Exploring Various Assessment Techniques for Analyzing Rutting Behavior in Flexible Pavement Layers

Shiva Prasad N [1], B V Kiran Kumar [2]

[1]*Research Scholar, SKSJ Technological Institute, Visvesveraya Technological University, Belagavi – 590018*

[2]*Associate Professor, SKSJ Technological Institute, Visvesveraya Technological University, Belagavi – 590018*

[1]shivaprasadce85@gmail.com, [2]dr.kirankumar@ka.gov.in

Abstract

Rutting is the result of accumulated plastic deformation in flexible pavement layers due to repeated traffic loads, particularly under high pavement temperatures and heavy wheel loads. The performance of flexible pavements is directly influenced by factors such as stresses, strains, deflections, moisture, temperature, and traffic, with temperature fluctuations significantly affecting the stiffness of asphalt layers. Researchers have undertaken substantial efforts to understand and mitigate rutting, aiming to develop resilient and durable road surfaces. Laboratory tests, including the Cooper Wheel Tracking Test and the Hamburg Wheel Tracking Device, are designed to evaluate rutting susceptibility under controlled conditions. The Simple Performance Tests and other assessments help delve into the mechanical properties of asphalt mixtures. A notable innovation in this field is the Roller compactor cum rut analyzer (RCRA), a hydraulic compactor with the ability to apply precise pressure, adjust rolling speed, and maintain predetermined temperatures. The RCRA offers automation, reliability, and the capability to replicate real-world conditions, making it a valuable tool for researchers and quality control in bituminous mix design. Overall, this paper highlights on research and testing methods for improving road surfaces, enhancing transportation infrastructure, and achieving longer-lasting and more sustainable pavement systems.

Keywords: *flexible pavements, roller compaction, rutting, wheel tracking.*

1. Introduction

Rutting is a common type of distress observed around the globe in case of bituminous pavements. The phenomenon of rutting is an accumulated plastic deformation in the bituminous layers, in general flexible pavement layers, which is caused due to repeated application of traffic loads. The early development of unacceptable levels of rut damage in bituminous mixes occurs as the stiffness of the bituminous mix reduce due to high pavement temperatures during day in combination with heavy wheel loads [1].

The performance of a flexible pavement over its design life is directly related to the parameters such as stresses, strains, deflections, moisture, temperature and traffic, the majority being the cumulative traffic loads and environmentally induced stresses and strains [2]. Temperature variation is one of the main environmental factors that affect the performance of flexible pavement materials that alters the stiffness of the asphalt layer. At high temperatures the pavement becomes flexible and shows visco-elastic behaviour. At low temperatures the pavement behaves as a rigid linear elastic brittle material [3]. In addition, temperature variation causes thermal contraction or expansion which will induce thermal stresses and strains within the asphalt layer. Low temperature and thermal fatigue cracking are the two major distresses that result from thermal strains and stresses [4].

2. Literature review

Over the course of the last few decades, there has been a remarkable surge in research efforts aimed at comprehending the intricate behaviour of bituminous mixtures, particularly in relation to rutting, a phenomenon that significantly affects the durability and performance of asphalt pavements. This surge in research activity has been the pressing need to develop more resilient and long-lasting road surfaces, given the ever-increasing demands placed upon our transportation infrastructure. To this end, researchers have adopted a multi-faceted approach, blending both in-situ methods and laboratory testing techniques to gain a comprehensive understanding of the factors influencing rutting and how these mixtures respond under different conditions [5].

In-situ methods, which entail on-site assessments of real pavement structures, have emerged as a pivotal means of scrutinizing the intricate dynamics of bituminous mixes [6]. To achieve this, instrumented pavement test track sections are typically employed, enabling researchers to measure various influencing factors and response parameters with quantitative precision [7]. These parameters include stresses, strains, deflections, moisture levels, temperature, and the impact of traffic loadings. By directly quantifying these variables in a real-world context, researchers are better equipped to grasp the nuanced responses of pavement surfaces, which is often challenging to achieve through theoretical analysis alone. The in-situ approach represents a crucial method for evaluating the dynamic structural behaviour of pavements, offering insights that can significantly impact the design and maintenance of road surfaces [8]. Complementing the in-situ methods are laboratory testing techniques, which allow researchers to simulate and evaluate the permanent deformation performance of hot mix asphalt (HMA) under controlled loading and environmental conditions [9]. This controlled environment provides a valuable means of assessing how bituminous mixtures behave under specific stresses and temperatures, mirroring the real-world scenarios they will encounter. This approach has become indispensable in identifying discrepancies between laboratory results and field performance, ultimately improving the accuracy of pavement analysis and design.

Within the realm of laboratory testing, there is a wide array of standardized methods employed to analyze rutting performance in bituminous mixes. The Asphalt Pavement Analyzer (APA) is a notable example of such laboratory testing equipment. It encompasses various assessments, including the Hamburg Wheel Tracking Test (HWTT) and the Cooper Wheel Tracking Test, both designed to gauge the rutting susceptibility of asphalt mixes under controlled conditions [10]. Additionally, the utilization of Simple Performance Tests, such as the Flow Time (FT) test, Dynamic Modulus (DM) test, and Flow Number (FN) test, allows researchers to delve into the fundamental mechanical properties of asphalt mixtures, aiding in their assessment and development [11]. In addition to these, several other tests, including the Repeated Load Permanent Deformation (RLPD) test, the French Rutting Test, the Repeated Shear at Constant Height test, and the Frequency Sweep at Constant Height test using the Superpave Shear Tester (SST), have been employed to delve even deeper into the understanding of rutting behaviour [12]. Collectively, these tests provide a comprehensive toolkit for researchers to study the rutting performance of bituminous mixtures, offering insights into how different materials and designs perform under various loading and environmental conditions.

The global scope of this research endeavour is evident as different regions and countries have adopted their own preferred methods and testing protocols to evaluate flexible pavements [13]. The quest for better, more durable road surfaces is a shared global concern, and the techniques and tests used to achieve this goal continue to evolve and diversify as we gain a deeper understanding of the complex interactions between bituminous mixtures and the external factors they face in the field. This collective knowledge is crucial for paving the way toward safer, longer-lasting, and more sustainable transportation infrastructure around the world.

3. Laboratory evaluation methods

Cooper wheel tracking test (CWTT) is a laboratory performance test that is used to assess the susceptibility of asphalt mixtures to deform plastically at high temperatures and tyre pressure [14]. In this test a 50 mm wide, freely rotating wheel of 200 mm diameter, rests on the surface of a movable slab specimen of size 305 x 305 x 50 mm, confined in a steel mould which subjected to a to-and-fro movement at a frequency of 26.5 +/- 1.0 cycles/min.

Fig. 1. Cooper wheel tracking test equipment (www.averest.com)

This causes a total travelling distance of 230 +/- 10 mm for the rotating wheel as a result of simple harmonic motion of the slab confined in the mould. A standard loading magnitude of 700 N is transferred to the slab with the help of an eccentrically suspended weight through the rotating wheel attached with the loading arm (Fig. 1). The LVDT automatically records the rut depth at certain increments of loading passes. The test automatically terminates upon reaching any of the two adopted failure condition viz., an average rut depth of 12.5 mm or completion of 10,000 loading passes.

The ***Hamburg Wheel Tracking Device(WTD)*** is a laboratory test device used to evaluate the performance of asphalt paving mixtures for combined rutting and moisture damage [15]. The Hamburg WTD consists of two compacted slabs, each of 320 x 260 x 80 mm in dimensions, submerged under water at high temperatures over which a vertical load of 650 N is applied. The device uses two steel wheels of 203.5 mm in diameter and 47 mm in width to apply the vertical load (Fig. 2). Typically rut depths at 10000 and 20000 wheel passes (N) are recorded. The number of wheel passes (N) at 10 mm rut depth is also recorded. In this test, the asphalt mixture typically undergoes three stages of rutting during the test viz., the primary – consolidation stage, the secondary – rutting stage and the tertiary – flow stage. The primary stage is characterised by an initially high rate of rutting, predominantly associated with volumetric change, which decreased with N. The secondary stage is characterised by a low rate of rutting, exhibiting a nearly constant rate of volumetric change, which tends to increase near the onset of the tertiary stage. The tertiary stage is characterised by a high rate of rutting largely associated with plastic (shear) deformation without volume change. According to *Ghazi Al-Khateeb and Imad Basheer*, the rutting behaviour of the asphalt mixtures tested with the Hamburg WTD is a cubic model that takes the third-order in the form:

$$RD = a\,N^3 + b\,N^2 + c\,N \qquad (1)$$

Where, RD = rut depth, N = number of wheel passes, and a, b and c = model coefficients that are formulated as function of the material properties in the three phase system of the asphalt mixture (air voids, asphalt binder and aggregates) and environmental or testing conditions such as stress state, loading rate and mixture temperature.

Fig. 2. Hamburg Wheel Tracking Device [16]

The ***Simple Performance Test (SPT)*** System is a fully integrated testing system having the capability to perform the three candidate uniaxial and tri axial compression tests recommended in NCHRP Project 9-19 – the Flow time, Flow number and Dynamic Modulus tests (Fig. 3).

These tests are used by several researchers to measure the rutting potential of asphalt concrete mixture. The SPT system includes a confining pressure system and environmental control over the temperature range of 20 to 60°C. The tests are performed on nominal 100mm diameter, 150mm high cylindrical specimens cut and cored from over-height 150mm dia. gyratory specimens [10].

In case of the Flow time test, a static load is applied to the specimen and the resulting strains are recorded as a function of time. Flow time is defined as the time when the minimum rate of change in strain occurs during the creep test, which is determined by differentiation of the strain versus time curve.

The Flow number test is a variation on the repeated load permanent deformation test in which an haversine axial compressive load pulses are applied to the specimen, the duration of the load pulse is 0.1 sec. followed by a rest period of 0.9 sec. The permanent axial deformation measured at the end of the rest period is monitored during repeated loading and converted to strain by dividing by the original gauge length. Flow number is the number of load pulses when the minimum rate of change in permanent strain occurs during the repeated load test which is determined by differentiation of the permanent strain versus the number of bad cycles curve.

Dynamic Modulus is the ratio of the stress amplitude to the strain amplitude for asphalt concrete subjected to sinusoidal loading. In case of the Dynamic Modulus test, a continuous haversine axial compressive load is applied to the specimen at a given temperature and loading rate, the applied stresses and resulting axial strains are measured as a fraction of time and is used to calculate the dynamic modulus and phase angle which are defined by equations 2 and 3 respectively.

$$|E^*| = \sigma_o / €_o \qquad (2)$$

$$\Phi = (T_1 / T_p)\, 360 \qquad (3)$$

The rutting resistance of the mixes increases as the DM at high temperature increases.

Based on the literature review conducted on the above laboratory performance evaluation tests, it is seen that majority of the tests are focussed on the evaluation of rutting behaviour of bituminous mixture layer of the flexible pavement. Also it is observed that the first stage of rutting phenomenon for newly constructed pavement is the primary consolidation stage which is not only confined to bituminous layer but the primary consolidation happens at the level of base, sub-base and sub-grade layers of the flexible pavement [17].

Fig. 3. Simple Performance Test (SPT) Device in FHWA Mobile Asphalt Laboratory [18]

4. Accelerated Pavement Testing (APT) methods

Accelerated Pavement Testing (APT) is a sophisticated technique employed to assess the performance of fully constructed pavements in a manner that significantly expedites the evaluation process when compared to traditional long-term pavement performance monitoring. Traditionally, investigating the deleterious effects of environmental conditions and vehicular traffic on the condition and overall performance of pavement structures necessitates extended periods, sometimes spanning years, of rigorous examination under actual field conditions. This protracted timeline for data collection can be attributed to the gradual, cumulative nature of the damage that pavements experience in real-world settings [19].

The concept underlying Accelerated Pavement Testing is to employ specialized, full-scale mobile or fixed testing equipment that replicates the effects of environmental factors and traffic-induced stresses on pavements in a compressed timeframe. In essence, APT creates an accelerated microcosm of the real-world conditions that pavements encounter, allowing researchers to observe how these conditions impact the pavement's condition and performance within weeks or months, rather than the decades that would be required for comprehensive, long-term monitoring. The central objective of APT is to furnish results that are gleaned from assessments of full-scale constructed pavements subjected to realistic loadings, all while expediting the process by artificially accelerating the damage through precise control of loading conditions and environmental variables. This expedited approach is instrumental in providing timely insights into the performance of pavements, which, in turn, can inform decisions regarding pavement design, materials, and maintenance (Fig. 4).

Fig. 4. HVS Mk VI of the Ministry of Transport, Kingdom of Saudi Arabia [19]

Traditionally, without APT, the assessment of pavement performance relies on the painstaking collection of data over many years or even decades. This extended period of observation is necessary because pavements, subjected to the incessant onslaught of traffic and environmental forces, gradually exhibit wear and damage over time. While long-term monitoring provides invaluable real-world insights, it lacks the agility to offer swift responses to evolving issues in pavement performance or to test and evaluate innovative pavement designs or materials in a timely manner. APT, on the other hand, empowers researchers to circumvent the time constraints associated with traditional long-term monitoring. By inducing controlled damage and degradation through the manipulation of loading conditions and environmental factors, APT can reveal the potential outcomes and effects that would typically take years to manifest in natural settings. This allows for a more rapid assessment of a pavement's vulnerability to various stressors, a crucial advantage for decision-makers tasked with maintaining and improving transportation infrastructure.

5. Roller compactor cum rut analyser

The ‘Roller compactor cum rut analyser (RCRA), is a compactor that boasts indigenous innovation and a host of distinctive features (Fig. 5). This compactor has the remarkable ability to consistently apply a pressure of 0.6 n/mm^2, and when necessary, it can elevate this pressure to as much as 3 n/mm^2. Furthermore, it allows for the adjustment of the rolling speed as needed. Another noteworthy feature is the incorporation of a temperature control unit, which adeptly maintains the predetermined compaction and rut test temperatures. One of the most valuable aspects of this equipment is its capacity to record densification data during the compaction process, enabling the derivation of essential compaction characteristics for the specimen under investigation [20].

Fig. 5. Roller compactor cum rut analyser [20]

The RCRA is a hydraulic compactor that incorporates a twin non-return valve system and is equipped with a Programmable Logical Circuit (PLC). The PLC is linked to vertical and horizontal transducers, facilitating the precise recording of changes within a range of ±5 mm. The RCRA stands out due to a range of innovative features, including the ability to replicate the field compaction effect, commonly referred to as the 'kneading effect', within a laboratory setting during the compaction of bituminous mix specimens. This capability is invaluable for replicating real-world conditions and their impact on specimen compaction. Additionally, the RCRA excels in its ability to meticulously record densification data throughout the specimen compaction process. This data provides essential insights into how the specimen responds to compaction efforts, aiding in the assessment of its characteristics.

The compactor's capacity to maintain a preselected temperature during compaction or rutting tests is a notable advantage, ensuring that experiments are conducted under controlled conditions. The stability of the RCRA is further underscored by its independence from the need for a dedicated foundation for installation. It is conveniently mounted on wheels, allowing for easy transport, making it a versatile tool that can serve as a quality control machine either at construction site labs or within a laboratory environment in academic institution. Ease of operation and minimal maintenance requirements make the RCRA a practical choice for researchers and technicians alike. Its ability to apply pressure ranging up to 3 N/mm² offers the flexibility needed to study the effects of varying tire and compaction pressures on the mix. Furthermore, the compactor allows for adjustments in rolling speed during the rolling or rutting processes, ensuring that the impact of different speeds on the mix can be thoroughly investigated.

An additional advantage of the RCRA is its high degree of automation. With minimal human intervention required, the entire process of slab compaction and rutting tests can be carried out seamlessly, reducing the potential for human error and enhancing the reliability of the test results. In essence, the RCRA represents a significant leap forward in compaction technology, introducing a host of features that not only expedite the testing process but also enhance the precision and reliability of results in bituminous mix design and quality control.

6. Conclusions

Rutting in bituminous pavements is a global concern due to the accumulation of plastic deformation from traffic loads and environmental factors, exacerbated by temperature fluctuations causing stiffness changes and thermal stresses. Extensive research has been conducted to understand and address this issue. Researchers use a multi-faceted approach, combining in-situ methods and laboratory testing. In-situ methods, like instrumented pavement test track sections, offer real-world insights into pavement behaviour. Laboratory testing techniques simulate and evaluate asphalt mix deformation under controlled conditions, using tests like the Cooper Wheel Tracking Test and Hamburg Wheel Tracking Device. Worldwide adoption of testing protocols underscores the global importance of improving road surfaces. Accelerated Pavement Testing (APT) plays a pivotal role in bridging the gap between theoretical pavement design and field performance by simulating environmental and traffic-induced damage more rapidly. APT expedites decision-making and contributes to the development of safer and more resilient roadways through efficient real-world insights.

Moreover, the introduction of the Roller compactor cum rut analyser (RCRA) represents a significant advancement in compaction technology. This equipment offers precise pressure control, adjustable rolling speed, and temperature control, making it an invaluable tool for researchers and quality control in bituminous mix design. Its high degree of automation reduces the potential for human error and enhances the reliability of test results. With the RCRA, experiments can be conducted under controlled conditions, allowing researchers to gain insights into how specimens respond to compaction efforts and assess their characteristics.

In conclusion, addressing rutting in bituminous pavements is a critical endeavour to ensure the durability and performance of road surfaces. The combination of in-situ methods, laboratory testing, and innovative equipment like the RCRA provides a comprehensive approach to understanding and mitigating rutting issues, ultimately contributing to safer and more resilient transportation infrastructure.

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