,629835
6	0,1	1,76	6,9696
9	0,11	1,85	6,364153
12	0,12	1,65	4,253906
15	0,102	1,58	5,398789
		Average	5,70051

Test 3-2(Limestone) Path2

Dist	Thickness	Time	Dielectric constant
0	0,11	1,71	5,437376
3	0,096	1,53	5,715088
6	0,96	1,65	0,066467
9	0,1	1,78	7,1289
12	0,12	1,9	5,640625
15	0,095	1,57	6,14518
		average	5,022273

Points	estimated	observed	diff
A	9,9	7,9	2
B	11	7	4
C	10	6,9	3,1
D	11	7,1	3,9
E	12	6,9	5,1
F	10,2	6,9	3,3
G	11	7	4
H	9,6	6,3	3,3
I	9,6	7,9	1,7
J	10	8,7	1,3
K	12	7,8	4,2
L	9,5	8,5	1
		RMSE	3,314488