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Defect Identification in Asphalt Pavement Using Ground Penetrating Radar

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A B S T R A C T

Pavements serve as critical components of infrastructure, designed to provide durable, smooth, and safe surfaces for vehicular and pedestrian traffic. Pavement deterioration due to traffic load, environmental effects, and material deficiencies results in structural and functional defects. Traditional destructive testing methods, although direct, are time-consuming and detrimental to pavement integrity. Ground Penetrating Radar (GPR), a non-destructive technology, is emerging as a fast, reliable method for subsurface defect identification.Defect identification in asphalt pavement using Ground Penetrating Radar (GPR) leverages high-frequency electromagnetic wave propagation to produce rapid, high-resolution subsurface images. This approach enables the precise localization and characterization of internal pavement distresses—such as cracks, delamination, debonding, and voids—through advanced 2D and 3D imaging and signal processing. Field validation demonstrates that GPR detection correlates strongly with direct measurement methods while allowing for continuous monitoring across diverse compaction and moisture conditions. Automated algorithms further enhance defect recognition accuracy, facilitating timely maintenance and improved road durability."This paper reviews pavement structures, typical defects, and fundamentals of GPR, enriched with current advancements in signal processing, AI-based defect detection, UAV integration, and digital twin frameworks for real-time monitoring. This comprehensive account aims to guide researchers and engineers in effective asphalt pavement assessment and maintenance.

Keywords: Asphalt pavement, Non-destructive testing, Ground Penetrating Radar, Pavement defects, Infrastructure maintenance, Artificial intelligence, UAV, Digital twin

1. aIntroduction

A pavement is a durable surface layer constructed to support vehicle or pedestrian traffic, often referred specifically to roadways made of concrete or asphalt.Asphalt pavement is a composite material used extensively for roads, parking lots, airports, and similar infrastructure. It is created by mixing mineral aggregates—such as sand, gravel, or crushed stone—with bitumen, a sticky, black byproduct of petroleum that acts as a binder to hold the aggregates together.Pavements underpin transportation safety and efficiency. Continuous loading and environmental fluctuations cause cracking, rutting, potholes, moisture damage, and other defects that require timely and accurate detection to prevent catastrophic failure. Traditional destructive tests give precise evaluation but at the expense of pavement damage and limited spatial coverage.

Non-destructive testing (NDT) allows comprehensive, damage free subsurface assessment. Ground Penetrating Radar (GPR) has proven effective in detecting and characterizing defects early by analyzing subsurface electromagnetic wave reflections, providing a powerful tool for maintenance optimization and cost reduction.Ground Penetrating Radar(GPR) is highly important for defect identification in construction, infrastructure maintenance, and geotechnical engineering due to its non-destructive, rapid, and accurate capabilities. GPR allows professionals to locate defects below the surface, such as cracks, cavities, corrosion, and delamination, often with high precision and minimal disruption to structures or operations. Ground penetrating radar is NDT that uses ultra wide band EM signals into subsurface ,detecting features and defects without excavation. A GPR sends a short pulse which reflects back when they hit interfaces with different dielectric properties. The reflected signal is captured and processed into an image or profile.The image or profile is used to find out the subsurface defects such as crack, moisture build-up, voids etc.

2. Pavement Structures And Characteristics.

Four layers make up typical pavement :

- Surface Course: Surface course is the topmost layer that is vulnerable to traffic loads directly. Typically composed of cement concrete for rigid pavements or bituminous materials (asphalt concrete), it offers a smooth, long-lasting, and skid-resistant surface. This layer guards against abrasion and weathering, keeps water out, and shields underlying layers.

- Base course: Base course is the main layer that spreads loads evenly and is usually made up of bitumen-bound aggregates or compacted, high-quality granular aggregate. The objective is to give the foundation layers structural strength and to disperse traffic stresses widely. It must withstand shearing force and distortion over the pavement's lifespan.
- Sub-base Course: The subbase is composed of higher-quality, well-graded aggregate material, crushed stone, gravel, slag, or burnt clinkers and is situated above the subgrade. It minimises soil migration from the subgrade to upper levels, facilitates construction traffic, improves drainage, and distributes loads more evenly. Subbase elevates the pavement above the natural water table level and shields the subgrade from freeze-thaw cycles. For frost protection, a capping layer is occasionally positioned between the subbase and subgrade.
- Subgrade: This is the layer of natural soil that is put together to sustain the loads from pavement.It acts as the base offering consistent support and bearing capacity.California Bearing Ratio (CBR) test is used to gauge its strength.In order to maintain the strength of subgrade drainage is mandatory.

Characteristics Of Pavement

- Structural Strength: The structural strength of the pavement must be sufficient to sustain high traffic loads over time without experiencing undue distortion or failure. In order to prevent overload strains on the underlying soil, it should securely distribute the wheel loads to the subgrade. The quality and thickness of the pavement layers as well as the state of the subgrade have a significant impact on the strength.
- Longevity: Pavements with a long lifespan require less upkeep and replacement. For flexible pavements, the normal design life is 10–20 years, while for rigid pavements, it is roughly 20–30 years. Maintenance, traffic volume, climate, and the quality of the materials and construction all affect their lifespan.
- Water Impermeability: The subgrade and base layers are shielded from moisture-induced deterioration by impermeable pavements, which stop water infiltration. Water can weaken soil and lead to cracks or potholes. Pavement integrity is preserved by using waterproof surface coatings in conjunction with appropriate drainage systems.
- Temperature Behaviour: Pavement materials are affected by variations in temperature. Asphalt in flexible pavements may become brittle and shatter at low temperatures or soften at high temperatures, resulting in rutting. The forces of expansion and contraction can cause rigid pavements to curl or break. To reduce damage, pavement design must take local temperature variations into account.

3. Pavement Types

There are two types of pavements:

Flexible Pavements

Flexible pavements are asphalt-bound and distribute stress through contact between aggregate particles.Flexible pavement is made up of several layers, such as surface course, base course, binder course, subbase, and subgrade.It uses bitumen as binder which is mixed with aggregate to form the top layer.Flexible pavement transfers the load to subgrade through grain-to-grain contact.It is Ideal for the majority of highway, rural, and urban roads, particularly those with varying budgets and traffic volumes.Design life is typically 20 years.

Structure: Multiple layers that transfer load through grain-to-grain contact and lateral distribution.

Materials: Asphalt (bitumen)

Key Feature: Flexible and can adjust slightly to subgrade movement.

Types of Flexible Pavements:

•Conventional flexible pavements (hot mix asphalt)

•Semi-rigid pavements (with stabilized base layers)

•Full-depth asphalt pavements

Rigid Pavements

Rigid pavement consists of slabs of Portland Cement Concrete (PCC) set directly on top of a granular subbase.The concrete slab's flexural strength transfers load by acting as a rigid plate that disperses weight over a large subgrade surface.Rigid pavement is incredibly robust and has a roughly 30-year design life.Ideal for ports, busy streets, urban roadways, and areas with large, slow-moving trucks.

Structure: Strong concrete slabs that distribute load over a wider area.

Materials: Portland cement concrete (PCC).

Key Feature: High flexural strength, less deformation under load.

Types of Rigid Pavements:

•Jointed Plain Concrete Pavement (JPCP)

•Jointed Reinforced Concrete Pavement (JRCP)

•Continuously Reinforced Concrete Pavement (CRCP)

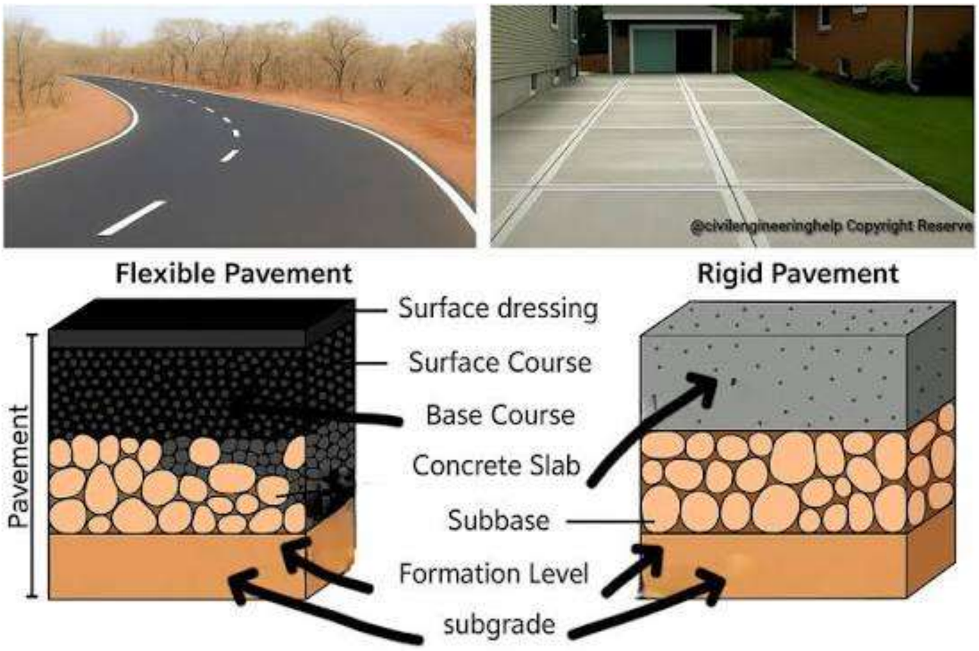

Fig.1:Flexible pavement and Rigid pavement

4. Defects In Asphalt Pavement

Asphalt pavement defects include cracks (alligator, block, transverse, longitudinal, reflection, edge, slippage), deformations (rutting, depressions, shoving, upheavals), and surface defects like potholes and raveling.These problems are caused by things like too much traffic, bad drainage, the weather, and using the wrong materials or building techniques. Defects that go unfixed may cause further deterioration and a loss of structural integrity.

DEFECT TYPE	DESCRIPTION	CAUSES
Potholes	Bowl-shaped holes in the surface	Water infiltration, freeze-thaw cycles, poor drainage
Alligator Cracking	Interconnected cracks resembling alligator skin	Repeated traffic loading, weak base or subgrade
Rutting	Longitudinal surface depressions in wheel paths	Plastic deformation, poor compaction, weak subgrade
Raveling	Loss of aggregate particles from the surface	Aging binder, low-quality mix, poor compaction
Bleeding	Bitumen rises to the surface, making it shiny and sticky	Excessive asphalt content, poor mix design
Edge Cracking	Cracks near the pavement edge	Poor shoulder support, water infiltration
Corrugation/Shoving	Wavy surface patterns	Improper mix, unstable base, excessive stop-and-go traffic
Depressions/Settlements	Localized surface dips	Settlement of subgrade, poor compaction

Fig.2:Different defects in asphalt pavement

5. Pavement Maintenance And Non Destructive Testing Methods

In order to protect and prolong the life of paved surfaces, including roads, highways, and parking lots, pavement maintenance is vital. Preventive maintenance and prompt fixes of minor pavement faults cut down the rate of degradation and delay the need for significant repairs or expensive reconstruction. This leads to substantial financial savings during the pavement's lifespan. Additionally, well-maintained pavements give safer driving conditions by lowering dangers like potholes, cracks, and uneven surfaces and improve traffic flow by minimizing delays caused by construction.Maintaining pavements properly also makes them smoother and more aesthetically pleasing, which enhances user comfort. In the end, pavement care maximize service life, protects the infrastructure investment, and guarantees that roads continue to be usable, secure, and visually appealing for the community.

Non-destructive testing procedures are evaluation and testing strategies used to evaluate the structural integrity and condition of pavement without causing any harm. These techniques provide the early detection of problems such cracks, voids, delamination, moisture penetration, and load-bearing capacity difficulties, enabling prompt maintenance and rehabilitation. Typical pavement non-destructive testing (NDT) techniques include:

- Ground Penetrating Radar: GPR uses electromagnetic waves to produce cross-sectional photographs of pavement layers, ground penetrating radars(GPR) identify underlying irregularities, voids, cracks, and thickness without causing any disturbance to the pavement.
- Falling Weight Deflectometer (FWD): The Falling Weight Deflectometer (FWD) helps determine load distribution and overall condition by applying a dynamic load to the pavement surface and measuring deflections to assess structural capacity and stiffness.
- Infrared Thermography: Using infrared thermography, surface fractures and delamination can be found by detecting temperature changes on the pavement surface that are suggestive of subsurface flaws or moisture content.
- Ultrasonic Pulse velocity:Ultrasonic Pulse Velocity (UPV) is a non-destructive testing technique that measures the velocity of ultrasonic waves travelling through asphalt pavement to find flaws such fractures, voids, segregation, and material irregularities.

6. Ground Penetrating Radar

One well-known non-destructive testing (NDT) method for evaluating pavement condition and identifying underlying flaws is ground penetrating radar (GPR). High-frequency electromagnetic waves are sent into the pavement layers by GPR, which then records the reflected signals from interfaces—like layer borders or defects—where material properties change.GPR finds a variety of flaws, including moisture intrusion, voids, delamination, inadequate compaction, and cracking, by examining reflected signals and layers. Stripping (loss of asphalt binder), debonding or delamination between layers, voids beneath the surface, and moisture accumulation are the primary flaws in asphalt pavements that GPR finds.GPR provide quick, ongoing, and non-invasive evaluation capacities.

7. GPR-Identified Defects

The following are typical pavement flaws found by GPR:

- Air Voids:The difference between the air (low dielectric) and the surrounding materials causes air voids between layers to be detected as reflections with a higher amplitude. Voids inside base layers or under asphalt overlays can be precisely identified.
- Cracks and Fractures: Under the surface, GPR can identify longitudinal or transverse cracks, particularly when they are filled with moisture or debris and reflect as linear or hyperbolic reflections.
- Stripping: Changes in dielectric characteristics that result in anomalous reflections and amplitude reductions in the radargram—which often appear as zones with reduced velocity and disrupted layer continuity—allow GPR to detect stripping.
- Delamination: Due to the air gap or low-density material producing a large dielectric contrast, delamination or debonding between asphalt layers or overlays appears in the radargram as strong, irregular reflections at the interface.
- Poor Compaction: Lower compaction or density regions result in minor but noticeable variations in travel time and amplitude, which are frequently seen as slow rises or drops in velocity and decreased signal coherence.

The Principles And Workings Of GPR

8.1 Principle

High-frequency electromagnetic (EM) waves propagate, reflect, transmit, and refract in the subsurface, which is the foundation of the Ground Penetrating Radar (GPR) principle. Short bursts of electromagnetic energy, or radio waves, are sent into the ground or pavement by a GPR system using a transmitting antenna. When these waves come into contact with an interface between materials that have distinct electromagnetic characteristics, namely dielectric permittivity, some of them are reflected back toward the surface, while the rest keep spreading. The signals that are reflected are then picked up by the receiving antenna. Electrical permittivity, electrical conductivity, and magnetic permeability are the main electromagnetic characteristics that affect GPR signals; dielectric permittivity is the most important in regulating wave velocity and reflection strength. Since the permittivity of different materials affects the EM wave's velocity, the travel time of the reflected signals collected at the surface can be translated into depth data to map underlying structures.

Strong reflections are produced by interfaces with significant differences in dielectric characteristics, such as metallic objects or air-filled gaps, whereas weak or no reflections are produced by equivalent materials. A radargram, a type of cross-sectional profile that displays the location and depth of subsurface objects, is created by moving the antenna across the surface and continually capturing the reflection data to create GPR photographs.

8.2 Working

i) Transmission of Radar Pulses: A GPR system uses a transmitter antenna to send brief electromagnetic energy pulses into the pavement or subsurface, usually between 10 MHz and 2.6 GHz.

ii) ii) Wave Propagation and Reflection: These electromagnetic waves move through the material in a downward direction until they come to rest on a boundary between various subsurface materials with dissimilar electrical characteristics (such as a layer interface, void, or fracture). A portion of the wave energy is reflected back toward the surface at this limit, but the remainder keeps moving deeper.

iii) Reflected Signal Reception: Reflected waves that return to the surface are picked up by a receiver antenna. The system calculates the strength (amplitude) of the signals that are returned as well as the time it takes for the pulses to descend, reflect, and return.

iv) iv) Data processing and imaging: Using the wave velocity, which is dependent on the materials' dielectric characteristics, the time delay of the reflected pulses is translated into depth information. A radargram, which is a cross-sectional image of the subsurface displaying layer boundaries, flaws, and anomalies, is created by processing the amplitude fluctuations and trip duration of the reflections.

v) Interpretation: Types of subsurface features can be identified by differences in signal reflection patterns. For instance, voids produce powerful reflections without polarity change, but metallic objects provide high-amplitude reflections with polarity flip. Advanced data processing techniques, such as migration, can be used to adjust for dipping or angled reflectors and enhance image.

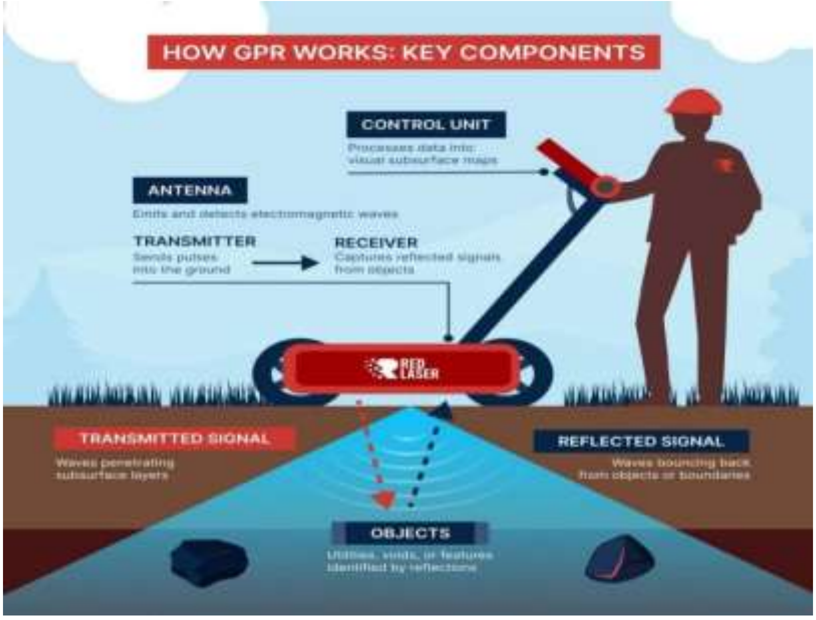

Fig.3:Ground Penetrating Radar

9. Factors Affecting GPR Data

Wave reflection and attenuation are impacted by the dielectric constant and electrical conductivity, which are raised by moisture in the pavement or underlying layers. Signal quality is impacted by temperature, moisture content, and layer bonding.In clay-rich or saline soils, the penetration depth is limited, and computing resources and competent operators are needed. Costs associated with equipment and analysis Sophisticated processing requires highly precise equipment and computational power.

10. Future Directions

- Artificial Intelligence: The interpretation of GPR data is moving towards automated, data-driven solutions driven by deep learning and machine learning, especially when it comes to detecting hyperbolic characteristics (which are signs of buried objects, voids, and cracks.
- 3D and Multi-Frequency GPR Imaging: In order to examine various layer depths and resolutions simultaneously, the industry is shifting towards 3D GPR data collecting techniques, which combine several B-scans in grid layouts and make use of multi-frequency antennas.

11. Conclusion

In summary, Ground Penetrating Radar (GPR) is now a vital non-destructive technique for identifying flaws in asphalt pavements since it provides quick, high-resolution profiling without causing structural damage or causing traffic jams. Air voids, delamination, stripping, moisture buildup, poor compaction, and cracks are just a few of the many defects that GPR has been shown to be highly effective at detecting through distinctive electromagnetic reflection patterns that can be automatically or visually interpreted using sophisticated image processing and machine learning techniques.The combination of automated severity grading and 3D visualization allows for a thorough, quantitative evaluation of pavement health, assisting with asset management and preventative maintenance plans.

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