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Analysis of Key Technologies for On-site Detection of Subgrade and Pavement of Municipal Roads

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Abstract: On-site inspection of municipal road subgrade and pavement is of great significance for ensuring the quality, safety, and durability of urban road infrastructure. This paper analyzes its key technologies, introduces non-destructive testing methods such as ground-penetrating radar and ultrasonic testing, elaborates on the multifaceted roles of inspection in engineering construction as well as relevant standards, explores site challenges, key technologies, and corresponding measures, and points out future research directions in intelligent sensing and predictive maintenance.

Keywords: Municipal roads; Subgrade and pavement inspection; Key technologies

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1. Introduction

The on-site detection of municipal road subgrade and pavement is essential for ensuring the quality, safety, and durability of urban road infrastructure. With the continuous development of urbanization, the importance of accurate detection technologies has become even more prominent. In recent years, relevant policies have been introduced to support the development of this field. For example, the "Urban Road Infrastructure Construction and Maintenance Guidelines" emphasizes the need to improve the level of on-site detection of subgrade and pavement to enhance the overall quality of urban roads. Advances in non-destructive testing technologies, as highlighted in recent research, further underscore the progress in this area [1]. This paper delves into the key detection technologies, analyzes the challenges faced, and explores future research directions, aiming to contribute to the sustainable development of urban road construction.

2. Overview of municipal road subgrade and pavement detection

2.1. Core detection technologies

Ground penetrating radar (GPR) is a widely used technology in the on-site detection of municipal road subgrade and pavement. It works by emitting electromagnetic waves into the ground and analyzing the reflected waves to identify subsurface structures, voids, or thickness changes in the subgrade and pavement layers. GPR can provide high resolution images of the internal structure of the road, helping engineers accurately assess the integrity of the roadbed and pavement [2].

Ultrasonic testing is another important nondestructive testing method. Ultrasonic waves are transmitted through the road materials, and the time of flight and amplitude of the waves are measured. By analyzing these parameters, information about the internal structure, such as cracks, porosity, and layer interfaces, can be obtained. This method is effective in detecting small scale defects and changes in material properties within the subgrade and pavement.

These nondestructive testing methods play a crucial role in on-site detection of municipal road subgrade and pavement. They allow for a quick and accurate assessment of the structural integrity without causing damage to the road surface, which is essential for timely maintenance and repair of municipal roads, ensuring their long-term serviceability and safety.

2.2. Role in construction engineering

The detection of municipal road subgrade and pavement plays a pivotal and multi-faceted role in construction engineering. Firstly, it serves as a quality gatekeeper. By accurately assessing the physical and mechanical properties of the subgrade, such as soil compaction degree and bearing capacity, and the performance of the pavement like thickness and flatness, it ensures that the road construction meets the predefined quality standards. Faulty subgrade or pavement can lead to premature road failures, affecting traffic safety and durability [3].

Secondly, the detection helps in cost control. Early detection of potential problems allows for timely adjustments and rectifications during the construction process. For example, if the subgrade is not compacted properly, discovering this issue early can prevent the need for costly reconstruction later on, which would involve removing and rebuilding a large section of the road.

Thirdly, it contributes to environmental protection in construction. By detecting the quality of materials used in the subgrade and pavement, it can ensure that no harmful substances are released during construction or in the long-term service life of the road. This is in line with the sustainable development requirements of modern construction engineering.

In summary, the on-site detection of municipal road subgrade and pavement is an essential link in construction engineering, safeguarding quality, cost, and environmental friendliness simultaneously.

3. Detection requirements and standards

3.1. Municipal engineering specifications

In municipal engineering specifications, when it comes to on-site detection of subgrade and pavement of municipal roads, the comparison of technical requirements among different standards is crucial. ASTM (American Society for Testing and Materials) and AASHTO (American Association of State Highway and Transportation Officials) standards have their own characteristics in road compaction, bearing capacity, and layer thickness measurements. For example, in road compaction testing, ASTM may emphasize certain test procedures and equipment specifications to accurately measure the degree of compaction. AASHTO might focus more on the relationship between compaction and traffic load bearing capacity.

On the other hand, Chinese GB (Guobiao, national standards) also has its own set of strict requirements. In road compaction, Chinese standards not only consider the basic physical properties of the soil or materials but also take into account the long-term stability and durability of the road under local climate and traffic conditions. For bearing capacity testing, Chinese GB standards are designed to ensure that the subgrade and pavement can withstand the expected traffic loads during their service life. Regarding layer thickness measurements, precise methods are specified to guarantee the proper structure and performance of each road layer. By comparing these standards, engineers can select the most suitable detection methods and ensure the quality of municipal road construction, taking into account both international best practices and local engineering needs [4].

3.2. Site-specific challenges

Urban traffic presents significant constraints for on-site detection of subgrade and pavement in municipal roads. The high volume of vehicles in urban areas makes it difficult to conduct continuous and comprehensive detection. For example, in peak traffic hours, the detection equipment may not be able to operate freely, leading to interrupted data collection, which in turn affects the accuracy and integrity of the detection results [5].

Underground utility interference is another crucial challenge. Municipal roads are often criss crossed with various underground utilities such as water pipes, gas pipelines, and power cables. These utilities can interfere with the detection signals of subgrade and pavement, causing false readings or inaccurate data. For instance, electromagnetic signals from power cables can disrupt the electromagnetic based detection methods used to assess the subgrade condition.

Environmental factors also play a role in influencing detection accuracy. Weather conditions like heavy rain, snow, or extreme heat can impact the performance of detection equipment. High humidity may cause corrosion of sensors, while extreme temperatures can affect the physical properties of the detection materials, leading to inaccurate measurements. In addition, urban dust and pollution can accumulate on the detection equipment, potentially reducing its sensitivity and reliability. All these site-specific challenges need to be carefully considered and addressed to ensure accurate and effective on-site detection of subgrade and pavement in municipal roads.

4. Critical technology analysis

4.1. Non-destructive evaluation

4.1.1. GPR applications

Ground Penetrating Radar (GPR) is a crucial nondestructive evaluation tool in the on-site detection of subgrade and pavement of municipal roads. It operates based on the principle of electromagnetic wave reflection analysis. When GPR emits electromagnetic waves into the subgrade and pavement structures, the waves travel through different materials. The dielectric properties of various substances within the structures, such as voids, different soil types, and pavement layers, are distinct, causing the electromagnetic waves to reflect at the interfaces between these materials.

For void detection, the reflected waves from voids show characteristic patterns. The amplitude and travel time of the reflected waves can be analyzed to determine the presence, location, and approximate size of voids. A sudden change in the reflection signal indicates a potential void area [6]. In terms of density profiling, the propagation speed of electromagnetic waves is related to the density of the medium. Denser materials generally cause the waves to travel more slowly. By measuring the travel time of the waves through different layers and analyzing the reflection signals, engineers can estimate the density distribution within the subgrade and pavement. This information is vital for assessing the quality and integrity of the road structures, helping to identify areas that may be prone to future damage or settlement, and guiding appropriate maintenance and repair strategies.

4.1.2. Ultrasonic pulse velocity

Ultrasonic Pulse Velocity (UPV) is a crucial nondestructive evaluation technique for on-site detection of subgrade and pavement of municipal roads. In the context of municipal pavement quality control, it can be effectively used to assess the homogeneity of concrete.

When using UPV, ultrasonic waves are transmitted through the concrete structure of the pavement. The velocity of these ultrasonic pulses depends on various factors such as the density, elasticity, and internal structure of the concrete. Homogeneous concrete will allow the ultrasonic waves to travel at a relatively consistent velocity. By analyzing the waveforms of the received ultrasonic signals, engineers can gain insights into the internal condition of the pavement [7].

If there are voids, cracks, or inhomogeneous material distributions within the concrete, the ultrasonic pulse velocity will change. For example, a lower-than-normal velocity may indicate the presence of a void or a crack, as the wave has to travel through a less dense medium or a disrupted path. On the other hand, an abnormal increase in velocity might suggest a region of higher density or more compacted concrete.

The UPV method offers several advantages for on - site detection. It is nondestructive, meaning it does not cause damage to the pavement structure, allowing for continuous monitoring over time. It is also relatively quick and can provide real - time results, enabling prompt decision making during the construction or maintenance of municipal roads. This technique, therefore, plays an essential role in ensuring the quality and integrity of subgrade and pavement in municipal road projects.

4.2. Destructive testing methods

4.2.1. Dynamic cone penetrometer

The dynamic cone penetrometer is a crucial tool in destructive testing methods for on-site detection of subgrade and pavement of municipal roads. It can rapidly and effectively evaluate the strength characteristics of subgrade materials.

This device operates by driving a cone shaped penetrator into the soil under dynamic impact. The resistance encountered during penetration is related to the strength properties of the soil. The measured penetration resistance can be used to estimate parameters such as the California Bearing Ratio (CBR) of the subgrade, which is essential for assessing the load bearing capacity of the subgrade.

When using the dynamic cone penetrometer, factors like the mass of the falling weight, the height of the drop, and the cone angle need to be precisely controlled. These parameters directly influence the penetration resistance values obtained. The testing procedure typically involves multiple penetration measurements at different locations within the test area to ensure the representativeness of the results.

Compared with some traditional static testing methods, the dynamic cone penetrometer offers the advantage of quick operation, which is beneficial for large scale on-site inspections. However, it also has limitations. For example, the results may be affected by soil heterogeneity and the presence of gravel or other inclusions in the soil. To overcome these limitations, it is often necessary to combine the results of dynamic cone penetrometer tests with other testing methods. In conclusion, the dynamic cone penetrometer plays an important role in the on-site detection of subgrade and pavement, but its application should be carefully considered in light of the specific characteristics of the test site [8].

4.2.2. Core sampling analysis

Core Sampling Analysis involves carefully extracting cylindrical samples from the subgrade and pavement. This method is crucial as it provides direct access to the internal structure and composition of the materials. For the subgrade, cores are taken to determine its density, moisture content, and soil particle distribution. By analyzing these parameters, engineers can assess the subgrade’s load bearing capacity and stability. In the case of the pavement, especially asphalt pavement, core sampling helps in verifying the thickness of different layers, such as the asphalt layer, base layer, and sub base layer. It also allows for the examination of the asphalt aggregate ratio and the quality of compaction.

Laboratory tests are then carried out on these core samples. For density measurement, methods like the wax sealing method or the core cutter method can be used. To determine the moisture content, samples are dried in an oven at a specific temperature until a constant weight is achieved. The analysis of aggregate gradation in the asphalt mixture from the core samples follows standard sieve analysis procedures. Through these detailed laboratory tests on core samples, accurate data can be obtained to evaluate the quality and performance of the subgrade and pavement, ensuring that they meet the design requirements and can withstand the long-term traffic loads and environmental impacts [9].

5. Technological challenges and solutions

5.1. Environmental limitations

5.1.1. Moisture interference mitigation

Moisture interference is a significant challenge in the on-site detection of subgrade and pavement of municipal roads. Groundwater and surface moisture can greatly affect the accuracy of detection results, especially in dielectric constant measurements. For example, moisture can change the electrical properties of subgrade and pavement materials, leading to inaccurate readings of dielectric-based detection methods.

To mitigate this moisture interference, multi sensor fusion approaches are proposed [10]. By integrating data from multiple sensors, such as dielectric sensors, resistivity sensors, and moisture specific sensors, a more comprehensive understanding of the moisture condition can be achieved. Dielectric sensors can provide information about the dielectric properties of the materials, which are related to moisture content. Resistivity sensors, on the other hand, can measure the electrical resistivity of the materials, which also varies with moisture levels. Combining these two types of sensors can help cross validate the moisture information. Additionally, moisture specific sensors can directly detect the presence and amount of moisture in the materials. The fusion of data from these different sensors can reduce the uncertainty caused by moisture interference. Through data fusion algorithms, the complementary information from each sensor is integrated, enabling more accurate determination of the subgrade and pavement conditions, even in the presence of moisture. This approach improves the reliability and precision of on-site detection, ensuring that the results can better reflect the real-world state of the municipal road subgrade and pavement.

5.1.2. Temperature compensation models

Developing accurate temperature compensation models is crucial for the on-site detection of subgrade and pavement of municipal roads, especially in seasonal pavement monitoring. Temperature variations can significantly affect the performance and measurement results of detection technologies. For example, in cold seasons, materials contract, while in hot seasons, they expand, potentially leading to inaccurate readings of pavement thickness, subsidence, or crack widths.

To address this, algorithms for thermal expansion correction are developed. These algorithms take into account the physical properties of pavement materials, such as their coefficient of thermal expansion. By accurately measuring the ambient temperature during on-site detection and using the established thermal expansion models, the raw measurement data can be adjusted. For instance, if the measured crack width seems larger in a hot environment, the algorithm can correct this value based on the known thermal expansion characteristics of the pavement material [11].

The temperature compensation models also need to consider the time dependent effects of temperature changes. The rate at which the pavement material responds to temperature variations can vary, and this dynamic behavior must be incorporated into the model. Additionally, different layers of the subgrade and pavement may have different temperature related responses. By comprehensively analyzing these factors and refining the temperature compensation models, more accurate and reliable on-site detection results can be obtained, enabling better assessment of the health and condition of municipal road subgrades and pavements.

5.2. Equipment optimization

5.2.1. Portable detection systems

Portable detection systems play a crucial role in on-site detection of subgrade and pavement of municipal roads. These systems face several technological challenges. One significant issue is achieving high precision data collection in a portable form factor. The limited space and power supply in portable devices restrict the installation of large-scale, high-performance sensors. To address this, integrated sensor platforms with edge computing capabilities are developed [12]. These platforms can process data in real time at the edge of the network, reducing the need for large scale data transfer to a central server. By integrating multiple types of sensors, such as ground penetrating radar sensors for subgrade structure detection and optical sensors for pavement surface condition monitoring, into a compact and portable unit, more comprehensive data can be collected. Moreover, the edge computing function enables immediate data analysis, providing quick feedback on potential problems like subgrade voids or pavement cracks. This not only improves the efficiency of on-site detection but also ensures that timely measures can be taken to maintain the quality of municipal road subgrades and pavements. Additionally, the portability of these systems allows for easy access to various road sections, including those in hard-to-reach areas, which is essential for comprehensive road condition assessment.

5.2.2. Automated interpretation software

Automated interpretation software plays a crucial role in on-site detection of subgrade and pavement of municipal roads. One of the main technological challenges lies in accurately recognizing complex signal patterns in the data collected from various detection equipment. Traditional methods often rely heavily on operators' experience and manual interpretation, which not only consumes a great deal of time but also has high subjectivity, leading to inconsistent results [13].

To address this, machine learning based automated interpretation software has emerged. By training on a large number of labeled data, the software can learn the characteristics of different signal patterns related to subgrade and pavement conditions. For example, it can distinguish between normal and abnormal signals indicating issues like cracks, voids, or unevenness. This significantly reduces the dependency on individual operators' skills and knowledge.

Moreover, the software can be designed to adapt to different types of detection equipment and data formats. It can preprocess the raw data, remove noise and standardize the data structure to ensure better pattern recognition. Additionally, real time processing capabilities are integrated into the software, enabling immediate feedback during on-site detection. This allows engineers to take timely measures, improving the efficiency and accuracy of the entire detection process for municipal road subgrades and pavements.

5.3. Data integration strategies

5.3.1. BIM-GIS convergence

In the context of on-site detection of subgrade and pavement of municipal roads, the convergence of Building Information Modeling (BIM) and Geographic Information System (GIS) faces several technological challenges. BIM mainly focuses on the detailed 3D modeling of buildings and structures, while GIS emphasizes spatial analysis and geographical data management. Integrating these two systems requires resolving differences in data formats, data granularity, and data storage mechanisms. For example, BIM data is often in a proprietary format with high level details for construction elements, while GIS data is more general - purpose and suitable for large scale spatial analysis.

To address these challenges, one solution is to develop unified data standards. By establishing common data models and exchange formats, seamless data transfer between BIM and GIS can be achieved. Another approach is to use middleware or conversion tools. These can act as bridges to translate BIM data into a format that GIS can understand and vice versa. Additionally, semantic integration is crucial. This involves mapping the semantics of BIM elements to GIS features, enabling more meaningful data integration. For instance, a road segment in BIM can be semantically linked to a corresponding linear feature in GIS for better spatial analysis and lifecycle management of municipal road infrastructure [14]. Through these strategies, the BIM - GIS convergence can be effectively realized, providing a more comprehensive and powerful platform for on-site detection and management of municipal road subgrade and pavement.

5.3.2. Multi-temporal analysis frameworks

Multi-temporal analysis frameworks play a crucial role in accurately predicting the pavement deterioration trend through the establishment of time series evaluation systems. One of the main technological challenges lies in handling the vast amount of multi - temporal data collected from various sources during the on-site detection of subgrade and pavement of municipal roads. These data may come from different sensors, survey methods, and time intervals, which can lead to issues such as data heterogeneity and inconsistent data formats.

To address these challenges, effective data integration strategies are essential. For example, a standardized data format should be defined for all data sources related to multi temporal analysis. This ensures that data can be easily combined and analyzed. Additionally, advanced algorithms can be utilized to preprocess the data, removing noise and outliers while normalizing different data types.

In terms of the multitemporal analysis frameworks themselves, a hierarchical model can be adopted. At the lower level, detailed data from each detection time point is analyzed to identify short term changes and anomalies. At the higher-level, long-term trends are extracted by integrating data over multiple time points. This hierarchical approach helps in both detecting immediate problems and predicting long term pavement deterioration trends, enabling more comprehensive and accurate evaluation of the subgrade and pavement conditions of municipal roads.

6. Conclusion

In conclusion, the analysis of key technologies for on-site detection of subgrade and pavement of municipal roads has illuminated significant aspects of modern urban infrastructure management. The technological advances in this field, as discussed, have enabled more accurate, efficient, and nondestructive ways to assess the condition of subgrades and pavements. These advancements not only contribute to maintaining the structural integrity of municipal roads but also enhance the overall safety and durability of the transportation network.

The proposed implementation roadmaps for construction quality assurance serve as practical guidelines for construction teams and relevant authorities. By adhering to these roadmaps, it is possible to ensure that new construction and maintenance projects meet high quality standards, thereby reducing the long-term cost of road management.

Looking ahead, the future research directions in smart sensing and predictive maintenance systems hold great promise. Smart sensing technologies can provide real time data on road conditions, enabling proactive measures to be taken before serious damage occurs. Predictive maintenance systems, on the other hand, can optimize maintenance schedules based on data driven models, leading to more efficient use of resources. Overall, continuous research and innovation in these areas will be crucial for the sustainable development of municipal road infrastructure, ensuring that it can meet the growing demands of urbanization and modern transportation.

Disclosure statement

The author declares no conflict of interest.

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