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Review on Case Studies of Highway pavement crack recognition under complex environment

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Abstract- Pavements are complex structures involving many variables, such as materials, construction methods, loads, environment, maintenance, and economics. Thus, various technical and economic factors must be well understood to design, build pavements, and to maintain better pavements. Moreover, the problems relating to pavement maintenance are still complex due to the dynamic nature of road pavements where elements of the pavement are constantly changing, being added or removed. These elements deteriorate with time and therefore to be maintained in good condition requires substantial expenditure.

Keywords – pavement; deterioration; maintenance; dynamic nature.

I. INTRODUCTION

Transportation planning and traffic planning are the initial stages of transportation engineering pertaining to road transport. Having planned highways, the next stage is the construction of the highways. The roads have to be constructed in different ground conditions and in different environments. The conditions and environments pose complex issues in highway construction. In many countries's context, these issues are:

- Congestion on urban roads
- Accidents
- Major roads running through built up areas (Cities and townships)
- Narrow roads
- Structural inadequacy of pavements
- Poor geometrical design
- Small structures such as bridges
- Funding for maintenance and rehabilitation
- Funding for expansion and new facilities
- Environmental pollution

These issues provide the following challenges to the highway engineer.

1. Challenges of design, construction, rehabilitation, reconstruction and expansion

- Design and reconstruct using modern technologies
- Redesign older facilities to meet today's demands.
- Secure budget provisions.
- Adopt cost effective and environmentally sound solutions.

2**. Challenges of safety and environment**

- Identify necessary safety requirements of the road system especially, to protect vulnerable road users.
- Implement regulations controlling noise, air and water pollution.

II. PAVEMENT DESIGN

The main purpose of a pavement is to provide a means of reducing the stress due to the wheel load to a value bearable to ground under the pavement.

Fig. 1.1 shows how the high stress that exists at the point of wheel contact is reduced down the pavement structure until the stress is brought down to a level acceptable to the less competent naturally existing ground called the subgrade.

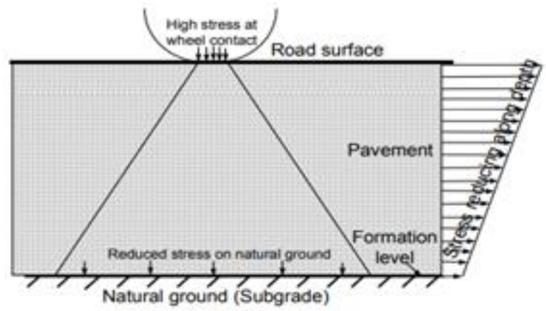

Fig. 1.1 Distribution of wheel load to the ground.

The pavement may be a single layer of one material or multiple layers of different material. There are three types of pavements, which are,

1. Flexible pavements
2. Rigid pavements
3. Composite pavements

Flexible pavements are constructed using granular material and bitumen. They can be subdivided into three types, conventional flexible pavements which consist of two or more layers of different material, full depth flexible pavements which have only one layer and CRAM.

Rigid pavements are constructed of Portland cement concrete (PCC) Composite pavements have a base layer of PCC and a surface layer of hot-mix asphalt. They have strength of rigid pavements and smooth surface of flexible pavements. There are two factors which lead to the development of layered flexible pavement construction.

They are
(i.) the stresses from vehicles travelling on the road are highest near the surface
(ii.) A smooth riding surface is necessary to reduce fatigue due to varying stresses on surface.

III. PAVEMENT MAINTENANCE

Pavement maintenance has advanced from a notion in the 1960s to present-day common and practical implementations in many countries. Pavement maintenance management systems were well-developed in different organizations across the world, but they did not take shape until the mid-to-late 1970s when they incorporated all of these operations into a functioning PMS. The World Bank has carried out a variety of road projects since 1968 and has established many assessment modules, including models of pavement efficiency. They have spread worldwide (to over 100 countries) and need to be tailored to local conditions.

Road transport infrastructure deteriorates as a result of aging, vulnerability to weather and traffic, and backlog repairs. As a consequence, one primary issue involves the viability of these infrastructures. The latest developments suggest that there are substantial and growing expenses surrounding sustainable transport networks. As a result, the overall thinking regarding infrastructure management that takes maintenance needs into account is gaining importance.

From 2008 to 2028, it is projected that an annual expenditure of $USD 101 billion will be needed to sustain all USA highways and that failure to deliver the funds will further weaken road networks. The USA already invests over USD 184 billion annually to repair and expand its road networks. More than GBP 15 billion is expected to be spent in England to expand its road networks. Flexible pavements experience numerous distress indicators, including cracks, potholes, erosion, etc. It is not easy to identify the existence of various distress indicators. Distress position, scale, severity, and mapping are key problems.

IDENTIFICATION OF DEFECTS
By way of physical inspection of affected highway stretches deteriorated, the maintenance activities were categorized under three operations viz, Routine Maintenance, Periodic Maintenance and Special Repairs. During the inspection the defects in existing flexible road pavement were generally classified into the following groups:

- Road stretches which are structurally deficient where distress and failures of the pavements occurs at frequent intervals be identified. Unless the structural deficiency is made up by appropriate strengthening measures/overlay construction, rapid rate of failure would continue to occur in these stretches.

IV. RESEARCH MOTIVATION

Effective and efficient pavement condition assessment is critical for determining pavement assessment performance and planning repairs. Numerous studies have shown that timely and accurate inspection of pavement cracks can help transportation agencies reduce road maintenance costs and extend pavement life. However, the traditional crack detection mainly relies on manual visual inspection, which is time-consuming and labor-intensive in actual operation, and it is difficult to objectively evaluate the degree of road deterioration. Therefore, it is necessary to develop an automatic, accurate and efficient pavement crack detection method. With the development of computer vision and civil engineering image processing, image-based automatic crack detection technology has gradually replaced the traditional artificial visual detection.

RESEARCH OBJECTIVES
Following objectives are perform given research work-
1. To Identification of road cracks and its Causes.
2. To reduction of Highway crack Treatment cost.
3. To observation its effects and novel approach to gives its reduction technique.

V. LITERATURE REVIEW

[1] Zhihua Zhang et al.The pavement is vulnerable to damage from natural disasters, accidents and other human factors, resulting in the formation of cracks. Periodic pavement monitoring can facilitate prompt detection and repair the pavement diseases, thereby minimizing casualties and property losses. Due to the presence of numerous interferences, recognizing highway pavement cracks in complex environments poses a significant challenge. Nevertheless, several computer vision approaches have demonstrated notable success in tackling this issue. We have employed a novel approach for crack recognition utilizing the ResNet34 model with a convolutional block attention module (CBAM), which not only saves parameters and computing power but also

ensures seamless integration of the module as a plug-in. Initially, ResNet18, ResNet34, and ResNet50 models were trained by employing transfer learning techniques, with the ResNet34 network being selected as a fundamental model. Subsequently, CBAM was integrated into ResBlock and further training was conducted. Finally, we calculated the precision, average recall on the test set, and the recall of each class. The results demonstrate that by integrating CBAM into the ResNet34 network, the model exhibited improved test accuracy and average recall compared to its previous state. Moreover, our proposed model outperformed all other models in terms of performance. The recall rates for transverse crack, longitudinal crack, map crack, repairing, and pavement marking were 88.8%, 86.8%, 88.5%, 98.3%, and 99.9%, respectively. Our model achieves the highest precision of 92.9% and the highest average recall of 92.5%. However, the effectiveness in detecting mesh cracks was found to be unsatisfactory, despite their significant prevalence. In summary, the proposed model exhibits great potential for crack identification and serves as a crucial foundation for highway maintenance.

[2] Brahim Benmhahe et al. Crack detection is crucial for assessing pavement health, as cracks can deteriorate into more severe distresses like potholes and bumps. Consequently, numerous studies have been conducted to detect pavement cracks, achieving high levels of accuracy. Further research is ongoing to identify cost-effective and easily deployable solutions. This paper introduces a novel approach to pavement crack detection and identification using Map Fusion. The method integrates 2D features, such as grayscale levels, with 3D features, including roughness and normal change rate, into a unified map. 3D points that meet predefined criteria are identified as potential crack candidates. Noise is removed first, followed by the Graham Scan algorithm to delineate the crack skeleton. The method was validated on longitudinal and transversal cracks, demonstrating high precision compared to image-based and 3D model-based feature selection techniques.

[3] Jinhuan Shan et al. Efficient road inspection and maintenance are essential to extend pavement lifespan and enhance safety. However, automated crack detection remains challenging due to varied environmental conditions and differences in image collection equipment, making robust algorithm development a critical need. Vision Transformers, with their capacity to capture long-range dependencies, offer significant advantages for crack detection in complex scenarios by effectively extracting global features. Nevertheless, existing Transformer-based methods encounter difficulties in boundary delineation due to decoder design limitations, which lead to suboptimal fusion of low-level and high-level features. To address this issue, we propose a comprehensive approach that integrates semantic preservation, detail refinement, and detail delineation. These concepts are realized through our novel Dual-Cross Attention Module (DCA) and Upsampling Attention Module (UA). The DCA module progressively filters redundant details from low-level feature layers using high-level semantic information, while preserving boundary details to refine high-level feature boundaries. In addition, the UA module employs progressive local cross-attention in upsampling, facilitating more precise boundary definitions and surpassing conventional dynamic upsampling methods. Our approach, utilizing both lightweight (MiT-B0, LVT) and middleweight (Swin-T) backbones, demonstrates state-of-the-art performance on three diverse datasets—Crack500, CrackSC, and UAV-Crack500—highlighting its robustness across varied conditions. This work contributes to advancing Transformer-based architectures for defect segmentation in complex engineering contexts, underscoring the critical role of improved feature fusion in crack detection.

[4] Haoran Zhu et al. To improve the detection efficiency of internal cracks in semi-rigid base asphalt pavements and alleviate the challenges associated with interpreting grayscale mapping, a comprehensive crack detection and signal interpretation is proposed in this study, grounded in extensive engineering practice. High-precision three-dimensional ground penetrating radar (3D-GPR) is employed to capture the internal structure signals. Subsequently, practical approaches tailored for transverse and longitudinal cracks are proposed. Extensive core extraction verification was conducted to summarize the radar grayscale mapping features. The horizontal profile is the primary basis for crack identification and can be used to accurately locate cracks without secondary damage. Furthermore, the time–frequency domain characteristic signals of cracks and normal pavement are summarized in datasets and compared. Eight characteristic signals for transverse cracks and five for longitudinal cracks are identified, offering a perspective based on underlying radar signals. The integration of mapping features and time–frequency domain characteristic signals enhances the crack recognition methods. Identification accuracy of both transverse and longitudinal cracks is greater than 95%, improving the accuracy of interpretation of 3D-GPR.

[5] Biao Yue et al. Crack segmentation is of great significance in automatic pavement crack detection based on image recognition. Although recent convolutional neural network (CNN)-based segmentation methods have shown promising performance, accurate pavement crack segmentation still faces some challenges, such as various crack sizes, class imbalance issues, and background interference. To overcome these challenges, a compact two-stage pavement crack segmentation network based on encoder-decoder architecture (TSPCS-Net) is proposed, which includes a classification network and a segmentation network. The classification network, consisting of a feature extraction module transferred from the segmentation network and a lightweight feature fusion module, is used to quickly classify and eliminate crack-free images that existed in large numbers in actual pavement image datasets. The segmentation network is constructed based on an encoder-decoder architecture for precise pixel-level segmentation of the

samples determined as crack images. Specifically, to extract multi-scale crack features, a novel multi-scale encoder module is designed by combining dilated convolution and residual structure. Then, a left-side path (LSP) is designed to alleviate the influence of class imbalance on feature extraction. Finally, an attention module with high-dimensional features guiding low-dimensional features (AM-HGL) is proposed to focus on crack-relevant features and suppress interference information. The effectiveness of the proposed TSPCS-Net is validated on a self-made unmanned aerial vehicles pavement crack (UAVPC) dataset and two public pavement distress datasets, and extensive experiments show that the proposed method outperforms current state-of-the-art methods in terms of segmentation performance and efficiency, which can meet the needs of pavement crack segmentation in practical application scenarios.

[6] Michał A. Glinicki et al.Diagnostic tests were carried out on specimens drilled from a section of jointed, unreinforced highway pavement after 15 years of service. The section of highway was exposed to heavy road traffic, environmental actions of wet-freeze climate zone and associated winter maintenance including application of deicing salt. Premature pavement damage was manifested by visible cracking, mostly along transverse joints and in slab corners. Tests performed on core specimens included petrographic analysis of concrete and its components, using optical and scanning electron microscopy, also evaluation of elastic and transport properties, expansion potential, cracks and air void system. Numerous cracks in the grains of coarse quartzite aggregate were found. Reactive forms of quartz in quartzite aggregate - microcrystalline and cryptocrystalline quartz - were abundant. The gel-like products in cracks in quartzite grains and in surrounding cement paste were identified as alkali-silica reaction products. Expansion of specimens exposed to an alkali-silica reaction-promoting environment indicated the potential for further development of such reaction. Substantial cracking and reduction of modulus of elasticity was correlated with the presence of reactive quartz in quartzite aggregate. The role of additional destructive factors, such as the impact of heavy vehicles traffic and freeze-thaw aggression was indicated by greater cracks in the slow traffic lane compared than in the emergency lane, associated with local marginal air entrainment of concrete.

[7] Zhenwei Yu et al.The application of deep learning techniques for semantic segmentation of crack images has become a significant research direction in road maintenance and safety. Despite the extensive research in recent years on semantic segmentation algorithms based on convolutional neural networks, their relatively small actual receptive fields cannot effectively handle long and fine pavement cracks. In contrast, transformer-based models can effectively utilize contextual semantic information. Therefore, a robust pavement crack segmentation network, CSTF, is proposed based on the Swin Transformer encoder. Within CSTF, a feature pyramid pooling module is introduced to provide global priors, and a dual-branch decoder is designed to preserve and learn semantic information, enabling CSTF to handle large-scale images and wide-spanning cracks. The results demonstrate that CSTF achieved an mIoU of 0.813 and 22.97 FPS on the large-scale dataset constructed in this study, enabling high-precision real-time detection. Moreover, it exhibits robustness against common interfering patterns like striped patches or other disturbances found in pavement crack images.

[8] Shuangxi Zhou et al.To enhance the safety and comfort of vehicle travel, detecting pavement cracks is a critical task in road management. This article introduces an advanced single-stage target detection method utilizing the YOLOv5s algorithm to enhance real-time performance and accuracy. Initially, Squeeze-and-Excitation Networks are integrated into the model to facilitate self-learning for improved crack characterization. Subsequently, anchors computed through the K-means clustering algorithm are closely aligned with the fracture dataset, achieving an adaptation rate of 99.9 % and enhancing the recall rate of the model. Furthermore, the inclusion of the SimSPPF module from YOLOv6 diminishes memory usage and expedites detection speed. By replacing the original nearest up-sampling method with transposed convolution, optimization of up-sampling for crack datasets is achieved. Performance assessments reveal that the refined YOLOv5s algorithm attains an F1 score of 91 %, a mean Average Precision (mAP) of 93.6 %, and a 1.54 % increase in frames per second (fps) for pavement crack detection. This enhancement in detection technology signifies a substantial advancement in the maintenance and longevity of road infrastructure.

[9] Jiayv Jing et al. Current 2D and 3D image-based crack detection methods in transportation infrastructure often struggle with noise robustness and feature diversity. To overcome these challenges, the paper use CSF-CrackNet, a self-adaptive 2D-3D image fusion model utilizes channel and spatial modules for automated pavement crack segmentation. CSF-CrackNet consists of four parts: feature enhanced and field sensing (FEFS) module, channel module, spatial module, and semantic segmentation module. A multi-feature image dataset was established using a vehicle-mounted 3D imaging system, including color images, depth images, and color-depth overlapped images. Results show that the mean intersection over union (mIOU) of most models under the CSF-CrackNet framework can be increased to above 80 %. Compared with original RGB and depth images, the average mIOU increases with image fusion by 10 % and 5 %, respectively. The ablation experiment and weight significance analysis further demonstrate that CSF-CrackNet can significantly improve semantic segmentation performance by balancing information between 2D and 3D images.

[10] Mohammadhosein Pourgholamali et al. The motivation for cost-effective management of highway pavements is evidenced not only by the massive expenditures associated with these activities at a national level but also by the consequences of poor pavement condition on road users. This paper presents a state-of-the-art review of multi-objective optimization (MOO) problems that have been formulated and solution techniques that have been used in selecting and scheduling highway pavement rehabilitation and maintenance activities. First, the paper presents a taxonomy and hierarchy for these activities, the role of funding sources, and levels of jurisdiction. The paper then describes how three different decision mechanisms have been used in past research and practice for project selection and scheduling (historical practices, expert opinion, and explicit mathematical optimization) and identifies the pros and cons of each mechanism. The paper then focuses on the optimization mechanism and presents the types of optimization problems, formulations, and objectives that have been used in the literature. Next, the paper examines various solution algorithms and discusses issues related to their implementation. Finally, the paper identifies some barriers to implementing multi-objective optimization in selecting and scheduling highway pavement rehabilitation and maintenance activities, and makes recommendations to overcome some of these barriers.

VI. CONCLUSION

Nano crack repair in highways involves using advanced materials like nano-silica, carbon nanotubes, or nano-polymer sealants to address microscopic cracks before they expand. Techniques include spraying nano sealants that penetrate cracks through capillary action, injecting nano materials into deeper cracks, or applying self-healing asphalt mixes with embedded microcapsules or conductive fibers. These materials strengthen the pavement, enhance durability, and prevent further damage. While initially costly, nano crack repair extends pavement lifespan, reduces maintenance frequency, and improves overall road performance under various environmental and traffic conditions.

REFERENCE

1. Zhang, Z., Yan, K., Zhang, X., Rong, X., Feng, D., & Yang, S. (2024). Automated highway pavement crack recognition under complex environment. Heliyon, 10(4).
2. Benmhahe, B., Basmassi, M. A., & Chentoufi, J. A. (2024). Map Fusion-Based pavement longitudinal and transversal cracks recognition using 2D and 3D models features. Measurement, 116483.
3. Shan, J., Huang, Y., & Jiang, W. (2024). DCUFormer: Enhancing pavement crack segmentation in complex environments with dual-cross/upsampling attention. Expert Systems with Applications, 125891.
4. Zhu, H., Wei, G., Ma, D., Yu, X., & Dong, C. (2024). Research on the detection and identification method of internal cracks in semi-rigid base asphalt pavement based on three-dimensional ground penetrating radar. Measurement, 116486.
5. Yue, B., Dang, J., Sun, Q., Wang, Y., Min, Y., & Wang, F. (2025). TSPCS-net: Two-stage pavement crack segmentation network based on encoder-decoder architecture. Engineering Applications of Artificial Intelligence, 141, 109840.
6. Glinicki, M. A., Jóźwiak-Niedźwiedzka, D., Antolik, A., Dziedzic, K., Dąbrowski, M., & Bogusz, K. (2022). Diagnosis of ASR damage in highway pavement after 15 years of service in wet-freeze climate region. Case Studies in Construction Materials, 17, e01226.
7. Yu, Z., Chen, Q., Shen, Y., & Zhang, Y. (2024). Robust pavement crack segmentation network based on transformer and dual-branch decoder. Construction and Building Materials, 453, 139026.
8. Zhou, S., Yang, D., Zhang, Z., Zhang, J., Qu, F., Punetha, P., ... & Li, N. (2025). Enhancing autonomous pavement crack detection: Optimizing YOLOv5s algorithm with advanced deep learning techniques. Measurement, 240, 115603.
9. Jing, J., Yang, X., Ding, L., Wang, H., Guan, J., Hou, Y., & El-Badawy, S. M. (2024). Self-adaptive 2D3D image fusion for automated pixel-level pavement crack detection. Automation in Construction, 168, 105756.
10. Pourgholamali, M., Labi, S., & Sinha, K. C. (2023). Multi-objective optimization in highway pavement maintenance and rehabilitation project selection and scheduling: A state-of-the-art review. Journal of Road Engineering.