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Artificial Intelligence-Based Prediction of Asphalt Binder Aging and Pavement Distress

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Abstract- Asphalt binder aging significantly affects the long-term performance and durability of flexible pavements, leading to various pavement distresses such as cracking, rutting, and raveling. Accurate prediction of asphalt binder aging and associated pavement deterioration is essential for effective pavement design, maintenance planning, and lifecycle cost management. In recent years, Artificial Intelligence (AI) techniques have emerged as powerful tools for modeling complex, nonlinear relationships among environmental factors, material properties, traffic loading, and aging characteristics of asphalt binders. This work explores the application of Artificial Intelligence–based methods for predicting asphalt binder aging and pavement distress. Various AI techniques such as Artificial Neural Networks (ANN), Support Vector Machines (SVM), Machine Learning (ML), Deep Learning (DL), and hybrid optimization models are examined in terms of their ability to analyze large datasets and provide accurate predictions. The study existing literature on AI-driven predictive models that incorporate factors such as temperature variation, oxidation processes, traffic load, binder composition, and environmental conditions. Furthermore, the paper highlights the advantages of AI models over traditional empirical and mechanistic methods, including improved prediction accuracy, adaptive learning capability, and efficient data-driven decision-making. The work also identifies current research gaps, challenges in data availability, and opportunities for integrating AI with mechanistic–empirical pavement design approaches. Overall, the study provides a comprehensive overview of recent advancements in AI-based prediction of asphalt binder aging and pavement distress, emphasizing its potential to enhance pavement performance evaluation, optimize maintenance strategies, and support sustainable infrastructure development.

Keywords- Asphalt pavements, bleeding prediction, Artificial neural network (ANN), pavement performance, skid resistance, sensitivity analysis.

I. INTRODUCTION

Flexible pavement conditions have an enormous impact on road safety and performance and are affected by a variety of factors like traffic patterns, climate, development parameters, construction methodology, and protective methods. Since service life depends on the flexible pavement situation, it is essential to conduct a control procedure as a management system of pavement. To ensure the long-term sustainability of roadways, minimize maintenance costs, and conserve resources, paving materials must be carefully chosen. The optimum design of both the pavement mixture and roadway is of great importance [1].

Artificial Intelligence (AI) is a branch of informatics in which computers perform human-like tasks, such as correctly detecting and learning inputs for perception, problem solving, reasoning, knowledge representation, and planning. Different innovative AI technologies have been designed to mimic the cognitive capacities of humans to deal with more complex problems intentionally, intelligently, and adaptively. In general, AI may be considered a combination of machine learning and data analysis [2]. Scientists hope to find more precious or attractive information underlying the physical effect of additives and experimental data. AI, as an evidence-based technique with high potential, has had success and dependability in many academic topics and projects. Therefore, this research systematically analyzed the utilization of AI in various types of flexible pavement, including pavement design, construction, cost, and maintenance. Prior studies on this topic over the last decade, especially since 2014, were gathered for this research. Specifically, the analysis aimed to distinguish the modern challenges and future headings of the research, allowing scientists to detect significant areas for subsequent study.

II. PAVEMENT CONDITION ASSESSMENT

Pavement condition assessment is an important element of the decision-making procedure of a pavement management system. It presents a quantitative measure for evaluating pavement section deterioration for a whole pavement network [1]. There are two purposes behind the assessment of pavement condition: to recognize maintenance and rehabilitation requirements and to monitor the pavement network conditions [2]. Pavement condition can be classified by a range of performance indicators such as the Pavement Condition Index (PCI), International Roughness Index (IRI), or the Present serviceability index (PSI) by utilizing various features of road surfaces. For highway pavements, these indicators usually comprise pavement surface deterioration, deflection, rut depth, roughness, and skid resistance [1].

Many agencies use conventional and statistical approaches for determining pavement performance indicators without considering uncertainty. Therefore, previous studies applied artificial intelligence techniques in the pavement performance determination. For pavement classification, many techniques have been used over the years. Sagheer et al. established a knowledge-based system for pavement deterioration classification by using logic programming and Prolog language to diagnose distresses in flexible pavements [3]. Khurshid et al. developed an analytical methodology to find an optimal facility performance threshold for the pavement maintenance system based on cost effectiveness [4]. Terzi used data mining technique for modelling pavement serviceability index PSI for flexible pavement [5].

Many indices that combine the effects of all distresses found in pavement sections are being used by highway authorities for estimating maintenance need priorities for each section. Calculation procedures for different indices range from simple subjective condition assessment to mathematical equations [17]. The most common condition indices are present serviceability index (PSI), an evaluator used to describe the functional condition with respect to ride quality, and also Pavement condition index (PCI) which is another index commonly used to describe the extent and severity of distresses on a pavement section [10].

III. PAVEMENT CHARACTERISTICS AND DETERIORATION

Asphalt pavements consist of several layers, including the asphalt layer at the top, followed by the base layer, subbase layer, and subgrade layer. The overall performance of the pavement is affected by the material properties of each layer, the thickness of each layer, applied traffic, and environmental conditions. Asphalt pavements experience various distresses in the field, including rutting (or permanent deformation), cracking, and moisture damage. Rutting, cracking, and roughness increase with time. Pavement engineers conduct regular distress surveys to rate the conditions of pavement and determine the need for surface treatments. Performance decay models are often used in an asset management system to predict future performance in response to maintenance and rehabilitation treatments. Numerous factors cause pavement deterioration. In most cases, traffic level has a significant impact on pavement deterioration. Pavement characteristics such as the layers' elastic moduli and strength affect how the pavement deteriorates. Environmental factors also influence this deterioration. Environmental factors include moisture, how often freeze-thaw occurs, whether the sections are underlain with permafrost, and many others.

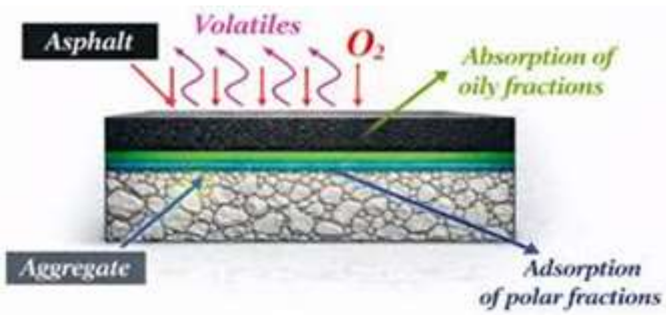

Fig.1. Asphalt pavements.

IV. MATERIAL AND METHOD /PROPOSED METHODOLOGY

Overview

This chapter presents the detailed methodology adopted for the prediction of asphalt binder aging and pavement distress. The research methodology includes the selection and characterization of asphalt binder materials, laboratory simulation of short-term and long-term aging processes, evaluation of physical, rheological, and chemical properties of aged binders, pavement distress assessment, and development of predictive models. The experimental results obtained from laboratory investigations are integrated with statistical and machine learning approaches to establish relationships between binder aging characteristics and pavement performance.

RESEARCH METHODOLOGY FRAMEWORK

The overall research methodology consists of the following stages:

1. Selection of asphalt binder materials
2. Initial characterization of virgin asphalt binder
3. Laboratory aging simulation
4. Evaluation of aged binder properties
5. Pavement distress data collection
6. Identification of aging indicators
7. Development of prediction models
8. Model validation and performance evaluation

Materials Used

Asphalt Binder

The primary material used in this research is asphalt binder. Conventional paving grade asphalt binder is selected based on its suitability for highway pavement applications. Asphalt binder is a dark-coloured, sticky, semi-solid or viscous material obtained as a by-product during the refining of crude petroleum. It is one of the most important components of flexible pavement construction because it acts as a binding agent that holds aggregate particles together and provides strength, flexibility, and durability to asphalt mixtures.

In asphalt pavement systems, the binder surrounds and coats the aggregate particles, creating a strong adhesive bond and providing resistance against traffic loading and environmental effects. The performance of asphalt pavement is highly dependent on the physical, chemical, and rheological properties of the asphalt binder.

V. RESULT AND SIMULATION

Analysis Criteria

This chapter presents the experimental results and detailed analysis of asphalt binder aging behaviour and pavement distress evaluation. The study investigates the effect of short-term and long-term aging on asphalt binder properties through physical, rheological, and chemical characterization tests. The results obtained from virgin binder, RTFOT-aged binder, and PAV-aged binder samples are compared to understand the progression of aging.

The experimental results are further analysed to identify the most significant aging indicators and their relationship with pavement distress parameters. Based on the obtained dataset, prediction models are developed to estimate pavement distress caused by asphalt binder aging.

The analysis includes:

- Physical characterization results
- Rheological characterization results
- Chemical aging analysis
- Aging index development
- Asphalt mixture performance evaluation
- Pavement distress prediction analysis
- Machine learning model performance evaluation

Physical Characterization Results Of Asphalt Binder

Physical properties of asphalt binder were evaluated for three aging conditions:

1. Virgin Asphalt Binder (Unaged)
2. RTFOT Aged Binder (Short-Term Aging)
3. PAV Aged Binder (Long-Term Aging)

The measured properties include:

- Penetration value
- Softening point
- Ductility
- Rotational viscosity

Penetration Test Results

Penetration value indicates the hardness and consistency of asphalt binder. A reduction in penetration value represents binder hardening due to aging.

Table 1 Variation of Penetration Value with Aging

Aging Condition	Penetration (0.1 mm)	Reduction (%)
Virgin Binder	68	-
RTFOT Aged Binder	57	16.17
PAV Aged Binder	43	36.76

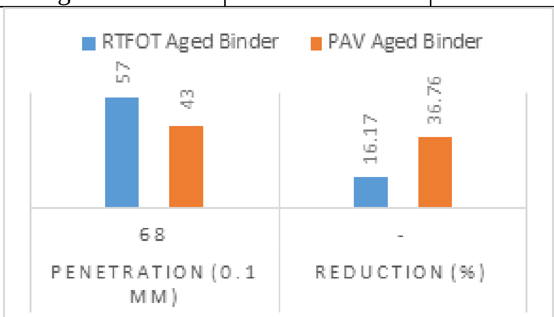

Fig.2 Variation of Penetration Value with Aging.

Softening Point Results

Softening point represents the temperature susceptibility and high-temperature stability of asphalt binder.

Table 2 Variation of Softening Point

Aging Condition	Softening Point (°C)
Virgin Binder	48.5
RTFOT Aged Binder	53.2
PAV Aged Binder	59.8

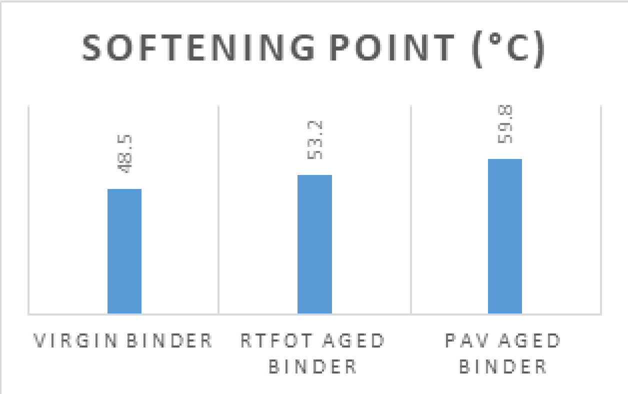

Fig.3 Variation of Softening Point.

Ductility Test Results

Ductility represents the ability of asphalt binder to deform before failure.

Table 3 Variation of Ductility

Aging Condition	Ductility (cm)
Virgin Binder	112
RTFOT Aged Binder	82
PAV Aged Binder	54

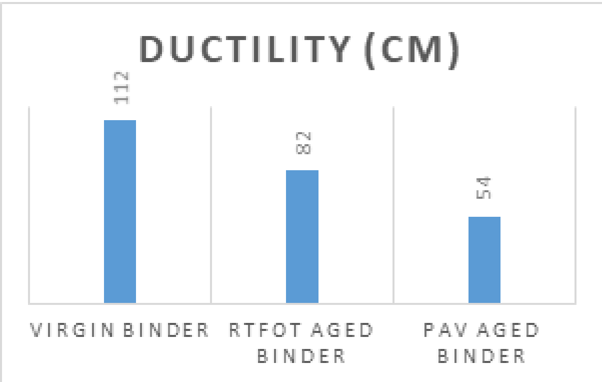

Fig.4 Variation of Ductility.

Analysis

The ductility test results demonstrate the effect of aging on the flexibility and deformation capability of asphalt binder. The virgin asphalt binder exhibited a ductility value of 112 cm, indicating high flexibility and better ability to withstand tensile deformation without cracking. After short-term aging using the Rolling Thin Film Oven Test (RTFOT), the ductility value decreased to 82 cm, showing a reduction in flexibility due to oxidation, volatilization of lighter components, and increased binder stiffness.

The long-term aged binder obtained from the Pressure Aging Vessel (PAV) test showed a further reduction in ductility to 54 cm, indicating significant hardening and loss of deformation capacity after prolonged aging. The continuous decrease in ductility with aging confirms that oxidation-induced molecular changes make asphalt binder more brittle and less capable of accommodating traffic-induced stresses and temperature variations. Therefore, reduced ductility is considered an important indicator of increased cracking susceptibility and deterioration of long-term pavement performance.

Asphalt Binder Aging Experimental Readings (Input Dataset)

Table 4: Binder Aging Properties

Aging Time (Year)	Penetration (0.1mm)	Viscosity (Pa.s)	Complex Modulus G* (kPa)	Phase Angle (°)	Carbonyl Index	Rut Depth (mm)	Fatigue Life (Cycles)
0	68	0.42	1.85	82.5	0.021	7.8	82500
2	62	0.55	2.65	78.4	0.031	6.9	74000
5	57	0.68	3.42	75.8	0.045	5.4	61300
8	50	0.89	4.85	70.6	0.063	4.8	49500
10	43	1.15	6.75	65.4	0.086	4.2	38700
15	36	1.48	8.90	60.2	0.112	3.7	29500
20	30	1.92	11.60	55.8	0.145	3.2	21500

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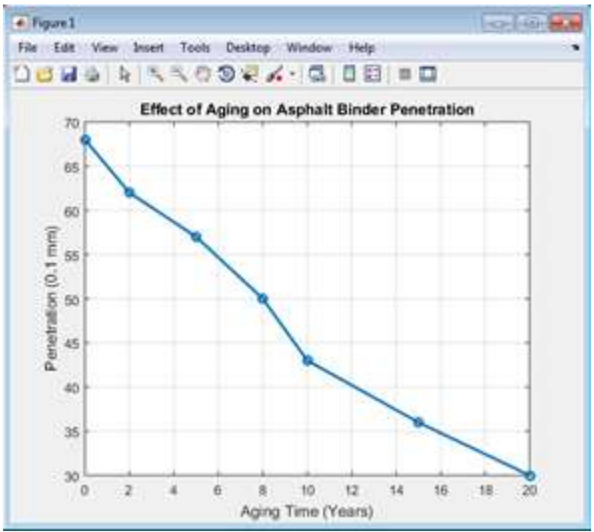

Fig.5 ANN result Year vs Binder Penetration and Viscosity.

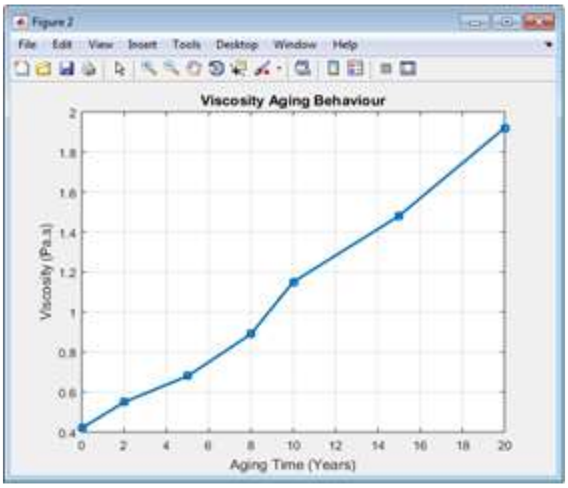

Fig.6 ANN result Year Vs Rheological Characterization Results and Chemical aging.

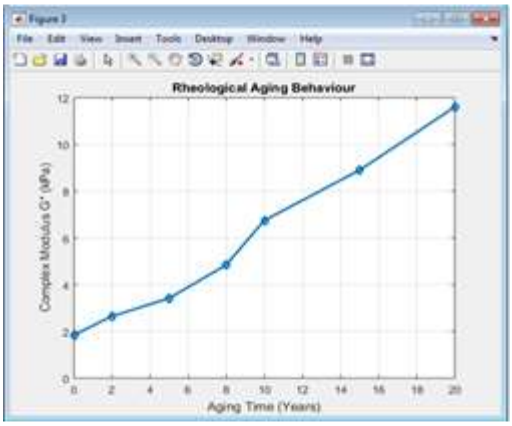

Fig.7 ANN result Year Vs Fatigue Life.

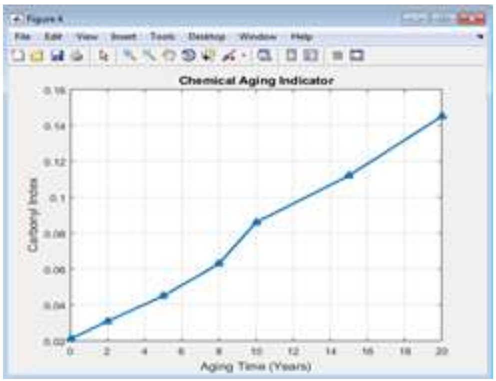

Fig. 8 ANN result Year Vs Predicted Fatigue Life.

VI. CONCLUSION AND FUTURE SCOPE CONCLUSION

The present research work entitled "Prediction of Asphalt Binder Aging and Pavement Distress" was focused on understanding the influence of asphalt binder aging on material properties, pavement performance, and the development of a prediction framework for estimating pavement distress. The study investigated the changes occurring in asphalt binder due to short-term and long-term aging through physical, rheological, and chemical characterization techniques. The experimental findings were further correlated with pavement distress parameters to establish the relationship between binder deterioration and pavement performance.

The physical characterization results confirmed that asphalt binder undergoes significant hardening with increasing aging severity. The penetration value decreased from 68 (0.1 mm) for virgin binder to 57 (0.1 mm) after RTFOT aging and 43 (0.1 mm) after PAV aging, indicating progressive loss of softness and flexibility due to oxidation. The softening point increased from 48.5°C for virgin binder to 53.2°C after RTFOT aging and 59.8°C after PAV aging, demonstrating improved high-temperature stability but increased stiffness of aged binder.

Future Scope

The future scope of this research lies in improving the prediction of asphalt binder aging and pavement distress through the integration of advanced machine learning and artificial intelligence techniques. Future studies may include field performance data, real-time pavement monitoring systems, and environmental factors such as temperature, moisture, and traffic loading to enhance prediction accuracy.

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