REVIEW PAPER

PAVEMENT STRUCTURAL ASSESSMENT USING AUTOMATED TOOLS: A COMPARATIVE STUDY

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Abstract: Pavement distress evaluation was traditionally conducted through visual observation. Traditional practice requires a person to walk along the stretch of pavement in order to survey distresses, take photos, and measure defects occurred at the deteriorated surface. However, this approach is too subjective causes inconsistencies of information, less reliable and time-consuming. Due to these shortcomings, the practitioners in pavement maintenance sector seek for a reliable alternative tools and techniques to arrest incapability of traditional approach. This research aimed to investigate feasibility of automated tools for pavement structural assessment conducting a comparative study. Series of interviews with expert panels and comparison matrix have been conducted comparing Ground Penetrating Radar (GPR), Infrared Thermograph (IR), and Portable Seismic Pavement Analyzer (PSPA) by investigating across parameters; cost-time effectiveness, operating principle, depth of performance, method of application, and limitations of pavement evaluations. The research indicated the Ground Penetrating Radar (GPR) is highly advantageous over IR and PSPA for pavement structural assessment. The GPR, as a geophysical tool, has extensive capabilities to accommodate data in pavement assessment, geotechnical investigation and structural assessment. GPR can considerably perform at high speed and save time. It is also beneficial for long-term investment with deeper information. Notably, the interpretation of radar gram images of GPR tool needs sufficient time and skill.

Keywords: *Pavement assessment, Geophysical tools, Ground penetrating radar (GPR), Infrared thermograph (IR), Portable seismic pavement analyser (PSPA)*

1.0 Introduction

There are numerous technical definitions of good pavement by which the utmost comfort for users to commute is essential. The pavement upkeep issues became crucial in order to serve public satisfaction which later demands for better and effective pavement distress management. The increasing shift in resource allocation from new pavement construction to pavement rehabilitation highlights the importance of accurate and comprehensive assessment of deteriorating pavements (Mooney *et al.*, 2000). Traditionally, pavement distress survey has been conducted through human observation, interpretation and effort manually. A person can walk along a stretch of pavement to conduct pavement distress survey, take photo and measurements of defects occurred at deteriorate surface within the pavement stretch. According to Oh (1998), visual survey is a common method used by most of engineers, however it lead to significant drawbacks such as; slow in progress, labour intensive, and expensive, subjective approach generating inconsistencies and inaccuracies in the determination of pavement condition, inflexible and does not provide an absolute measure of the surface. Also, it has poor repeatability since the assessment of given pavement section may be differ from one survey to the next, and could expose a serious safety hazard to the surveyors due to high speed and high volume traffic.

There are various approaches have been made and introduced to tackle above drawbacks. The advancement in technology has applied geophysical tools into pavement distress evaluation which proven as non-destructive test (NDT) method with extensive amount of data to be obtained and assists remedial works. A variety of remote sensing, surface geophysical, borehole geophysical and other non-destructive methods can be used to determine conditions of bridges and roads (Benson, 2003). The advantages of performing geophysical tests include faster and economical testing, non-destructive methods, provide theoretical basis for interpretation, and applicable for soil and rocks (Federal Highway Administration, 2005). Conclusively, the significant of this study is to investigate the geophysical tools for pavement distress evaluation in Malaysia due to its effectiveness in cost, time and perseverance of pavement.

2.0 Problem Statement

There are three (3) identified problems that are vital to initiate this study; included the current situation of pavement evaluation management, demand of non-destructive methods for pavement distress evaluation, and the effectiveness of integrating geophysical tools in pavement distress evaluation. There are numerous types of defects could be found on the pavement such as fatigue cracks, potholes, shoving, depression, rutting and so forth. Above all, fatigue cracks and potholes are the two (2) most popular types of defects can be found on most of the pavement in Malaysia. Several major roads like Jalan Tun Razak, Jalan Pahang heading to Jalan Danau Kota, Jalan Ulu Kelang, Jalan Sultan Ismail, Jalan Taman Desa, along Jalan Ampang and others appear to have potholes, thus, posing serious risks to commuters. Potholes and cracks appear on the road due to surface fatigue. The problem is exacerbated by high traffic volumes and heavy wheel loads (BERNAMA, 2010). Thus, many companies engaged for pavement maintenance are putting their best efforts in managing pavement distress.

Initially, destructive test is preferred for pavement evaluation, however this method has no longer became important as people start to concern on environmental protection, cost and time saving. That is why geophysical tools are integrated and optimized in pavement distress evaluation. Most of the countries like; United States, Japan, Australia, and China have integrated geophysical tools into pavement evaluation, and currently, India is moving on the same line. The application of Ground Penetrating Radar (GPR) for pavement evaluation is relatively new concept in India due to lack of technical expertise and limitation of financial front (Bala *et al.*, 2012). The purpose of tools integration is to promote a non-destructive ways for pavement distress survey process which at the same time provide extensive information that will be useful to assist in decision making and other managerial aspects. The importance of non-destructive test (NDT) for pavement engineering is evident, if it is considered as an actual poor condition of road in many countries and the limited financial resources that government plan to spend for maintenance (Benedetto and Rosaria, 2010).

To address the above-mentioned challenges, this study aimed to investigate the current pavement maintenance management practices, and to compare the performance among automated tools for pavement structural assessment cross the following parameters; cost-time effectiveness, operating principle, depth of performance, method of applications, and limitations.

3.0 Pavement Structure and Types of Pavement Distress

Pavement structural layers consists of six (6) most common layers which represents different structural capacity, thickness, proportions of materials, CBR (California bearing ratio) values and etc. Pavement is made of bituminous wearing course, bituminous binder course, dense bituminous course, crush aggregate, sub base and sub grade. A flexible pavement structure typically consists of layers of different materials that increase with strength as you move towards the surface (MDOT, 2007) (refer to Figure 1). In other words, pavement structures are divided into surface course, base course, sub base course and sub grade. Surface course is the top layer that comes in contact with traffic. The surface course is the layer in contact with traffic loads and normally contains the highest quality materials. It provides characteristics such as friction, smoothness, noise control, rut and shoving resistance and drainage. In addition, it serves to prevent the entrance of excessive quantities of surface water into the underlying base, sub base and sub grade (NAPA, 2001). While base course, located below the surface course which consists of stabilized or non-stabilized crush aggregate and followed by sub base course and sub grade.

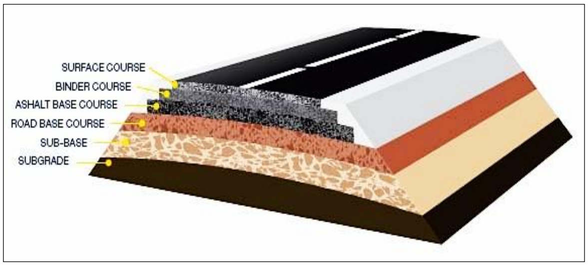

Figure 1: Typical Pavement Layers (Source: MDOT, 2007)

Assessing pavement condition starts with collection of distress data. Collecting distress data consists of type of distress, quantity of distress and level of severity. Distress data collected can tell what type of damage we dealt with. There are various types of pavement distress can be found along the pavement and separate into distinctive groups. Table 1 shows the major distress categories, types and brief definitions (Maintenance Technical Advisory Guides (MTAG), 2003).

4.0 Geophysical Tools applications in Pavement Distress Evaluation

The implementation of geophysical methods for pavement, structures, and geotechnical assessments has started few decades ago in most developed countries. Since early 1970's the electromagnetic wave (EM) as geophysical test methods has been use for detection of land mines, evaluation of tunnels, bridge decks, and geological investigation (Mississippi Department of Transportation, 2006). In early 1980's several commercial Ground Penetrating Radar (GPR) devices were introduced with claims to detect voids beneath pavement and to measure thickness profiles; these are Penetradar (California Department of Transportation, 1985), Donohue Remote Sensing (Donohue Engineers and Architects, 1983), and Gulf Applied Radar Van (Gulf Bulletin, 1987). A variety of remote sensing, surface geophysical, borehole geophysical and other non-destructive methods can be used to determine conditions of bridges and roads (Benson, 2003). Geophysical tools provide information about physical properties of the subsurface and are routinely applied to mining related problem of a geotechnical nature (Anderson, 2003). Geophysical tools can retrieve information from bottom structural layer without altering or disturbing the soil condition. Traditional investigation methods, such as boreholes and test pits, provide information about the conditions in the immediate vicinity around them. They also can be costly, due to the large amount of testing required to properly characterize a large or complex site using these traditional methods alone (William, 2013).

Table 1: Common Distresses on Flexible Pavement

Categories	Distress	Definitions
Crack	Fatigue	Cracks in asphalt layers that are caused by repeated traffic loadings.
	Longitudinal	Cracks that are approximately parallel to pavement centre line and are not in the wheel path.
	Transverse	Cracks that are predominately perpendicular to pavement centre line and are not located over portland cement concrete joints.
	Reflective	Cracks in HMA overlay surfaces that occur over joints in concrete or over cracks in HMA pavements.
	Block	Pattern of cracks that divides the pavement into approximately rectangular pieces.
	Edge	Crescent-shaped cracks or fairly continuous cracks that intersect the pavement edge and are located within 2 feet of the pavement edge, adjacent to the unpaved shoulder
Deformation	Rutting	Longitudinal surface depression that develops in the wheel paths of flexible pavement under traffic.
	Corrugation	Transverse undulations appear at regular intervals due to the unstable surface course caused by stop-and-go traffic.
	Shoving	A longitudinal displacement of a localized area of the pavement surface.
	Depression	Small, localized surface settlement.
	Overlay bumps	Cracks in old pavements were recently filled.
Deterioration	Potholes	Bowl-shaped holes of various sizes in the pavement surface.
	Ravelling	Wearing away of the pavement surface in high-quality hot mix asphalt concrete that may be caused by the dislodging of aggregate particles and loss of asphalt binder.
	Stripping	The loss of the adhesive bond between asphalt cement and aggregate, most often caused by the presence of water.
	Polished Aggregate	Surface binder worn away to expose coarse aggregate.
	Pumping	Seeping or ejection of water and fines from beneath the pavement through cracks.
Mat Problem	Segregation	Separation of coarse aggregate from fine aggregate.
	Bleeding	Excess bituminous binder occurring on the pavement surface.
Seal Coats	Rock loss	Wearing away of the pavement surface in seal coats.
	Segregation	Separation of coarse aggregate from fine aggregate.
	Bleeding	Excess binder occurring on the surface treated pavements.
	Fat spot	Localized bleeding.
	Delamination	Clear separation of the pavement surface from the layer below.

4.1 Ground Penetrating Radar (GPR) and its Application in Pavement Distress Evaluation

Ground Penetrating Radar (GPR) is a tool that works on the basic of electromagnetic wave principle. GPR is a non-destructive technique that has been widely used in the world over than 30 years. GPR technique uses discrete pulses of energy with a central frequency varying from 10MHz to 2.5GHz to resolve the locations and dimensions of electrically distinctive layers and objects in materials (Saarenketo, 2006). GPR is a high resolution electromagnetic technique that is designed primarily to investigate the shallow subsurface of the earth, building materials, roads, and bridges (Daniels, 2000). The operation of GPR based on electromagnetic pulses that transmitted into different medium of dielectric properties. So, whenever GPR detects transition of different medium or structural layers the pulses will rebound to the antenna or in other word, reflected. This process will continuously happen through different layers and finally will produce a hyperbolic result. The reflected energy displayed in a hyperbola form on the radar screen. It shows the amplitude and time elapsed between wave transmission and rebound process (Plati & Loizos, 2006). Hyperbolic image is processed based on the dielectric constants of structural layers and its thickness (Maser & Vandre, 2006).

GPR can give extensive information that will be useful for pavement maintenance mostly, rehabilitation, design, forecasting, planning and other managerial aspects. Furthermore, it can be performed under normal driving speed unlike traditional method which consume much time, limited to certain depth and destructive for pavement. There are multiple methods implemented to assess existing pavement structural capacity, define structural needs and estimate the required asphalt overlay thickness to preserve pavement (Goel & Das, 2008; Flintsch & McGhee, 2009). In contrast of traditional method, GPR is able to provide continuous pavement subsurface profile without the need to core and disruption of traffic. The method allow much larger amounts of data to be collected and longer lengths of pavement to be investigated for a given time and cost. GPR is a non-destructive especially when compared to traditional method; coring therefore GPR can be considered as cost effective. As a result the use of GPR has become frequently implemented for structural pavement assessment (Maser, 1996; Saarenketo & Scullion, 2000; Qadi *et al.*, 2003; Benedetto & Pensa, 2007).

Furthermore, GPR has high rate of data acquisition, sensitive to water chloride contents, sensitive to environmental conditions and provide a 3-D image construction (Bala, Garg & Jain, 2012). GPR has been explored for a variety of road applications with numerous advantages such as; it has been used for measuring air voids content (Saarenketo & Scullion, 1994), detecting presence of moisture in asphalt layers (Grote *et al.*,2005), detecting location and extent of stripping a moisture related mechanism between bitumen and aggregate (Romelia & Scullion, 1997; Hammons *et al.*, 2009)], determining localized segregation during paving (Gardiner & Brown, 2000), detecting transverse cracking (Saarenketo & Scullion, 2000), rutting observation occurrence (Rodis *et al.*1992), able to locate the same detectable longitudinal dielectric changes with high accuracy repeatedly (Poikajarvi *et al.*, 2012), and determination of pavement layer thickness. According to multiple studied, the layer thickness based on GPR data collected is sufficient and effective (Maser, 1996; Saarenketo & Scullion, 2000; Plati & Loizos, 2007).

GPR is a method of measurements that able to capture accurate layer thickness data at short intervals at relative high speed (Hartman *et al.*, 2004). As conclusion, GPR offers many advantages such as cost effective, high speed, save time, preserving pavement, safer, highly accurate, exceptionally reliable and understandable procedures (Smith & Scullion, 1993).

4.2 Infrared Thermograph (IR) and its Application in Pavement Distress Evaluation.

Infrared Thermograph (IR) is firstly discovered in 1800 by a famous astronomer Sir William Hershel. IR can be optimized for investigation of structure and equally for damage assessment. IR can be defined as a science of acquisition and analysis of data from non-contact thermal imaging (Prakash, 2008). The primary component of any thermal imaging system is the optical scanner. This unit is used to detect radiation in the infrared spectrum. Other essential components are a display monitor, video camera, computer and software for data acquisition, analysis and storage. The area surveyed by the camera is determined by minimum resolution requirements and the height of the equipment above the surface. Up to a full-lane width can be surveyed at one time (Manning & Holt, 1986) with an appropriately placed camera. Therefore, all objects that emitted infrared radiation in the form of heat can be detected by an infrared scanner. These natural impulses are converted into electrical pulses then processed to create a visual image of the object's thermal energy. The colour used to represent the thermal imaging can be user selected to represent surface temperature changes such as blue for colder regions and red for warmer regions [Brock and Jakob, 1998; Pla-Rucki & Eberhard, 1995; Weil and Haefner, 1989).

Besides that, IR camera has ability as a thermometer (Bojan *et al.*, 2012). IR camera can also be applied as a means of quality control in all processes that require the participation of thermal energy. As all objects emits heat will be detected by IR sensor and visualized in an image of temperature distribution over large area (Boja *et al.*, 2012). The great advantage about IR it can provide and record a real time temperature visual distribution image over large area, assists contractor to locate and identify areas near the joints that require immediate attention before the mat cools down, addresses the need to construct long-lasting pavements and to minimize user delays through repetitive repair and rehabilitation activities (Mostafa, 2013), assists in locating non uniform densities in hot mix asphalt paving, oil spills on the pavement, detect problems quickly without interrupting service, assess priorities for corrective action, and to minimize preventive maintenance and troubleshooting time (FLIR, 2013).

IR was used in pavement distress evaluation to assists engineers on thermal segregation detection, void detection prior compaction, premature pavement distress, provide continuous plot of temperature on a particular road (Bojan *et al.*, 2012), detection of subsurface pavement distresses like; baby blister, blister, cavity, delamination (Stimolo, 2003), identification of pavement strips (Stimolo, 2003), assists for road thermal mapping especially in seasonal countries (Marchetti *et al.*,2010), assess density of HMA overlay constructed on top of rigid pavement as an indicator of reflective cracking potential (Mostafa, 2013), used for quality control purposes because it can be used during paving operations (Mostafa, 2013).In fact, recently the Washington State Department of Transportation (WDOT) had successfully used infrared cameras to detect segregation due to temperature differentials in asphalt concrete pavements (Mostafa, 2013).

4.3 Portable Seismic Pavement Analyzer (PSPA) and its Application in Pavement Distress Evaluation

The Portable Seismic Pavement Analyser (PSPA) was originated from Seismic Pavement Analyzer (SPA) which used to perform seismic tests in a rapid and cost-effective manner and was developed under funding from the Strategic Highway Research Program (SHRP) (Nazarian *et al.*, 1993). With continuous support from the Texas Department of Transportation (TxDOT), the device has been refined to become more robust and more user- friendly (Yuan et al, 1991). The PSPA consists of two transducers and an impact echo hammer (IE) that packaged into a hand-portable system, which can perform high frequency seismic tests. The operating principle of the PSPA is based on generating and observing stress waves in the pavement layers (Stein & Sadzik, 2007). The device measures the velocity of propagation of surface waves that operable from a computer can be readily translated to a modulus. PSPA is a non-destructive device used for the evaluation of the seismic stiffness of a pavement structure. The device can be used to obtain basic information on the condition of the pavement structure, including parameters such as the seismic stiffness of the combined layers, indications of layer thicknesses and detail behavior of upper layer pavement (Stein & Sadzik, 2007).

PSPA can be used to determine the modulus of the material (Nazarian *et al*. 1997), determine the modulus of the top pavement layer without an inversion algorithm (Soheil & Imad, 2006), PSPA works on the principle of seismic wave propagation that record process of pavement layers response towards applied stress. Factors such as layer thicknesses, material type and material density affect the way in which such waves are reflected and attenuated in the pavement. The strength of seismic technology is its ability to obtain modulus profiles with relatively high resolution in comparison with most of other non-destructive testing methods. Typical applications of the technology can be found in the petroleum industry which is to locate sources of crude oil inside rock masses, in geotechnical engineering which used to quantify rock and soil (Wightman et al, 2003) and pavement engineering to evaluate pavement layer properties. Typical applications of the seismic technology in pavement engineering is to enable measurement of the seismic stiffness of the various pavement layers and to track changes in pavement layers over time due to vehicular and or environmental loading or to track construction practices to evaluate quality control (Celaya and Nazarian, 2006).

Nazarian et al (2002) conducted research using the PSPA for quality control during construction, and also developed a protocol for such quality control projects. Other field studies are also reported where the seismic moduli of pavement layers were measured and evaluated (Chen & Bilyeu, 2001). According to Daniel (2007), there are three (3) advantages of PSPA usage in pavement such as;

i. The usage of Time Record Analysis (TRA) is faster to be perform and data reduction is very simple
ii. High sensitivity of USW to the top layer and enable to give specific results
iii. IE can be used to determine thickness of top layer and flaws sensitive

5.0 Comparative Study

The comparative study encompasses two approaches for tools assessment; included, expert inputs, and comparative matrix development. Experts' interviews have been conducted among five (5) panels in road maintenance sector that divided into two different practices; traditional method and automated method. The major purpose of these interviews was to investigate the current road assessment practices available in road maintenance industry. There are three (3) geophysical tools compared in this study; named, Infrared Thermograph (IR), Portable Seismic Pavement Analyzer (PSPA), and Ground Penetrating Radar (GPR). These tools have been selected based on ability to acquire information repeatedly at high speed without destructing the pavement layers, effectiveness in cost and time, operating principle, depth of performance, applications and limitations. Table 2 summarizes the content analysis on geophysical tools, GPR and IR and PSPA across different aspects,

5.1 Analysis and Results of Expert Input Interviews

The interviews were conducted among five (5) expert panels in road maintenance sector. Interview questions are divided into three (3) sections, which consist of panels' information, preliminary questions, and detailed response on the adopted method. Summary of results are shown in Table 3.

Table 2: Content Analysis of Geophysical Tools Comparison, GPR and IR and PSPA

Aspects	GPR	IR	PSPA
Effectiveness in Cost and Time	GPR benefit/cost ratio is about 20-30% based on study conducted by DOT however, less cost effective for a very small section due to large mobilization cost and investment in proper training and data analysis expertise (Maser, 2006)	The measurement was carried out along 30km road lasted nearly 30minutes (Marchetti *et al.*, 2010).	A complete testing cycle at one point with PSPA takes about one minute and it can perform up to three seismic tests. The data collections at one particular point with PSPA take less than 30sec (Yuan *et al.*, 1999).
	Acquisition, processing and interpretation are relatively rapid thus, GPR ranked as the most cost effective in functions and overall usefulness of interpreted results (Anderson, 2003).	IR has 30 sec data collection time at the rate of 60fpm (Schmitt *et al.*, 2013).	PSPA consumed about 45sec for a one point test (Schmitt *et al.*, 2013).
Operating Principles	Electromagnetic waves reflect to measure materials (Schmitt *et al.*, 2013).	Rate of heat radiation and emissivity (Schmitt *et al.*, 2013)	Ultrasonic wave radiate and detect materials properties (Schmitt *et al.*, 2013).
	A well established technique that uses radio waves to detect object and determine their distance from echoes they reflect (Loizos and Plati, 2007)	The amount of infrared radiation seen from an object is composed or reflected, transmitted, and emitted radiation. For opaque material, no transmission of radiation can be seen while for HMA is between 90 – 98% of infrared radiation emitted (Ircon, n.p).	The PSPA is a simple and non-destructive device that rapidly measure s Young modulus via ultrasonic waves (Bell, 2006).
	The GPR techniques uses discrete pulse of energy with a central frequency varying from 10MHz up to 2.5GHz to resolve the locations and dimensions of electrically distinctive layers and objects in materials (Saarenkato, 2006).	Mainly, any defects or damages that generates a disturbance in thermal flow, disturbing the temperature surface distribution of the pavement is detected through IR tools as elevated temperature from surroundings (Stimolo *et al.*, 2003).	Stress waves are propagated through solid or liquid media which depends on the mechanical properties (density) of medias (Daniel, 2007).
Depth of Performance	The GPR subsurface depth exploration in dry sand can reach up more than 20m while in wet saturated clays, GPR is limited to shallow depth between 1 – 3m (Wightman et. al, 2003).	IR mostly can detect the surface course condition that related to crack, moist ingress and voids (Saarenketo, Matintupa & Varin, 2012). So, the performance of IR is within surface course areas.	Surface layer only (Yuan *et al.*, 1999).
	At 1.0Ghz frequency GOR system can penetrate typically between 0.5-0.9m (Saarenkato and Scullion, 2000).	It is confirmed that layer debonding at the depth of 40 mm – 70 mm from the surface of pavements can be found by surface temperature differences measured by Infrared Thermograph (Tsubokawa, Mizukami and Esaki, 2007).	PSPA can obtain more detailed information on the behaviour of the upper layer (up to 300mm thk) of pavement structures (Steyn and Sadzik, 2007).

Table 2 (cont'): Content Analysis of Geophysical Tools Comparison, GPR and IR and PSPA

Aspects	GPR	IR	PSPA
Applications	Most common applications have been focused on pavement thickness measurements (Maser, 1994), detecting voids under concrete slabs (Scullion *et al.*, 1994), detecting deteriorated areas in bridge decks (Alongi *et al.*, 1992).	IR can detects, estimates and measures level of segregation (Gardiner and Brown, 2000) and can perform thermal mapping for road (Marchetti, 2010).	To estimate the in situ seismic modulus for flexible and rigid pavements (Bell, 2006).
	Ground Penetrating Radar has the potential to identify and quantify segregation (Tahmoressi, Head, Saenz, & Rebala, 1999; Saarenakato and Roimela, 1998).	IR able to detect temperature of HMA material in paving machinery as well as on large pavement areas makes it suitable tool for quality control during paving (Bojan *et al.*, 2012).	To determine the top layer thickness and depth of delaminated interfaces (Daniel, 2007).
Limitations	Sensitive to wet surface or layers (Schmitt *et al.*, 2013).	High temperature gradients are required (Schmitt *et al.*, 2013).	Limited to pavement temperature below 50˚C (Schmitt *et al.*, 2013).
	Data interpretation could be affected by backscattered signals collected by GPR that largely depends on the unknown dielectric properties of materials thus, it cannot detect different layers unless difference of dielectric properties is sufficiently great (Bala, Garg and Jai, 2012).	IR cannot distinguish between gradation and temperature segregation; it sees both as cold spots (Gardiner and Brown, 2000).	In manual mode, data reduction may occur (Yuan et a., 1999).
	Operating restriction of GPR could be due to environmental conditions like rainfall, freezing etc, traffic interference and safety, operating speed because some places have speed limit, and signal interference (Waheed, 2006).	IR readings can be affected by shades and wind (Gardiner and Brown, 2000; Strahan, 2001)	Sensitive to surface condition and easily affecting results (Daniel, 2007).

Table 3: Summary of Interviews on Adopted Road Maintenance Practices

Parameters	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
Agency	Government	Government	Private	Private	Private
Designation	Civil Engineer	Civil Engineer	Civil Engineer	Manager	Manager
Experiences	>10 years	8-10 years	4-7 Years	>10 years	8-10 years
Types of road maintenance practices	Traditional Method (Human Observation)	Traditional Method (Human Observation)	Traditional Method (Human Observation)	Automated Method (200Mhz,400 Mhz and 1.6GHz GPR)	Automated Method (FWD and Road Scanner)
Types of information collect for pavement maintenance	Functional distresses, structural deformation, and road furniture.	Functional distresses, structural deformation, frictional resistance (upon demand) and road furniture.	Functional distresses and structural deformations.	Functional distresses and structural deformations	Frictional, Functional Distress, Structural Deformation, Strength and etc.

Table 3 (cont'): Summary of Interviews on Adopted Road Maintenance Practices

Parameters	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
Agency	Government	Government	Private	Private	Private
Designation	Civil Engineer	Civil Engineer	Civil Engineer	Manager	Manager
Experiences	>10 years	8-10 years	4-7 Years	>10 years	8-10 years
Reason for adopting the method	Low cost though this method consumes greater time.	Substantial costs are needed in order to apply current technologies available.	Low cost and practically been used over a period of time.	Faster in data acquisition and flexibility in numerous application.	Fast and cost saving for long term run. Can perform at high speed, repeatable and non destructive, accurate and reliable.
Time and Cost effectiveness towards current practice	The current practice consumes lots of time but maintain at low cost.	This practice is time consuming. It is very cost subjective because depends on the schedule of rate, additional works and budgeted funds.	Costs saving because of labor cost. Very high time consuming. Improper time management can lead to outstanding number of roads not surveyed.	This method is well dependable, faster, save time and beneficial for long term cost saving, specially, in labors costs.	This method is effective with time consumption that reduces human effort to generate information, assists in better decision making and treatment prioritizing.
Advantages of current adopted method	Bad roads been tackled accordingly within the budget but some remains unattended due to limited funds or incapability to extend additional funds.	Huge improvement made in road line marking requirements for luminosity specification and work operation.	Has slightly improved in detection of potholes and drainage problem, and improving in time response issue.	It can arrest insufficient work quality especially in overlay thickness problems, for example in sinkhole.	The advancement of technology does not require substantial improvement except to maintain the integrity of the current tools and techniques used.
Drawbacks of current method adopted	Insignificant but there are small percentage of discrepancies of information that affected the survey.	It has deficiencies especially in road structures like culvert.	Mostly related to drainage problems; overgrowth or malfunction. For problematic roads which reoccurring potholes.	No	No
Factors that contribute to the mentioned problems	Human error	Human error and attitude.	Human error, under motivated workers, difference and lack of technical knowledge, less awareness, less sense of ownership and exhaustion.	No	No
Comparison between Traditional Method and Automated Method	It is more accurate and highly repeatable that will assists greatly in reasonable decision making and prioritization of work.	There are discrepancies or inconsistencies of information generates through human observation.	It is more accurate, reliable, and faster at higher cost.	The automated method is faster and adopt latest technology.	Inconsistent and slow but this method is more preferable in the industry, save time, more information given, non destructive, reliable and highly repeatable.

Table 3 (cont'): Summary of Interviews on Adopted Road Maintenance Practices

Parameters	Panel 1	Panel 2	Panel 3	Panel 4	Panel 5
Agency	Government	Government	Private	Private	Private
Designation	Civil Engineer	Civil Engineer	Civil Engineer	Manager	Manager
Experiences	>10 years	8-10 years	4-7 Years	>10 years	8-10 years
Expectations	I would like to use automated methods, such as, IKRAM Scanner.	Improvement on the efficiency is expected prior funds availability and KKR approval.	In pavement assessment but this may need further consent from top management in terms of purchasing cost.	Automated method has less demand in the market probably due to non acceptance by most practitioners, less training and awareness in the industry, and no enforcement on GPR practice.	It is much useful and effective. The government should encourage or enforce usage of automated tools in road maintenance sector.

5.2 Analysis and Results of Comparison Matrix Development

As mentioned in methodology, there are three (3) tools chosen for comparison which are; Infrared Thermograph (IR), Portable Seismic Pavement Analyzer (PSPA) and Ground Penetrating Radar (GPR). The obtained information's are gathered from previous study that incorporates GPR, IR and PSPA in assessing pavement structures. GPR is compared and evaluated with IR and PSPA based on its effectiveness in cost and time, operating principle, depth of performance, applications and limitations. Consequently, it enables us to identify the strength and weaknesses in each tool for further verification.

6.0 Findings and Discussion

There are two types of data collection in this study which encompasses; interviews and tools comparative analysis. From the interview, most of the panels prefer automated survey system in managing road defects however, high initial/investment costs has hindered the application of automated equipment. Subsequently, comparison among automated tools were conducted and shown that, GPR is more useful than IR and PSPA for pavement structural assessment application.

6.1 Interviews Analysis Findings

Based on interviews conducted, it is concluded that automated method has long term benefits compared to the traditional method as discussed below. It is obvious that several comments made by expert panels are likely reflect the dissatisfaction level of users, issues of discrepancies in information, insufficient funds to adopt high technology tools, cost saving and time efficiency, work prioritizing, and to overcome workmanship issue (see Table 4).

i. Satisfaction Level

Traditional method is a tedious work process from surveillance to corrective action. There are many issues that related to dissatisfaction for example, in terms of information discrepancies, slow progress, double handling work, exhaustion and human error. Information discrepancy becomes a major concern because most of the ground personnel that carried out surveillance were not expert and has lack of technical understanding about road structures. Furthermore, different interpretations over similar problems significantly lead to data inconsistencies in road surveillance work. In addition, it will cause indecisiveness in decision making.

ii. Pavement Management

All agencies had set up unique road management system to address any pavement distress issues arise. The tremendous improvement made by these agencies shows the advancement of Malaysian road management system compare to many years ago. The main role of the system is to undertake all road deficiencies that occur within their responsibilities, scope of work and allocated funds. The tendency for the system to be less reliable for traditional application is likely high because all information is generated by human. Some agencies have taken initiative to arrest significant drawbacks of this method by reviewing their policies, standard of procedures and operation however, with too much reliance on human observation, the improvements probably become ineffective in a longer period of time. The panels have stated effective pre and post construction evaluation of applying automated tools.

iii. Cost – Time Effectiveness

Automated method is costly but improved whole work flows and contrarily, traditional method is cheap but very slow. Automated method is very effective in cost saving compare to traditional method because we need to account for tools purchasing costs in earlier time only. Furthermore, it can provide extensive information at one time compare to traditional method which needs several tests to be conducted just to get the same amount of information or maybe less than what automated tools can provide. Moreover, the cost of hiring labors can be reduced without affecting the productivity of surveillance process.

iv. Planning and Prioritization

Traditional method is less effective in decision making due to limitation in knowledge of the defects. Visual inspections is limited to identification of road surface condition and restrained information for subsurface conditions which might be subjected to any structural problem like; settlement. There is an issue happens where some roads may look good physically but actually not. Thus, with the ability of automated tool to provide information will help to assist managers for in work prioritization and planning for resources, budget and time.

v. Information Discrepancy

Traditional method has higher intensity of information discrepancies rather than automated method. There are several possible factors aggravate the situations such as; lack of technical knowledge, human error, work attitude, lack sense of ownership, natural flaws of human, and etc. This is a crucial issues that should be accounted and overcome because the management of work is depends on the information retrieved from site.

Table 4: Expert panels' rating analysis on the tool selection parameters

Parameter		Expert panels' Rating			Average Rating (%)
i. Satisfaction Level		/	/		40%
ii. Pavement Management		/	/		40%
iii. Cost – Time Effectiveness	Practice as highly time-consuming but maintained at low cost.	/	/	/	60%
	Practice as faster and cost-saving.	/	/		40%
iv. Planning and Prioritization	Practices are continuous improving	/	/	/	
	Practices are effective in advances planning and identify obstacles	/	/		40%
v. Information Discrepancy		/	/	/	60%

6.2 *Tools Comparisons Matrix Analysis*

Table 5 to Table 8 present the comparative analysis results between tools prior selection in pavement structural assessment application. Comparative analysis between tools were done thoroughly based on effectiveness in cost and time, operating principle, depth of performance, applications and limitations. Reasonable arguments on tools selections are provided accordingly.

6.2.1. Cost-Time Effectiveness

From the literature analysis between tools as shown in Table 5, GPR shows the highest time-cost effectiveness factor compared to IR and PSPA. Most of the study stated that GPR can accommodate effectively in data acquisition, work execution and image processing but some state that GPR is least effective in image interpretation phase. Meanwhile, IR and PSPA are concluded to be easier in data acquisition stage only because it can perform in less than a minute compare to GPR. However, GPR is found to be more flexible with its ability to accommodate wide-ranging information in pavement assessment studies rather than IR and PSPA. Thus, GPR is more considerable to be assessed in this study with respect to its benefit in pavement application at a reasonable time and cost.

6.2.2. Operating Principle

The selected tools shared two features in common which can be performed none destructively at higher repeatability and operates based on the principle of electromagnetic waves. These tools have different penetration depth into medium or materials with respect to the wave frequency in used. The different in wave frequency resulted in variation of penetration depth. For example GPR travel at lower frequency than IR thus, level of performance when using GPR is greater which allows for subsurface exploration rather than looking at the surface layers only. Similarly, PSPA has the same performance level with IR therefore; both are more applicable and useful for surface exploration. Obviously, GPR is more considerable to be assessed in this study with respect to its benefit in pavement assessment at a greater depth of penetration when compare to IR and PSPA (see Table 6).

Table 5: Comparative Analysis Between Tools in Effectiveness in Cost and Time

Tools	Author (Year)	Cost	Time
GPR	Bala, Garg & Jai (1996)	Effective	
	Saarenkato & Scullion (2000)	Effective	Effective
	Qadi *et al.* (2003)	Effective	
	Benedetto & Pensa (2007)	Effective	
	Anderson (2003)	Effective	Effective
	Maser (2006)	Effective	
	MDOT (2006)	Effective	Effective
	Infrasense (2009)	Effective	Effective
	Benedetto & Rosaria (2010)	Effective	
	Plati & Loizos (2012)	Effective	
	Wong (2012)	Effective	Effective
	Bala, Garg, & Jai (2012)	Effective	Effective
IR	Maldague (1993)	Effective	Effective
	Prakash (2008)		Effective
	Marchetti *et al.* (2010)		Least Effective
	Mostafa (2013)		Effective
	Schmitt *et al.* (2013)		Effective
PSPA	Nazarian *et al.* (1993)	Effective	Effective
	Yuan *et al.* (1999)		Effective
	Bell (2006)	Effective	Effective
	Daniel (2007)		Effective
	Schmitt *et al.* (2013)		Effective

Table 6: Comparative Analysis Between Tools in Operating Principles

Tools	Author (Year)	Operating principle
GPR	Saarenkato (2006)	Discrete pulse of energy
	Plati & Loizos (2007)	Discrete pulse of energy
	Qadi, Jiang & Lahour (2006)	Transmit and receive signals
	Plati & Loizos (2007)	Radio waves
	Schmitt *et al.* (2013)	Electromaganetic waves
IR	Meegoda *et al.* (2002)	Thermal flow disturbance
	Stimolo *et al.* (2003)	Heat radiation emitted
	Schimitt *et al.* (2013)	Rate of heat and emissivity
PSPA	Yuan *et al.* (1999)	Low frequency and high frequency vibration
	Bell (2006)	Ultrasonic waves
	Daniel (2007)	Stress waves
	Schmitt *et al.* (2013)	Ultrasonic waves

6.2.3. Depth of Performance

The sketch below shows a typical pavement cross section for GPR, IR and PSPA. It is proven that GPR can penetrate at greater depth compare to IR and PSPA. GPR can penetrate up to sub grade layer (layer V) while IR and PSPA minimally penetrate within the surface course (layer I). For pavement structural assessment purposes, it requires tool that can perform at greater penetration in order to show surface and subsurface condition within pavement layers. Thus, the best tool to be adopted in this study is GPR due to its sufficiency to penetrate all layers as shown in Figure 2.

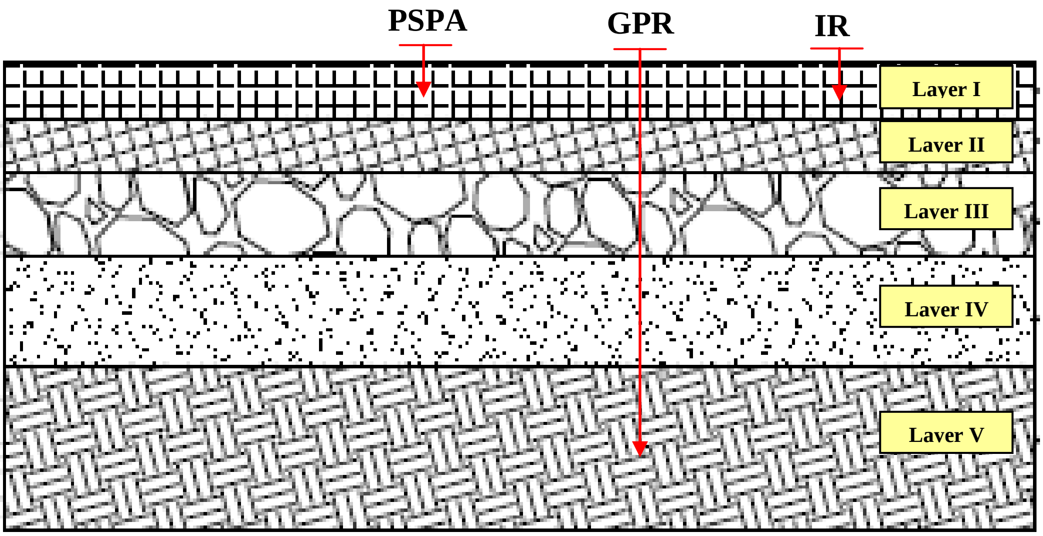

Figure 2: Comparative Analysis between Tools in Depth of Performance

6.2.4 Applications

There are numerous advantages of using GPR, IR and PSPA in assessing pavement structures as tabulated below. GPR has more flexibility in application compare to IR and PSPA therefore, it is vital to choose GPR for pavement assessment in this study (seeTable 7).

Table 7: Comparative Analysis Between Tools in Variety of Applications

Variety of Applications	GPR	IR	PSPA
Determine pavement thickness layer	/		/
Detection of moisture ingress and voids	/	/	
Identification of surface defects and patched zones	/	/	/
Identify subsurface issue like settlement, dislodged culverts	/		
Segregation of aggregate	/	/	
Detection of underground utilities	/		
Identification of damage layers and sinking problems	/		
Bridge structural assessment	/	/	/
Concrete structural assessment	/		/
Culvert structural assessment	/		
Assists in quality control aspect	/	/	

6.2.5. Limitations

The final parameter evaluated is tools limitations as shown in Table 8. All tools are compared accordingly and suitability of tool is chosen not only based on its limitations in practice but in consideration of other four (4) parameters adopted in this study. Conclusively, GPR is selected for further evaluation in this study with respect to its availability, performance, and applications. Nevertheless, specific precaution steps will be taken to address the GPR limitations in application and operation.

Table 8: Comparative Analysis Between Tools in Limitations

Limitations	GPR	IR	PSPA
Sensitive to wet surface or layers	/		
Noises or backscattered signal	/		
Environmental conditions exposure	/	/	/
Sufficient conductivity of materials required	/		
Unable to distinguish gradation and segregation		/	
High temperature gradient is required		/	
Complexity of work process			/

In comparing automated method and traditional method, it seems that automated method is more efficient in work process because all site information are generated by automated tools and analyzed by computer software. Traditional method has conquered the road maintenance industry for years and it is a challenging process to change the custom of maintenance method in the industry. In consideration of automated tools capability compared to human efforts, the probability of misleading information is manageable and adequately prevents work repetition. This situation is far efficient than traditional ways thus, it is high time for the Government to revise the policy and incorporate advanced tools and technology into road maintenance practice.

7.0 Conclusion

This study was initiated based on several issues and problems occur within the scope of road maintenance practice. Several objectives were list out accordingly in this study to assist in data collection and to ease in study flows. The first objective is to investigate the current pavement maintenance management practice. There are two types of maintenance method practiced in the industry such as traditional method and automated method. Traditional method defines as manual observation using human while automated method uses other than human effort like machines, tools and etc. to generate information on site. Five (5) expert panels were interviewed in this study came from different backgrounds, experience and years of service.

There are three (3) different tools compared in this study. The purposes of comparison between tools are to identify the most feasible and effective tool to be incorporate in pavement structural assessment for road maintenance. These tools namely are; Ground Penetrating Radar, Infrared Thermograph, and Portable Seismic Pavement Analyzer. Tools were compared according to the outlined research parameters in this study. Through the comparative study, GPR is proved to be useful in providing extensive information which in normal practice required for multiple testing on site. In contrast, IR and PSPA are evaluated as less suitable for pavement structural assessment purpose.

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References

Advance Pavement Technologies (2008). Eight Rules for Preserving Your Asphalt Investment. Advanced Pavement Technologies.

Amir et al (2012). Assessing the Benefits of Ground Penetrating Radar Technology – Does it Improve the Accuracy of FWD Results and Overlay Design. Advances in Pavement Evaluation and Instrumentation Session. Conference of the Transportationof Canada Frederiction, New Brunswick.

Anderson (2003) A Generalized Protocol of Selecting Appropriate Geophysical Techniques. Geophysical Technologies for Detecting Underground Coal Mine Voids; An Interactive Forum. U.S Department of Transportation. Retrieved from website http://www.fhwa.dot.gov/engineering/geotech/hazards/mine/workshops/ktwkshp/ky0307.cfm on 20th November 2013.

Bala, Garg & Jai (2012). GPR Based Detection of Structurally Weak Zones of Road Pavement. 2012 International Conference on Traffic and Transportation Engineering (ICTTE 2012) IPCSIT vol.26 (2012).

Bell (2006). Operating Portable Seismic Pavement Analyzer. Final Report. Geotechnical and Structures Laboratory, Engineer Research and Development Centre, ERDC/GSL SR-06-9

Benedetto &Pensa (2007). Indirect Diagnosis of Pavement Structural Damage using Surface GPR Reflection Techniques. Journal of Applied Geophysics 62 (2007) (107 – 133).

Bernama (2010). 10 MP: RM2.8 billion for improving urban public transport, Bernama Oct 15 2010, www.bernama.com.

Benedetto & Rosaria (2010). Applications of Ground Penetrating radar to Road Pavement: State of Art and Novelties. GeoShanghai 2010 International Conference. Geotechnical Special Publications No.203.

Benson (2003). An Overview of Geophysical and Non Destructive Methods for Characterization of Roads and Bridges. Use of Geophysical Methods in Construction. Retrieved from website http://ascelibrary.org/doi/pdf/10.1061/40521%28296%291 on 15th November 2013.

Bojan, Josipa &Tatjana (2012). Application of Infrared Camera for Quality Control during Paving. 2nd International Conference on Road and Rail Infrastructure. CETRA 2012.

Carl (2006). Personal communications, WaveTech Consulting, May 2006.

Central Federal Highway Division (CFL) (2013), Baseline Condition Assessment Using Geophysical Methods. Federal Land Highway Programs. Retrieved from website http://www.cflhd.gov/resources/agm/engApplication/BridgeSystemSuperstructure/331BaselineConditionAssessUsingGeophyMethods.cfm

Daniel (2007). Portable Seismic Analyzer – PSPA. 498 – Experimental Methods. University of Illinois.

Dashevsky *et al.* (2005). Capacitance Sounding; A New Geophysical Method for Asphalt Pavement Quality Evaluation. Journal of Applied Geophysics 57 (2005), 95-106. Retrieved from website http://www.ac.els-cdn.com_S0926985104000849_1-s2.0-S0926985104000849-main on 15th November 2013.

David (2012). Use of Ground Penetrating Radar (GPR) for Pavement Assessment and Evaluation. TTE 5837 Pavement Management. University of Florida.

Doll W. E. (2008). The Path Behind and Highway Ahead: A Perspective on the Future of Geophysics in Engineering. Geo Congress 2008.

Dumoulin *et al.* (2009). Active Infrared Thermography Applied to detection and Characterization of Non Emergent Defects on Asphalt Pavement. NDTCE Conference, Nantes, 30th – 3rd July.

Gardiner, Law & Nesmith (2000). Using Infrared Thermography to Detect and Measure Segregation in Hot Mix Asphalt Pavements., International Journal of Pavement Engineering, 1:4, 265-284, DOI:10.1080/10298430008901710. Retrieved from website http://www.tandfonline.com/doi/pdf/10.1080/10298430008901710 on 3rd December 2013.

Gardiner and Brown (2000). Segregation in Hot-Mix Asphalt Pavements, NCHRP Report 441, Transportation Research Board, National Research Council, Washington, D.C.

Georgopoulus, Loizos, & Flouda (1995). Digital Image Processing as a Tool for Pavement Distress Evaluation. ISPRS Journal of Photogrammetry and Remote Sensing 50 (1): 23 – 33.

Grote *et al.* (2005). Evaluation of Infiltration in Layered Pavements Using Surface GPR Reflections Techniques. Journal of Applied geophysics. 57 (2), 129 – 153.

Hartman, Baston, Sedgwick, and Bohmer (2004). Pilot Study Assessing the Feasibility of Advanced Ground Penetrating Radar in Pavement Assessment. Bulletin 034. 8th Conference on Asphalt Pavements for Southern Africa (CAPSA' 04).

Hausman *et al.* (2002).Laboratory and Field Analysis of the TransTech Model 300 Pavement Quality Indicator TM for Determining Asphalt Pavement Density. 81st Transportation Research Annual Meeting, Washington, D. C.. Paper No. 02-4055. 2002.

Henault (1999). Development of Guidelines for Reduction of Temperature Differential Damage (TDD) for Hot Mix Asphalt Pavement Projects in Connecticut, Report 2222-1-99-5, Connecticut Department of Transportation.

Holzschuher *et al.* (2007), Accuracy and Repeatability of Ground Penetrating Radar for Surface Layer Thickness Estimation of Florida Roadways, Research Report, Department of Transportation Florida, State Materials Office, 07-505.

Ircon (n.p). Introduction to Infrared Thermometry, Technical Solution TS104, Retrieved from website http://www.ircon.com/techsolution.html#5.

Krapez and Cielo (1991). Thermograph No Destructive Evaluation: Data Inversion Procedures, Part **1:** 1-D Analysis and experimental results, Res. Nondestructive Evaluation 3(2): 8 **1-100.**

Loizos and Plati (2007). Accuracy of Pavement Thickness Estimation Using Different GPR Analaysis Approaches, NDT & E International 40, Amsterdam, Elsevier 2007, 147 – 157.

Mahoney *et al.* (2003). Application of Infrared Thermographic Imaging to Bituminous Concrete Pavements – Final Report, Connecticut Advanced Pavement Laboratory, Connecticut Transportation Institute, 2229-F-03-7

MALA GPR (2013). MAA GPR for Infrastructure and Construction Applications. MALA Geosciences. Retrieved from website www.malags.com/solutions/roads on 2nd October 2013.

Maldague (1993). Nondestructive Evaluation of Materials by Infrared Thermography, Springer-Verlag London Lirnited.

Marchetti et al. (2010). Implementation of and Infrared Camera for Road thermal Mapping. 10th International Conference on Quantitative Infrared Thermography, July 27 – 30, 2010 Quebec, Cananda.

Marc (2007). Using Ground Penetrating radar to Evaluate Minnesota Roads, Final Report, Minnesota Department of Transportation, Research Service Section, Minnesota.

Mark & Dave (2006). Using Ground Penetrating Radar as an Assessment Methodology in Roadway Rehabilitation. Soil and Materials Sessions. 2006 Annual Conference of the Transportation Association of Canada.

Maser &Vandre (2006). Network level Pavement Structure Assessment Using Automated Processing of Ground Penetrating Radar (GPR) Data. Airfield and Highway Pavements 2006.

MDOT (2006). Mississippi Department of Transportation State Study Phase I – GPR Final Report.

Meegoda *et al.* (2006), Correlation of Surface Texture, Segregation and Measurements of Air Voids, Final Report, New Jersey Department of Transportation, FHWA-NJ-2002-026.

Morcous & Erdogmus (2009). Use of Ground Penetrating Radar for Construction Quality Assurance of Concrete Pavement. NDOR Project Number P307. Nebraska Department of Roads & University of Nebraska, Lincoln.

Mooney, M. A., Miller, G. A., Teh, S. Y., & Bong, W. (2000). Importance of invasive measures in assessment of existing pavements. Journal of Performance of Constructed Facilities, 14(4), 149-154.

Mostafa (2013). Use of Infrared Thermography to Control the Quality of Joints Construction and to Detect Reflective Cracking in Asphalt Pavements. Transportation Infrastructure State of Good Repair. Retrieved from website http://www.evaccenter.lsu.edu/pub/13-04.pdf on 3rd December 2013.

Morris (1991). Digital Design, 2e edition.

MTAG (2003). Common Flexible Pavement Distress. Caltrans Department of Transportation. Maintenance

Technical and Advisory Guides July 2003. Retrieved from website http://www.dot.ca.gov/hq/maint/MTAG-CommonFlexiblePavementDistresses.pdf on 3rd December 2013.

Muller (2009). Application of Ground Penetrating radar to Road Pavement Rehabilitation. Institute of Public Works Engineering Australia Queensland State Conference. Queensland Road Edition No.7 March 2009.

NAPA, F. (2001). HMA Pavement Mix Type Selection Guide.

Nazarian *et al.* (2004). Implementation of Data Fusion techniques in Nondestructive Testing Of Pavements. Technical Report, Centre of Transportation Information System, Texas Department of Transportation, FHWA/TX-05/0-4393-2.

Oh, H. (1998). Image processing technique in automated pavement evaluation system.

Plati & Loizos (2012). Using Ground Penetrating Radar for Assessing the Structural Needs of Asphalt Pavements. Non Destructive Testing and Evaluation Vol. 27, No.3, September 2012, 273 – 284. Retrieved from website http://dx.doi.org/10.1080/10589759.2012.695784 on 1st October 2013.

Plati, Georgouli and Loizos (2013). Review of NDT Assessment of Road Pavement Using GPR. Nondestructive Testing of Materials and Structures. RILEM Bookseries 6.

Poikajarvi, Peisa&Narbro (2012). Geophysical Research Abstracts, Vol. 14 EGU2012-9233-1. EGU General Assembly 2012.

Prakash Rao (2008). Infrared Thermography and Its Application in Civil Engineering. Indian Concrete Journal. Retrieved from website http://icjonline.com/views/POV_2008_05_41_D.S.%20Prakash%20Rao.pdf on 3rd December 2013.

Qadi, Jiang & Lahour (2006). Analysis Tools for Determining Flexible Pavement Layer Thickness at Highway Speed. Proceedings of the Transportation research Board 85th Annual Meeting, Washington D.C.

Qadi, Lahouar, &Loulizi (2003). Successful Application of Ground Penetrating Radar for Quality Assurance – Quality Control of New Pavements. Transport Research Record 1861 (2003) (86 – 97).

Ragnar (2008). Performance Indicator. Joint Nordic/Baltic Symposium on Pavement Design and Performance Indicators. NVF 34 – Baltic Symposium 2008 – 02 -12. VIANOVA.

Romero &Kuhnow (2002). Evaluation of New Non-Nuclear Pavement Density Gauges Using Field Projects. 81st Transportation Research Annual Meeting, Washington, D. C.. Paper No. 02-2352. January 13-17, 2002.

Saarenkato (2006). Electrical Properties of Roads Materials and Subgrade Soils and The Uses of Gound Penetrating radar In Traffic Infrastructure Surveys, PhD. Dissertations, Faculty of Science, Department of Geoscience, University of Oulu.

Saarenketo & Scullion (1994). Ground Penetrating Radar Applications on Roads and Highways. Research Report 1923 – 2F. Texas Transportation Institute, College Station, TX, 1994.

Saarenketo & Scullion (2000). Road Evaluation with Ground Penetrating Radar. Journal of Applied Geophysics. 43(2 – 4) (2000) (119 -138).35. Saarenketo (2006). Electrical Properties of Road Materials and Subgrade Soils and The use of Ground Penetrating Radar in Tarffic Infrastructure Surveys, PhD. Dissertation., Faculty of Science, Department of Geosciences, University of Oulu, 2006.

Saarenketo and Roimela (1998). Ground Penetrating Radar Techniques in Asphalt Pavement Density Control, Proceedings of the Seventh International Conference on Ground Penetrating Radar, May 27-30, Lawrence, Kansas, Vol 2, pp. 461-46.

Sandro, Danilo, & Marco (2011). Ground Penetrating Radar Assessment of Flexible Road Pavement Degradation. International Journal of Geophysics. Hindawi Publishing Corporation. Retrieved on website http://www.hindawi.com/journals/ijgp/2011/1989136 on 2nd October 2013.

Schmitt *et al.* (2013), Selection of Non-Destructive Testing Technologies for Asphalt Pavement Construction, Airfiled and Highway Pavement 2013: Sustainable and Efficient Pavement, ASCE Journal 2013, 573-584.

Sebastiano (2006). Evaluation of Pavement Surface Distress Using Digital Image Collection and Analysis. Seventh International Congress on Advances in Civil Engineering October 11 – 13, 2006. Yildiz Technical University, Istanbul, Turkey.

Shawn (2012). Advancement in GPR for Sustainable Tomorrow. Annual Conference & Exhibition of the Transportation Association of Canada.

Smith & Scullion (1993). Development of Ground Penetrating Radar Equipment for Detecting Pavement Condition for Preventive Maintenance. Technical Paper Project H 104 Strategic Highway research Program. Natural Resources Defense Council, Washington DC, USA.

Steyn & Sadzik (2007). Application Of The Portable Pavement Seismic Analyser (Pspa) For Pavement Analysis. Document Transformation Technologies. 26th Southern African Transport Conference (SATC 2007) 1-920-01702-X Pretoria, South Africa.

Stimolo *et al.* (2003). Passive Infrared Thermography as Inspection and Observation Tool in Bridge and Road Construction. International Symposium Non Destructive Testing in Civil Engineering 2003. Retrieved from website http://www.ndt.net/article/ndtce03/papers/v083/v083.htm on 15th November 2013.

Tahmoressi, Head, Saenz, & Rebala (1999) Material Transfer Device Showcase in El Paso, Texas, Texas Department of Transportation, 1999.

Tsubokawa, Mizukami and Esaki (2007). Study on Infrared Thermographic Inspection of Debonded Layer of Airport Flexible Pavement. National Institute for Land and Infrastructure Management, FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE Atlantic City, New Jersey, USA

U.S. Department of Transportation (2005). Geotechnical Exploration and Testing. Geotechnical Aspects of Pavements and Reference Manual. U.S Department of Transportation. Retrieved from website http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/04b.cfm on 15th November 2013.

Vera, Boriana & Christo (2008). Software Tool for GPR Data Simulation and Basic Processing. Cybernetics and InformationTechnologies Volume 8, No 4. Bulgarian Academy Of Sciences

Waheed (2006). Ground Penetrating Radar Study – Phase I Technology Review and Evaluation, Mississippi Department of Transportation, FHWA/MS-DOT-RD-06-182.

Wong & Ernesto (2012). Ground Penetrating Radar (GPR) – A Tool for pavement Evaluation and Design. 25th ARRB Conference – Shaping the Future; Linking Policy, research and Outcomes, Perth, Australia 2012. ARRB Group Ltd and Authors.

Zaghloul *et al.* (2005). Implementation of a Reliability-Based Back calculation Analysis." Transportation Research Record 1905, Transportation Research Board, Washington, DC, pp. 97-106.